Prediction of Cryogenic Propellant Tank Active Pressure Control by Jet Induced Mixing

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Background

• Refueling in LEO for deep space missions have several challenges
• Cryogenic propellant storage tank
  – Liquid hydrogen (LH2) and liquid oxygen (LOX)
• Cryogenic fluid management technologies
  – Mixing destratification
  – Filling and venting
  – Refrigeration
  – Pressurization
  – Liquid acquisition device (LAD)
Background (Cont’d)

• “Heat is the enemy”
  – Radiation heat penetrates through insulation layers
  – Heat leaks through conduction from structural components such as struts (localized heating)
  – Causes thermal stratification in microgravity

• Thermodynamic vent system (TVS) operates with jet mixing technology
  – Reduces thermal gradients within the fluid
  – Promotes condensation at the interface to reduce tank pressure

![Diagram of Thermodynamic Vent System (TVS)]
Research Objective

• Develop a comprehensive nodal model to predict active pressure control of cryogenic propellant tanks

• Simulate jet induced mixing and interfacial heat and mass transfer
  – Need accurate closure relations using system level analysis code
  – Jet is not self-similar near the nozzle ($L/D < 25$)
  – Confined flow due to both wall and bubble interface

• Demonstrate the capabilities of SINDA/FLUINT for fast simulation of jet induced mixing inside a cryogenic propellant tank
Technical Approach

• Primarily leverage a nodal code, namely SINDA/FLUINT, to reduce computational cost
• Construct a nodal model representing ullage, jet flow, and bulk liquid regions in a cryogenic propellant tank
• Use CFD code simulations to obtain closures for internal flow parameters such as jet velocity, volumetric flow rate, and radius
• Implement various closures into the nodal model accounting for jet mixing and vapor condensation
• Validate predicted pressure evolution against Tank Pressure Control Experiment (TPCE) experimental results
• Jet induced mixing nodal model
  – Strategically discretized fluid domains
    • Ullage region
    • Jet region
    • Bulk liquid region
  – Requires correlations to resolve the internal flow
    • Volumetric flow rate of the jet flow
    • Radius of the jet flow
  – Requires correlation for mass and heat transfer at the interface
  – Liquid entrainment indirectly modeled
    • Mass flow rate increases downstream of jet due to entrainment
    • Satisfy conservation of mass within lumped nodes
Tank Pressure Control Experiment

- **Test conditions**
  - Working fluid: Freon 113
  - Acceleration: 1e-6g
  - System pressure $\approx 41$ kPa
  - Temperature $\approx 296$K (near saturation temperature)
  - Jet flow rate: 0.38 to 3.36 liters/min
  - Bond number : 0.034
  - Jet Reynolds number: 1,800 to 16,100
  - Jet Weber number: 0.29 to 22.29
  - Heaters A & B (0.05 to 0.12 W/cm²)

Experimental jet mixing case Run #6

Case Setup (Nodal)

- **Case description:** Tank depressurization due to jet induced mixing
  - Simulation time: 3 minutes (180 seconds)
  - Working fluid: Freon 113
  - Acceleration: 1e-6g
  - Fill level: 84%
  - Re = 2,217 ($u_j = 0.0933 \text{ m/s}$)

- **Initial conditions:**
  - Tank pressure = 47.15 kPa
  - $T_{\text{liq}} = 296.7\text{K}$

- **Boundary conditions**
  - Inlet: mass flow rate
  - Outlet: pressure outlet
Case Setup (Nodal)

- **Inlet temperature**

  \[ T(t) = at^6 + bt^5 + ct^4 + dt^3 + et^2 + ft + g \]

  ![Temperature graph](image)

  Polynomial coefficients:
  
  \[
  a = -9.1208 \times 10^{-13} \\
  b = 6.148 \times 10^{-10} \\
  c = -1.6252 \times 10^{-7} \\
  d = 2.1249 \times 10^{-5} \\
  e = -0.001437 \\
  f = 0.051365 \\
  g = 295.337
  \]

  RMSE = 0.0168
  \[ R^2 = 0.99797 \]

- **Pressure outlet**

  \[ p(t) = at^7 + bt^6 + ct^5 + dt^4 + et^3 + ft^2 + gt + h \]

  ![Pressure graph](image)

  Polynomial coefficients:
  
  \[
  a = -1.2934 \times 10^{-11} \\
  b = 5.3478 \times 10^{-9} \\
  c = -2.3603 \times 10^{-7} \\
  d = -1.8669 \times 10^{-4} \\
  e = 0.0343 \\
  f = -2.0247 \\
  g = 3.5741 \\
  h = 47130
  \]

  RMSE = 71.8239
  \[ R^2 = 0.9946 \]
Required Closures for Nodal Code

- Interfacial mass transfer

\[
\dot{m}_v = - \left( \frac{q_{il} + q_{iv}}{h_{fg}} \right) = - \left[ \frac{U_i A (T_{sat} - T_i) + U_v A (T_{sat} - T_v)}{h_{fg}} \right]
\]

- Liquid to interface heat transfer

\[
\text{Nu}_c = C \text{Pr}^m \text{Re}_{j,r}^n
\]

\[
\text{Re}_{j,r} = \frac{\rho vr}{\mu}
\]

\[
0.88 < C < 1.09
\]

\[
m = 1/3, \quad n = 1/2
\]

- Vapor to interface heat transfer
  - Assumes solid conduction (Nusselt number roughly equals to 1)


Required Closures for Nodal Code (Cont’d)

• Momentum closures for internal flow obtained through CFD model
  – 2D volume of fluid (VOF) model
  – Circular turbulent jet

E. Lan and S. Shi, "RANS-Based CFD Simulation of Jet-Induced Mixing and Jet Impingement on Large Bubble in Microgravity, Nuclear Technology, (2023).
• Nondimensionalized jet velocity
• Jet radius and volumetric flow rate from CFD simulation
• Volumetric flow rate obtained numerically by integrating the velocity profile up to jet radius
Results

• Tank pressure and temperature

\[ \text{Nu}_c = C \text{Pr}^m \text{Re}^n \]

\[ 0.88 < C < 1.09 \]

\[ m = 1/3 \]

\[ n = 1/2 \]
Results (Cont’d)

- Nodal code takes approximately 5 seconds to run a 3 minutes jet mixing case
- CFD code takes approximately 2 days
Conclusions

• A nodal framework was developed based on SINDA/FLUINT to simulate jet induced mixing and interface heat and mass transfer
• Jet closure models were obtained through CFD simulations
• A transient jet induced mixing case was simulated referencing TPCE jet mixing case Run #6
  – Pressure profile agrees well with experimental data
  – Liquid temperature agrees reasonably well
• Demonstrated capabilities of SINDA/FLUINT for fast simulation of jet induced mixing inside a cryogenic propellant tank
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Thank You and Questions?