Multi-Node Modeling of Cryogenic Tank Pressurization System using Generalized Fluid System Simulation Program

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Purpose & Objective

• Historically, Cryogenic Tank Pressurization is either modeled by a single node using Fluid System Code (GFSSP & ROCETS) or by high fidelity Navier-Stokes code (FLUENT or CFX).

• Use of multi-node modeling using Fluid System code has not been explored. The main purpose of this paper is to describe a multi-node system modeling of cryogenic tank pressurization in GFSSP.

• In recent years, a test program has been conducted at NASA/MSFC to measure boil-off of cryogenic liquid propellant in a flight tank to support United Launch Alliance’s IVF (Inter Vehicular Fluid) program where boil-off propellants are used to pressurize the tank.

• The model results have been compared with test data.
Example of Heat Exchanger Model to define Network elements of a conjugate heat transfer problem

**GFSSP (Generalized Fluid System Simulation Program)**

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**Unknown Variables**

1. Pressure
2. Flowrate
3. Fluid Temperature
4. Solid Temperature
5. Mass

**Governing Equations to Solve**

1. Mass Conservation Equation
2. Momentum Conservation Equation
3. Energy Conservation Equation of Fluid
4. Energy Conservation Equation of Solid
5. Thermodynamic Equation of State

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**Thermodynamic and Thermo-physical properties are obtained from built-in GASP and GASPAK**

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Nitrogen
- 250 °F
- \( m = 2.59 \text{ lb/s} \)

Nitrogen
- 70 °F
- \( m = 2.63 \text{ lb/s} \)
Program Structure & Numerical Scheme

Graphical User Interface (VTASC)
- Creates Flow Circuit
- Runs GFSSP
- Displays results graphically

Input Data File

Solver & Property Module
- Equation Generator
- Equation Solver
- Fluid Property Program

Output Data File

User Subroutines
- Time dependent process
- Non-linear boundary conditions
- External source term
- Customized output
- New resistance/fluid option

New Physics

Mass Conservation
- \( \dot{m} \), \( m \)

Momentum Conservation
- \( \dot{m} \), \( m \), \( \dot{m} \), \( m \)

Energy Conservation
- \( m \), \( h \), \( m \), \( h \)

Equation of State
- \( m \), \( p \), \( T_f \)

Heat Conduction
- \( T_s \), \( T_f \), \( T_f \), \( T_f \)

Thermodynamic Property
- \( p \), \( h \)
Review of Tank Pressurization Model

• In Liquid Propulsion System, accurate modeling of Cryogenic Tank Pressurization is needed to
  a) Ensure safe operation of the turbo-pump
  b) Estimate amount of pressurant requirement
  c) Estimate boil-off of Liquid Propellant

• Cryogenic Tank Pressurization model must account for
  a) Heat Transfer between ullage and wall
  b) Heat Transfer between ullage and liquid propellant
  c) Evaporative mass transfer between liquid propellant and ullage
Review of Tank Pressurization Model
Zero Dimensional Model

Helium
P = 67 psia
T = -264 °F
V = 25 ft³

LOX Propellant
P = 74.86 psia
T = -264 °F
V = 475 ft³
T = -264 °F

Fluid: He
P = 95 psia
T = 120 °F

C₁ = 0.6
A = 0.785 in²

Fluid: LOX
P = 74.76 psia
T = -264 °F

C₁ = 0.0
A = 4015 in²

LOX Propellant to Engine
P = 50 psia

Aluminum Tank
Diameter = 71.5 in
Wall thickness = 0.375 in

Ullage Node

Pseudo Boundary Node

Propellant Surface

Propellant Node

P = 50 psia
Zero Dimensional Model Results

Tank Bottom

Ullage Gas

Tank Wall

Boiloff Ibis
Zero Dimensional Model Validation

- **Collapse Factor Correlation (Epstein)**
  - Ratio of *actual* pressurant consumption to an *ideal* pressurant consumption which assumes **no** heat or mass transfer

