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
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.
Zero-Boil-Off Tank (ZBOT) Experiment

- 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:

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

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

Schrage Interfacial Mass Transfer:

\[ I_v = \frac{2 \sigma}{2 - \sigma} \frac{1}{\sqrt{2 \pi RT_I}} \left[ P_{sat}(T_I) - P_v \right] \]

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

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

Stefan Wind:

\[ I_v = - \left( \frac{\rho D_m}{1 - \omega_v} \right) \nabla \omega \cdot \hat{n} \quad \checkmark \]
Effects of Residual Air (Non-Condensable) in the Ullage on Transport
1G Self-Pressurization: Model Prediction vs Experiment

Time = 6000s

No air

Air at 20 Torr

With Residual Air
1G Self-Pressurization Simulations

Time = 6000s

- Temperature (°K)
  - 296.30
  - 296.07
  - 295.84
  - 295.61
  - 295.38

- Mass flow rate (kg/s)
  - Pure Vapor
  - Vapor w/ Air

- Distance along tank radius (m)

- Interface pressure
  - Vapor w/ Air

- Interface temperature
  - Pure Vapor
  - Vapor w/ Air
1G 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.
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

10260s

![Diagram of pressure control simulation](image)

- [Graph 1](image): Distance along tank radius (m) vs. ω_interface. Key points: 8350s
- [Graph 2](image): Distance along tank radius (m) vs. T_Interface. Key points: 8264s, 8350s

**Graph 1 Legend:**
- Red line: Vapor w/ Air

**Graph 2 Legend:**
- Blue line: Pure Vapor
- Red line: Vapor w/ Air
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

With Residual Air

Time = 43200s

Temperature (K)

311.00
307.75
304.50
301.25
298.00

Time = 43200s

Vapor Mass (kg)

0.999275
0.999262
0.999249
0.999236
0.999223

36000s

distance along axis (m)

Vapor w/ Air

36000s

Vapor w/ Air

36000s

Pure Vapor

Vapor w/ Air

36000s
ZBOT Simulations: Micro-G Pressure Control

• 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

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

8s

distance along axis (m)

$m_{\text{dot,interface}}$ (kg/s) vs. distance along axis (m)

$\omega_{\text{interface}}$

8s

$\omega_{\text{interface}}$ vs. distance along axis (m)

$T_{\text{interface}}$

8s

$T_{\text{interface}}$ vs. distance along axis (m)

Pure Vapor
Vapor w/ Air

ZBOT Simulations: Micro-G Pressure Control

- 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

Time = 500s

- \( \omega \) (Vapor)
- \( T \) [K]
- 0.9993
- 294.00
- 0.9982
- 303.75
- 0.9971
- 303.50
- 0.9961
- 308.25
- 0.9950
- 313.00

- \( m \) dot\(_{\text{interface}}\) [kg/s]
- 0.004
- 0.002
- 0.000
- -0.002
- -0.004
- -0.006
- -0.008
- -0.01
- -0.012

- distance along axis (m)
- 500s

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

- \( \omega \)\(_{\text{interface}}\)
- 0.99
- 0.985
- 0.98
- 0.975
- 0.97
- 0.965
- 0.96
- 0.955

- distance along axis (m)
- 500s

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

- \( T \)\(_{\text{interface}}\)
- 303
- 302
- 301
- 299
- 297
- 296
- 295

- distance along axis (m)
- 500s

- Pure Vapor
- Vapor w/ Air
- Vapor w/ Air - Marangoni Effect
ZBOT Simulations: Micro-G Pressure Control

No air

Residual Air

Residual Air-Marangoni

No Air-Marangoni
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)