14986 - Physics-Based Model for Online Fault Detection in Autonomous Cryogenic Loading System

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PHYSICS-BASED MODELING IN DESIGN & DEVELOPMENT NOV 2012
Contents

- Introduction
- Methodology
- Model Description
- Fault detection in transfer line
- Heat and mass leaks in the vehicle tank
- Work in progress
Loading Operation

Characteristic scales: L, D, d, Δt_p.
Flow rates: chilldown, reduced fill, fast fill, replenish
Fill time: T_{chill}, T_{red}, T_{fast}, T_{rep}
Total volume: V_{chill}, V_{red}, V_{fast}, V_{rep}

Horizontal pipe flow with small elevation
Typical Signals Measured During Loading

\[
\Delta V_w = \frac{\pi D L d \rho_w c_v (T_{am} - T_L)}{q_{ev} \rho_L}
\]
\[
\Delta V_R = \pi D L Q_R \Delta t_{load} / q_{ev} \rho_L
\]
\[
\Delta V_P = \pi D^2 L / 4
\]
\[
\Delta V_w + \Delta V_R + \Delta V_P \approx 60 \text{ gal}
\]

Complexity of the cryogenic loading operations is related to:

- Strongly non-equilibrium non-steady flow
- Chilldown
- Multiple fault regimes including mass and heat leaks
- Active control

Earlier Research

SINDA/FLUINT Tank model

Stratification (Continued) – GOES IV&V Pitch

Schematic of modeling elements

Paul Schallhorn, "LSP Upper Stage Propellant Tank Thermodynamic Modeling", 2010
Model of the Chilldown and Propellant Loading of the Space Shuttle External Tank

The Generalized Fluid System Simulation Program (GFSSP)

Figure 2. GFSSP Model of the KSC Ground System and Shuttle LOx Tank

Measured and predicted ullage pressure in the LH2 tank. Agreement is excellent until slow fill begins, at which point the model is no longer able to match the pressure cycling that occurs during loading. This may be caused by the two phase mixture present in the tank once slow fill begins.

Problem Formulation

The future autonomous system capable of accomplishing launch vehicle propellant load and drain without human interaction should be able to change its behavior in response to un-anticipated events.

The complexity of this problem dictates the necessity of

- development of a physics based model for loading operation that can reproduce accurately the time traces during the loading,
- predict system response to various deviations from the loading protocol,
- detect and localize system faults online.
Methodology

• The main element of the model is the NODE. In general it contains 3D conservation equations for the mass, momentum, and the energy

\[
\rho_t + (\rho u_\alpha)_\alpha = 0 \\
(\rho u_\alpha)_t + (\rho u_\alpha u_\beta)_{\beta} = -p_\alpha + \tau_{\alpha\beta,\beta} \\
(\rho E)_t + (\rho E u_\alpha)_\alpha = -(p u_\alpha)_\alpha + (u_\alpha \tau_{\alpha\beta})_{\beta} + (\kappa T_\alpha)_{\alpha}
\]

• In medium fidelity models the following assumptions are introduced
  ▪ Dynamics is one-dimensional (or quasi-two dimensional)
  ▪ Momentum equation is reduced $\nabla p = 0$ (in low Mach approximation $M << 1$). Except for the pipe and valve losses
  ▪ Equation of states of an ideal gas $E = c_v T$; $p = \rho R T$; $\rho E = \rho c_v / R = p / (\gamma - 1)$

\[
\dot{m}^{(i)} = J_{in}^{(i)} - J_{out}^{(i)} \\
\dot{p} = -\frac{\gamma p}{V} \dot{V} + \frac{\gamma - 1}{V} \sum_{k=1}^{N} \dot{Q}_k \\
T = \frac{p V}{\sum_{i=1}^{N} m^{(i)} R^{(i)}}
\]
Common types of the nodes

Ideal gas
\[ \dot{m}^{(i)} = J_{in}^{(i)} - J_{out}^{(i)} \]
\[ \dot{p} = -\frac{\gamma p}{V} \dot{V} + \frac{\gamma - 1}{V} \sum_{k=1}^{N} \dot{Q}_k \]
\[ T = \frac{pV}{\sum_{i=1}^{N} m^{(i)}R^{(i)}} \]

BL node
Correlations for the natural and forced convection

Interface
\[ \dot{Q}_i - \dot{Q}_v = J_{hv}h_{hv} + J_{hv}c_p(T_u - T_s)(\dot{Q}_i > \dot{Q}_v) \]

Wall
\[ \rho_v c_w V \frac{\partial T_w}{\partial t} = S_w h(T - T_w) \]

Liquid
\[ \dot{m}^{(i)} = J_{in}^{(i)} - J_{out}^{(i)} \]
\[ T = \text{const (20K or 77K)} \]

Pipe
\[ f = \begin{cases} \frac{fL}{	ext{Rey}} & \text{Rey} \leq 2000 \\ \frac{fT}{4000} & 4000 \leq \text{Rey} \\ \frac{fL + (fT - fL)(\text{Rey} - \text{ReL})}{\text{ReT} - \text{ReL}} & \text{otherwise} \end{cases} \]
Launchpad Sketch