\[
\frac{w_p}{w_p^0} = \left\{ \frac{T_0}{T_s} - 1 \right\} \left[ 1 - \exp(-p_1 C^{p_2}) \right] \times \left[ 1 - \exp(-p_3 S^{p_4}) \right] + 1 \times \exp \left[ -p_5 \left( \frac{1}{1 + C} \right)^{p_6} \left( \frac{S}{1 + S} \right)^{p_7} Q^{p_8} \right]
\]

where:

\[
w_p^0 = \rho_G^0 \Delta V \\
C = \frac{(\rho c_p^0 t)_w}{(\rho c_p)_G^0} \frac{T_s}{D_{eq} T_0} \\
S = \frac{h_c \theta_T}{(\rho c_p)_G^0 D_{eq} T_0} \\
Q = \frac{\dot{q} \theta_T}{(\rho c_p)_G^0 D_{eq} T_0}
\]

- **Pressurization Model Validation**
  - **GFSSP** Collapse Factor Prediction: **1.46**
  - Epstein Correlation Collapse Factor Prediction: **1.51**
    - **GFSSP** Prediction Discrepancy: **-3.3%**
One Dimensional Self-Pressurization Model of Cryogenic Tank

One Dimensional Discretization of Ullage

Multi Layer Insulation

Foam Insulation

Metal

Multi-Purpose Hydrogen Tank
Results of Self-Pressurization Model

![Graph showing predicted and measured ullage pressure over time.](image)

![Diagram of system components including Back Pressure Orifice, Spray Bar, Cold Side of HEX, and Heater.](image)

![Graph showing predicted and measured ullage temperature over time.](image)
Integrated Vehicle Fluid System Overview
Test Program at MSFC
Flight Tank provided by ULA
Two Dimensional Axisymmetric Model of Tank Pressurization

Tank was tested at 75% and 45% Fill Level

Working Fluid: Nitrogen, Tank Height \(\approx 10 \text{ ft} \), Tank Dia \(\approx 10 \text{ ft}\)
Heat and Mass Transfer Model at Liquid-Ullage Interface

Heat Transfer Coefficients using Natural Convection

\[ h_{UI} = K_H C \frac{k_f}{L_s} \text{Ra}^n = h_{IL} , \]

\( C = 0.27, \ n = 0.25, \ K_H = 0.5 \)

Net Heat Transfer Rate:

\[ Q_{\text{net}} = \dot{m} \left[ C_{P,i} (T_I - T_L) + h_f g \right] \]

Evaporative Mass Transfer:

\[ Q_{UI} = h_{UI} A (T_U - T_I) \]
\[ Q_{IL} = h_{IL} A (T_I - T_L) \]

\[ \dot{m} = \frac{Q_{UI} - Q_{IL}}{h_{fg}} . \]
Results for 75% Fill Level

**Ullage Pressure**

- GFSSP
- Test Data

**Ullage Temperature**

- 79%
- 92%
- 99.5%

**Wall Temperature**

- 97%
- GFSSP
- Test data

Temperature contour/stream traces

- Color scale from -130.005 to -144.45
Results for 45% Fill Level

Temperature contour /stream traces

Ullage Pressure

Time (Seconds)

Time (Seconds)

Boil-off

Ullage Temperature

Time (Seconds)
Conclusions

• This paper demonstrates the feasibility of system level modeling of tank pressurization using multiple nodes.
• The ullage of a flight tank has been modeled using 25 nodes and 40 branches where mass and energy conservation equations were solved at the nodes and momentum equations are solved at the branches.
• Gravity, heat and mass transfer at the liquid vapor interface, and heat transfer between solid and fluid are accounted for in the governing equations.
• The model results have been verified by comparing with test data.
• The advantage of using multiple nodes in a system level code is that it allows prediction of recirculation and stratification with a fraction of the computational cost of a high fidelity Navier-Stokes code.
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• More information about GFSSP is available at https://www.nasa.gov/gfssp
• GFSSP is available free of cost for US Government work from MSFC Tech Transfer Office https://software.nasa.gov/software/MFS-33019-1