Notice elevation at the Launchpad

\[ h = 25.8 \text{m} \] corresponding to \( \approx 18 \text{kPa} \)

FIGURE II-2  KSC LC 39 SSTO/DENSIFIED HYDROGEN BASELINE LOADING SYSTEM
Node Presentation of our Original Model

1. The reduced model is described by **16 state time-dependent variables**

- LH2, GH2 masses $m_{i1}$, $m_{i2}$ in Storage Tank (ST, $i = 1$) – 2 var
- LH2, GH2 and GHE $m_{i2}$, $m_{v2}$, $m_{g2}$ masses in External Tank (ET, $i = 2$) – 3 var
- Pressure $p_{vi}$ of GH2 in ST – 1 var
- Partial pressures $p_{v2}$, $p_{g2}$ of GH2 and GHE in ET – 2 var
- Vapor/gas volumes $V_{vi}$ in ST and ET – 2 var
- Vapor/gas temperatures $T_{vi}$ in ST and ET – 2 var
- Liquid temperatures $T_{li}$ in ST and ET – 2 var
- Film (surface) temperatures $T_{fi}$ in ST and ET – 2 var

2. There are total **7 constraints** on state variables

- 2 Equations of state for GH2 in ST and ET: $p_{vi}V_{vi} = m_{vi}R_{v}T_{vi}$
- 1 Equations of state for GHE in ST: $p_{g2}V_{v2} = m_{g2}R_{v}T_{v2}$
- 2 Equations relating vapor/gas volume to LH2 mass and total volume $V_{i} = V_{vi} + m_{v} / \rho_{v}$ in both tanks
- 2 Equations of state for film in both tanks: $p_{fi}(T_{fi}) = p_{vi} = p_{C}(T_{fi}/T_{C})$

3. There are total **9 ordinary time-dependent differential rate (and integral-differential) equations**
   for $16 - 7 = 9$ independent variables:
   - 5 mass conservation equations (for LH2 and GH2 in both tanks and GHE in ET)
   - 4 energy conservation equations (for GH2 and LH2 in both tanks)
9 Integral-Differential Equations

1) **5 Mass Conservation Rate Eqs:**

**ST tank**
- LH2: \[ \dot{m}_l = J_{lv1} - J_{boil} - J_{tr} \]
- GH2: \[ \dot{m}_v = J_{boil} - J_{v,vent1} - J_{lv1} \]

**ET tank**
- LH2: \[ \dot{m}_l = J_{lv2} + J_{tr} \]
- GH2: \[ \dot{m}_v = -J_{v,vent2} - J_{lv2} \]
- GHE: \[ \dot{m}_g = J_{g,in} - J_{g,vent2} \]

**Condensation-evaporation flow**
\[ J_{lvi} \] for \( i = 1, 2 \) is determined by film energy conservation in ET and ST (see next slide)

**Auxiliary rate equations:**

**Pressurizing mass flow from vaporizer:**
\[ \dot{J}_{boil} = \begin{cases} \frac{(J_{vap} - J_{boil})}{\tau_{vap}}, & J_{vap} - J_{boil} \geq 0 \\ 0, & \text{otherwise} \end{cases} \]

**Transfer line flow from ST to ET:**
\[ \dot{J}_{tr} = \left( \alpha_{eff}(t) \sqrt{|p_1 - p_2|} - J_{tr} \right)/\tau_{tr} \]

\( J_{vap}(p_1, t), \alpha_{eff}(t) \) are all determined by filling protocol
\( J_{v,vent i}(p_i, t), J_{g,vent 2}(p_2, t), J_{g,in}(p_2, t) \)
Comparison with Real Data: ET

Theoretical prediction for valve on-off oscillation loses its phase relative to experimental oscillations due to transient boil-off events in the ET, but once the transient decays, the phase of oscillation is recovered and the theoretical model correctly predicts real data.

- **Slow fill**: pressure rises quickly as tank chills and LH2 boils off, rate slows as tank gets cooler and boiling rate reduces.
- **Fast fill**: tank mostly chilled, so pressure rate mostly dependent on tank filling. As ullage space decreases, pressure rate is increased.
- **Reduced fast fill**: fill rate is reduced, so pressure rate reduces.

- In this first version of the model the frequency of the pressure pulses in the ET was reproduced qualitatively (2-3 times lower than measured).
- The fault detection based on the analysis of the pressure oscillations in the ET assumes that only one fault is detected while all other parameters take known nominal values.
- The fault detection required more than 200 sec to detect the fault.

**Topping**: vent valve opened.
Model of LH2 Loading

<table>
<thead>
<tr>
<th>Pressurization (GH2)</th>
<th>Pressurization (GHe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>F</td>
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<tr>
<td>0</td>
<td>0</td>
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<table>
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<th>Slow Fill: 553-2773s</th>
<th>1000</th>
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<tr>
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<td>F</td>
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<table>
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<th>Fast Fill: 2773-5570s</th>
<th>7500 gpm</th>
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<tbody>
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<table>
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<th>Reduced: 5570-6988s</th>
<th>850 gpm</th>
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</thead>
<tbody>
<tr>
<td>E</td>
<td>F</td>
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<tr>
<td>1</td>
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<table>
<thead>
<tr>
<th>Topping: 6988-9630s</th>
<th>800 gpm</th>
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<tbody>
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<table>
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<tr>
<th>Replenish: to EOR</th>
<th>mass preserving</th>
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</thead>
<tbody>
<tr>
<td>E</td>
<td>F</td>
</tr>
<tr>
<td>0</td>
<td>1</td>
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</table>
How many nodes should we add?

- In general IDAE model can be written in the form \( F_i \left( t, \dot{x}, x, a, u \right) = 0 \)

- The output of the model is a set of time series data \( \{ x_i(t, a, u) \} \)

- That have to be compared with experimental data \( \{ y_i(t, a, u) \} \)

\[
L = \sum_{i,j} \left( x_i(t_m) - y_i(t_m) \right)^2
\]

In a sense that the loss function is minimized and takes values below of some given threshold determined by the required accuracy of predictions.

We need minimum number of nodes that satisfy this criteria.
\[ \dot{m}_v = -J_{cd} + J_{\text{vap,in}} \]

\[ \dot{p}_u = -\frac{\gamma \rho u}{V_u} \dot{V}_u + \frac{\gamma - 1}{V_u} \left( J_{\text{vap,in}} h_{\text{vap,in}} - \dot{Q}_{wv} - \dot{Q}_v - J_{cd} c_p T_f \right) \]

\[ T_u = p_u V_u / m_v R_v \]

\[ \dot{T}_{w,i} = h_{w,i} (T_u - T_{w,i}) / \rho_w l_w c_w \]

\[ \dot{m}_l = J_{cd} - J_{tr} - J_{\text{vap,out}} \]

\[ T_l = 20K \]

\[ \dot{Q}_v - \dot{Q}_l + J_{cd} h_{cd} = 0; \quad T_f = f(p_{u,v}) \]

\[ p_v V_u = m_v R_v T_u \]

\[ p_g V_u = m_g R_g T_u \]

\[ (p_v + p_g) V_u = (m_v R_v + m_g R_g) T_u \]

\[ \dot{m}_{\text{vap}} = J_{\text{vap}}^{\text{out}} - J_{\text{vap}}^{\text{in}} \]

\[ J_{\text{vap}}^{\text{out}} = S_{\text{vap}} \lambda_{\text{vap}} \rho_l \sqrt{g \left( L_l + L_{ST} \right)} \]

\[ J_{\text{vap}}^{\text{in}} = \frac{0.62 \cdot m_{\text{vap}}}{\rho_l \pi R_w^2 \left( h_{ev} + 0.5 c_p (T_{\text{vap,w}} - T_f) \right)} \left[ \frac{\kappa_g \rho_f g h_{cd}}{\mu_g (T_w - T_f) D} \right]^{1/4} \]
3 Vaporizer Equations

\[ \dot{m}_{l,vap} = J_{\text{in}}^{\text{vap}} - J_{\text{out}}^{\text{vap}} \]

\[ J_{\text{in}}^{\text{vap}} = S_{\text{vap}} \lambda_{\text{vap}} \rho_l \sqrt{g \left( L_l + L_{ST} \right)} \]

\[ J_{\text{out}}^{\text{vap}} = S_{\text{vap,w}} \cdot q_{\text{vap}} \left/ \left( h_{ev} + 0.5 c_p \left( T_{\text{vap,w}} - T_l \right) \right) \right/ \]

\[ q_{\text{vap}} = N u_D \cdot \kappa / D \approx 0.62 \left[ \frac{\kappa_g \rho_g \rho_l g h_{cd}}{\mu_g \left( T_w - T_{sat} \right) D} \right]^{1/4} \]

\[ S_{\text{vap,w}} = 2\pi R_w L_{\text{vap,w}} = 2m_{l,vap} / \rho_l R_w \]

\[ \rho_g = 2 p_u / R \left( T_{\text{vap,w}} + T_{sat} \right) \]

\[ L_{\text{vap,w}} = \frac{V_{\text{vap}}}{\pi R_w^2} = \frac{m_{\text{vap}}}{\rho_l \pi R_w^2} \]

Wall film boiling correlations [1]

This is valve equation \( J_{\text{vap}} = \alpha_{\text{vap}} \sqrt{\Delta P} \)

2 Vaporizer Pressure Control

\[ \dot{S}_{vap} = \left( S_{vap,0} - S_{vap} \right) / \tau \]

\[ S_{vap,0} = S_{vap,stab} - A_{vap} \cdot \left( P_{ST} - P_{ST, fast} \right) / P_{ST, fast} \]

In stabilization regime

\[ \lambda_{vap} = \left( S_{vap} > 1.015 S_{vap,stab} \right) \left( 1 - \lambda_{vap} \right) + \left( S_{vap} > 0.985 S_{vap,stab} \right) \lambda_{vap} \]

1. Open to pressurize up to 3.75 x 10^5 Pa
2. Wait for ET to complete pressurization
3. Open to pressurize up to 76.5 x 10^5 Pa
4. Stabilize at the level 80.7 x 10^5 Pa
5 ET Equations

\[ \dot{m}_v = -J_{cd} - J_{vent,v} + J_b \]

\[ \dot{m}_g = J_{g,in} - J_{vent,g} \]

\[ \dot{p}_u = -\frac{\gamma p_u}{V_u} \dot{V}_u + \frac{\gamma - 1}{V_u} \left( J_{g,in} h_{g,in} + J_b c_{p,v} T_b - J_{vent,v} c_{p,v} T_u - J_{vent,g} c_{p,g} T_u - \dot{Q}_{wv} - \dot{Q}_v - J_{cd} c_p T_f \right) \]

\[ T_u = \frac{p_u V_u}{(m_v R_v + m_g R_{vg})} \]

\[ \dot{T}_{w,j} = h_{w,j} \left( T_u - T_{w,j} \right) / \rho_w l_w c_w \]

\[ \dot{m}_l = J_{cd} + J_{tr} - J_b \]

\[ T_l = 20 K \]

\[ \dot{Q}_v - \dot{Q}_l + J_{cd} h_{cd} = 0 \]

\[ T_f = f(p_{u,v}) \]

\[ \rho = \rho_v + \rho_g \]

\[ J_{vent,v(g)} = \lambda_{vent} \cdot S_{valve} \cdot \rho_{v(g)} \sqrt{\gamma p_g / \rho \Gamma^2} \]

\[ p_v V_u = m_v R_v T_u \quad p_g V_u = m_g R_g T_u \quad (p_v + p_g) V_u = (m_v R_v + m_g R_g) T_u \]

Added wall nodes and correct geometry of the ET.
ET Vent valve dynamics

\[ \lambda_{vent0} = \left( p_{ET} \geq p_{ET,\text{high}} \right) + \left( p_{ET,\text{low}} < p_{ET} < p_{ET,\text{high}} \right) \cdot \lambda_{vent0} \]

\[ \dot{\lambda}_{vent} = \frac{\lambda_{vent0} - \lambda_{vent}}{\tau_{vent}} \]

\[ J_{vent,v(g)} = \lambda_{vent} \cdot S_{vent} \cdot \rho_{v(g)} \sqrt{\frac{\gamma p_g}{\rho_\Gamma^2}}, \]

\[ \tau_{vent} = \begin{cases} \tau_{\text{slow}}, & \text{when open} \\ \tau_{\text{fast}}, & \text{when close} \end{cases} \]
Pipe Losses and Pipe Networks

Chezy Darcy's prediction $\Delta p = RQ^n$

$$\Delta p = \sum_{i=1}^{N} \Delta p_i = \sum_{i=1}^{N} R_i Q^2 = Q^2 \sum_{i=1}^{N} R_i$$

Example. Resistance of the skid valves

$$R_3 = \left( \lambda_K R_K^{\frac{1}{2}} + \lambda_L R_J^{\frac{1}{2}} \right)^{-2}$$

$$R_3^{(S,F)} = R_K$$

$$R_3^{\frac{1}{2}} = 0.1 (R_K)^{\frac{1}{2}} + R_J^{\frac{1}{2}}$$

$$R_K = \frac{\Delta p_K^F}{Q^2}$$
The differential pressure along the line

The model can reproduce quite accurately pressure changes along the line including losses at the control valves near the ST, at the skid, and orbiter inlet.

The measurements of the differential pressure signals provide a very sensitive tool for simultaneous fault detection along the line.
The analysis of the model predictions leads to the conclusion that the launch pad facility is not fill with the liquid until 1000 sec into the loading operation. This conclusion was later confirmed by the launch pad engineers demonstrating the consistency of the model.
Chilldown Model

\[ \dot{m}_{p,l} = J_{tr} - J_{p,b}; \quad T_l = 20K \]
\[ \dot{m}_{p,v} = J_{p,b} - J_{p,\text{out}} \]
\[ \dot{p}_p = -\frac{\gamma p_p}{V_p} \dot{V}_p + \frac{\gamma - 1}{V_p} \left( J_{pb} c_p T_{pb} - J_{p,\text{out}} c_p T_{p,\text{ET}} - \dot{Q}_{pw,v} \right) \]
\[ \dot{T}_{pw,i} = h_{pw,i}^{(v,l)} \left( T_{(v,l)} - T_{pw,i} \right) / \rho_{pw} l_{pw} c_{pw} \]
\[ J_{pb,i} = h_{pw,i}^{(l)} \left( T_{(l)} - T_{pw,i} \right) / \left( h_{ev} + 0.5 \left( T_{l,s} + T_{w,i} \right) \right) \]

\[ \dot{m}_v = -J_{\text{vnt,v}} + J_{p,\text{out}} \]
\[ \dot{m}_g = J_{g,\text{in}} - J_{\text{vnt,g}} \]
\[ \dot{p}_{\text{ET}} = \frac{\gamma - 1}{V_{\text{ET}}} \left( \dot{Q}_{he} + J_{p,\text{out}} c_p T_{p,\text{ET}} - \dot{Q}_{\text{vnt,v}} - \dot{Q}_{\text{vnt,g}} - \dot{Q}_{\text{wv}} \right) \]
\[ T_{\text{ET}} = p_{\text{ET}} V_{\text{ET}} / \left( m_v R_v + m_g R_{vg} \right) \]
\[ \dot{m}_{\text{ET,l}} = J_{tr} + J_{\text{cd}} - J_b \]
\[ \dot{T}_{w,i} = h_{w,i} \left( T_{\text{ET}} - T_{w,i} \right) / \rho_w l_w c_w \]
Forced convection correlation for horizontal pipes

• For the smooth tubes we use Petukhov correlation

\[ f = (0.79 \cdot \ln(Re_{Dh}) - 1.64)^{-2} \text{ for } 10^4 < Re < 10^6 \]

• For fully developed flow. The Nusselt Number is given by the Petukhov correlation

\[ Nu_{Dh,f} = \frac{(f/8)(Re_{Dh} - 1000)Pr}{1 + 12.7(Pr^{2/3} - 1)\sqrt{f/8}} \]

The effect of forced convection on external flow boiling for different flow velocities. Flow patterns during evaporation in a horizontal tube with a uniform heat flux. (From Collier and Thome, 1994.)
Flow boiling correlation for horizontal pipes

- The convection number $Co$:
  \[ Co = \left( \frac{1}{x} - 1 \right)^{0.8} \sqrt{\frac{\rho_{v, sat}}{\rho_{l, sat}}} \]

- The $Bo$ is the boiling number, defined as the ratio of the heat flux at the wall to the heat flux required to completely vaporize the fluid
  \[ Bo = \frac{h}{G h_{ev}} \]

- The Froude number $Fr$ is defined as the ratio of the inertial force of the fluid to the gravitational force
  \[ Fr = \frac{G^2}{\left( \frac{\rho_{l, sat}^2 g D_h}{\rho} \right)} \]

  according to Shah the Reynolds number should be evaluated using the liquid mass velocity, $G(1-x)$, while the Froude number should be evaluated using the total mass velocity, $G$.

\[ N = \begin{cases} 
  Co & \text{for vertical tubes or horizontal tubes with } Fr > 0.04 \\
  0.38 Co Fr^{-0.3} & \text{for horizontal tubes with } Fr \leq 0.04 
\end{cases} \]

The Shah correlation is expressed by Eqs. (7-17) through (7-21):

\[ \hat{h}_{cb} = 1.8 N^{-0.8} \]

\[ \hat{h}_{nb} = \begin{cases} 
  230 \sqrt{Bo} & \text{if } Bo \geq 0.3 \times 10^{-4} \\
  1 + 46 \sqrt{Bo} & \text{if } Bo < 0.3 \times 10^{-4} 
\end{cases} \]

\[ \hat{h}_{nb,1} = \begin{cases} 
  14.70 \sqrt{Bo} \exp(2.74N^{-0.1}) & \text{if } Bo \geq 11 \times 10^{-4} \\
  15.43 \sqrt{Bo} \exp(2.74N^{-0.1}) & \text{if } Bo < 11 \times 10^{-4} 
\end{cases} \]

\[ \hat{h}_{nb,2} = \begin{cases} 
  14.70 \sqrt{Bo} \exp(2.47N^{-0.15}) & \text{if } Bo \geq 11 \times 10^{-4} \\
  15.43 \sqrt{Bo} \exp(2.47N^{-0.15}) & \text{if } Bo < 11 \times 10^{-4} 
\end{cases} \]

\[ \hat{h} = \begin{cases} 
  \text{MAX}(\hat{h}_{cb,1}, \hat{h}_{nb,2}) & \text{if } N \leq 0.1 \\
  \text{MAX}(\hat{h}_{cb,1}, \hat{h}_{nb,1}) & \text{if } 0.1 < N \leq 1.0 \\
  \text{MAX}(\hat{h}_{cb}, \hat{h}_{nb}) & \text{if } N > 0.1 
\end{cases} \]
Modeling Chilldown

- Gas temperature
- Wall temperature at different instance of time

Node # along the pipe

V_{pipe}, m^3

T_{W,p}, K

m_{v,p}, K

T_{Sf}, K
New Capabilities and Sensitivity

We need Better Chilldown and Stratification Models.

Adding nodes to the ullage space
Fault Detection and Isolation

We now demonstrate that the developed model can be used to detect and isolate multiple faults including

- Blocking of the pressures control valve of the vaporizer
- Clogging of the valves along the transfer line
- Heat and mass leaks in the vehicle tank
Capabilities: pressure control fault

VAP OPN IND
VAP SPLY VLV SIG PRESS

experiment

model predictions

Physics-based Modeling In Design & Development, Denver, Nov 2012
Capabilities: pressure control fault

Experiment

Simulations

Flow is blocked although it appears that the valve area is stack at an intermediate value.
Simultaneous Detection of Multiple Faults

10% K valve clogging between t=5900 and t=6200 sec.

10% PV11 valve clogging between t=3200 and t=3500 sec.

10% PV12 valve clogging between t=3800 and t=4100 sec.

10% PV11 valve clogging between t=3200 and t=3500 sec.

10% PV12 valve clogging between t=3800 and t=4100 sec.
The LC-39 Pad B liquid hydrogen tank experiences on average about 550 gallons per day additional boil-o than the equivalent tank at Pad A. A large mold spot exists on the Pad B tank that is suspected to be the site of a large heat leak. IR camera photography reveals that this spot is indeed much colder than the rest of the tank. Photos of the effected area are shown in Figure. Mark Nurge, “LC-39B LH2 Tank Thermal Analysis”, May 8, 2009

The current model is capable of simulating this nontrivial and important fault
Physics of the Heat and Mass Flow

Main physical processes
1. heat and mass transfer
2. boiling,
3. evaporation-condensation,
4. stratification,
5. natural and forced convection,

We use
Full scale finite element 3D transient turbulent modeling to validate our low-fidelity FD&I models

Heat and mass leaks in the vehicle tank appear as small alterations of the heat and mass fluxes in the ullage space. Detection of this faults requires substantially higher fidelity model of the vehicle tank as compared to three-node model discussed earlier. To be able to process signals online such model will have to rely on free convection correlations. Therefore a special attention has to be paid to validation and verification of this model.
Mass and Heat Leaks Modeling

No LN2 leaks \( \frac{dv}{dt} \approx 0 \)

During the impulse \( \dot{Q}_{N2} \gg \dot{Q}_w \)
During the relaxation \( Q_{N2} = 0 \)

During the heat leak

\[
Adpc \cdot \frac{dT_w}{dt} = Ah_w (T - T_w) + \dot{Q}_{rad} + \dot{Q}_{heat, leak}
\]

During the gas mass leak the wall equation does not change, but

\[
\frac{dp}{dt} = \frac{\gamma - 1}{V} \left( \dot{Q}_{N2} - \dot{Q}_w - \dot{Q}_{gas, leak} \right)
\]

The problem is to estimate \( \dot{Q}_{heat, leak} \) and \( \dot{Q}_{gas, leak} \) that will result in the half impulse counting (considering half impulse counting detectable)

LN2 mass leaks

\[
\frac{dp}{dt} = -\frac{\gamma p}{V} \frac{dv}{dt} + \frac{\gamma - 1}{V} \left( \dot{Q}_{N2} - \dot{Q}_w \right)
\]

Mass or heat leaks could result in the pulses phase shifts or even a different number of pulses during the control time.

The idea of the approach is to substitute complex measurements of the nonlinear slope variation with simple pulse counting technique.

- In a sense these are direct measurements of the linear susceptibility of the system.
- Or active pulse interrogation of the system.

Modeling of such response imposed on the slow nonlinear variation of the state of the system requires development of a higher fidelity model.
Low Mach Number Approximation

\[ \rho_t + \nabla \cdot (\rho \vec{v}) = 0 \]
\[ (\rho \vec{v})_t + \nabla \cdot (\rho \hat{\vec{v}} \otimes \vec{v}) + \frac{1}{M^2} \nabla p = \frac{1}{Fr^2} \rho \vec{g} \]
\[ (\rho e)_t + \nabla \cdot ((\rho e + p)\vec{v}) = \frac{M^2}{Fr^2} \rho \hat{\vec{v}} \cdot \vec{g} \]
\[ p = (\gamma - 1) \left( \rho e - \frac{1}{2} M^2 \rho \hat{\vec{v}} \cdot \vec{v} \right) \]
\[ p = \frac{p'}{p_{\text{ref}}}; \rho = \frac{\rho'}{\rho_{\text{ref}}}; \nu = \frac{v'}{u_{\text{ref}}}; x = \frac{x'}{l_{\text{ref}}}; t = \frac{t'u_{\text{ref}}}{l_{\text{ref}}} \]

The following expansion is usually introduced:

\[ p = p^{(0)} + M^2 p^{(2)} \]

The convective interface velocities \( v^* \) are corrected by pressure in the second order:

\[ \vec{v}_I = \vec{v}_I^* - \frac{\Delta t \nu I_{\text{ref}}^{(2)}}{2} \frac{\nabla p_I}{\rho_I} \]
\[ \sum_{I \in J} |I| (\rho h \vec{v})_I \cdot \vec{n} = -\frac{|V|}{\gamma - 1} \frac{d p^{(0)}}{d t} \]

Eigenvalues of the Jacobian Flux Function

\[ f^M = \begin{pmatrix} \rho \hat{\vec{v}} \cdot \vec{n} \\ \rho \hat{\vec{v}} \cdot \vec{n} + \frac{1}{M^2} p \cdot \vec{n} \end{pmatrix} \]

\[ \vec{v} \cdot \vec{n}; \quad \vec{v} \cdot \vec{n} \pm \frac{c}{M}; \quad c^2 = \frac{\gamma}{M} p / \rho \]

degenerate when \( M = \frac{u_r}{\sqrt{p_r/\rho_r}} \to 0. \)

The Froude number is the ratio of the flow speed to the speed of infinitesimal (incompressible) gravity waves in the same medium: \( Fr = u_{\text{ref}} / \sqrt{g l_{\text{ref}}} \). In fluid dynamics, gravity waves are waves generated in a fluid medium which has the restoring force of gravity or buoyancy.

\( u_{\text{ref}} \) is independent of \( c_{\text{ref}} = \gamma \sqrt{p_{\text{ref}}/\rho_{\text{ref}}} \) to ensure that \( u_{\text{ref}} \) is well defined when \( M \to 0. \)

\( u_{\text{ref}} \) is usually chosen from the condition \( \rho u_{\text{ref}}^2 = l_{\text{ref}} g (\rho(T_u) - \rho(T_w)) \)

Energy equation as a divergence constraint

1. Use only 1st approximation $\nabla p^{(0)} = 0$ and neglect completely the momentum equation

$$(\rho \dot{v})_t + \nabla \cdot (\rho \dot{v} \otimes \dot{v}) + \nabla p^{(2)} = \frac{1}{Fr^2} \rho \ddot{g}$$

$$\rho_t + \nabla \cdot (\rho \dot{v}) = 0$$

$$(\rho e)_t + \nabla \cdot ((\rho e + p)\dot{v}) = 0$$

$$p = (\gamma - 1)\rho e$$

2. Use the fact that $p^{(0)} = \text{const}$ in the whole volume and $\rho e = \text{const}$ for each CV:

$$p_t + \gamma p \nabla \cdot \dot{v} = 0 \text{ or } \frac{V_j}{\gamma p} \frac{dp}{dt} = -\frac{dV_j}{dt} + \sum_{k \neq j} u_{kj} S_{kj}$$

3. Integrating over the whole volume we have

$$\frac{\gamma p}{\gamma - 1} = \frac{c_p p}{R} = c_p \rho T$$

$$\frac{V_j}{\gamma - 1} \frac{dp}{dt} = -\frac{\gamma p}{\gamma - 1} \frac{dV_j}{dt} + \sum_{k \neq j} c_p T \rho u_{kj} S_{kj} = -\frac{\gamma p}{\gamma - 1} \frac{dV_j}{dt} - \dot{Q}_w - \dot{Q}_f + \dot{Q}_{in,v(g)}$$
System of the ET equations (ULLAGE)

Mass and energy conservation for the bulk gas elements

\[ \dot{m}_{i,B} = J_{i+1,B} - J_{i,B} - J_{i,1,BL}, \quad J = \rho u S, \quad h = c_p T \]

\[ \frac{d}{dt} \sum_{\lambda=v,g} m_{i,B}^{(\lambda)} u_{i,B}^{(\lambda)} = -\dot{W}_{i,B}^{(\lambda)} + \sum_{\lambda=v,g} J_{i+1,B}^{(\lambda)} h_{i+1,B}^{(\lambda)} - \left( J_{i,B}^{(\lambda)} + J_{i,1,BL}^{(\lambda)} \right) h_{i,B}^{(\lambda)} \]

For the internal boundary layer gas elements

\[ \dot{m}_{i,L} = J_{i-1,L}^{(\lambda)} - J_{i,L}^{(\lambda)} + J_{i,BL}^{(\lambda)} \]

\[ \frac{d}{dt} \sum_{\lambda=v,g} m_{i,L}^{(\lambda)} u_{i,L}^{(\lambda)} = \dot{Q}_{i,e}^{(\lambda)} - \dot{W}_{i,L}^{(\lambda)} + \sum_{\lambda=v,g} \left( J_{i-1,L}^{(\lambda)} h_{i-1,L}^{(\lambda)} - J_{i,L}^{(\lambda)} h_{i,L}^{(\lambda)} \right) + J_{i,BL}^{(\lambda)} h_{i,B}^{(\lambda)} \]

For the lowest horizontal vapor layer

\[ \dot{m}_{1,B}^{(v)} = J_{2,B}^{(v)} - J_{1,L}^{(v)} + J_{ev}^{(v)} ; \quad \dot{m}_{1,B}^{(g)} = J_{2,L}^{(g)} - J_{1,L}^{(g)} \]

\[ \frac{d}{dt} \sum_{\lambda=v,g} m_{1,B}^{(\lambda)} u_{1,B}^{(\lambda)} = \dot{Q}_{v} - \dot{W}_{1,B}^{(\lambda)} + \sum_{\lambda=v,g} \left( J_{2,B}^{(\lambda)} h_{2,B}^{(\lambda)} - J_{1,L}^{(\lambda)} h_{1,L}^{(\lambda)} \right) + J_{ev} h_{vs} \]

For the upper horizontal vapor layer

\[ \dot{m}_{n,B}^{(\lambda)} = J_{n-1,L}^{(\lambda)} - J_{n,B}^{(\lambda)} + J_{\lambda,e}^{(\lambda)} \]

\[ \frac{d}{dt} \sum_{\lambda=v,g} m_{n,B}^{(\lambda)} u_{n,B}^{(\lambda)} = \dot{Q}_{top} - \dot{W}_{n,B}^{(\lambda)} + \sum_{\lambda=v,g} \left( J_{n-1,L}^{(\lambda)} h_{n-1,B}^{(\lambda)} - J_{n,B}^{(\lambda)} h_{n,B}^{(\lambda)} \right) + J_{\lambda,e} h_{\lambda,e}^{(\lambda)} \]

The system is closed using equations of state for ideal gas. The real tank geometry was used.
Heat release at the interface

\[ h_v(T_f) = h_v^0 \left( \frac{T_C - T_f}{T_C - T_l(0)} \right)^{1/2} \]

\[ T_C = 33K; \ h_v^0 = 4.5 \times 10^5 \ J / kg \]

1. Under non-equilibrium conditions (blow-down) there is continuous condensation/evaporation flow to/from the surface;
2. There is no accumulation of the mass;
3. The heat released \( (J_{lv}h_{lv}) \) can not be accumulated at the interface and is balanced by heat flow to/from interface on liquid and vapor sides;
4. The heat flow in vapor (liquid) phases are defined as follows

\[ \dot{Q}_{v(l)} = \dot{Q}_{v(l)}^{(cv)} + \dot{Q}_{v(l)}^{(cd)} = A\alpha_{v(l)} \left( T_s - T_{v(l)} \right) + \dot{Q}_{v(l)}^{(cd)} \]

5. During prepress and repress \( T_g > T_s > T_L = 20.4K \) and convective heat transfer can be neglected
Heat conduction

Heat conduction eq. with a given heat source and surface temperature

\[ \rho c \frac{\partial u}{\partial t} = \kappa \frac{\partial^2 u}{\partial x^2} + Q(x,t) \]

\[ u(x,0) = 0 \]

\[ u(0,t) = T_s(t) \]

General solution

\[ u(x,t) = u_1(x,t) + u_2(x,t) = \left[ \chi = \left( \frac{\kappa}{\rho c} \right) \right] \]

\[ \frac{x}{2\sqrt{\pi\chi}} \int^t_0 \frac{T_s(\tau)}{(t-\tau)^{3/2}} e^{-\frac{x^2}{4\chi(t-\tau)}} d\tau + \frac{1}{2\sqrt{\pi\chi}} \int^\infty_0 \int^t_0 \frac{Q(\xi,\tau)}{\sqrt{t-\tau}} d\xi d\tau \left\{ e^{-\frac{(x-\xi)^2}{4\chi(t-\tau)}} - e^{-\frac{(x+\xi)^2}{4\chi(t-\tau)}} \right\} \]

Surface temperature gradient for uniform heat source

\[ \frac{\partial u(x,t)}{\partial x} \bigg|_{x=0} = -\frac{1}{\sqrt{\pi\chi}} \int^t_0 \frac{\partial T_v(\tau)}{\partial \tau} \frac{d\tau}{\sqrt{t-\tau}} + \frac{1}{\sqrt{\pi\chi}} \int^t_0 \frac{\partial T_l(\tau)}{\partial \tau} \frac{d\tau}{\sqrt{t-\tau}} - \frac{1}{\sqrt{\pi\chi}} \int^t_0 \frac{\partial T_s(\tau)}{\partial \tau} \frac{d\tau}{\sqrt{t-\tau}} \]

\[ \dot{Q}_v - \dot{Q}_l = J_{lv} \left( h_{vs} - h_{ls} \right) \]
Optimal grid

Heat conduction at the interface can be found by solving numerically HCE

\[
\dot{Q}^{cd}_{l(v)} \approx \left[ \frac{\kappa_i (T_1 - T_0)}{h_{1/2}} - h_0 c_{l(v)} \rho_{l(v)} \frac{dT_0}{dt} \right],
\]

\[
h_i c_{l(v)} \rho_{l(v)} \frac{dT_i}{dt} = \kappa_{l(v)} \left[ \frac{(T_{i+1} - T_i)}{h_{i+1/2}} - \frac{(T_i - T_{i-1})}{h_{i-1/2}} \right], \quad i = 1, 2, \ldots, i - 1
\]

\[
T_0 (t) = T_s (t), \quad T_i (0) = T_L, \quad T_n = T_L
\]

on the optimal grid [1-3]

\[
h_0 = \frac{h_{\text{min}}}{1 + \exp \left( \pi / \sqrt{n} \right)}, \quad h_{1/2} = h_{\text{min}} = \sqrt{\frac{\kappa_i t_{\text{min}}}{c_i \rho_i}}, \quad h_{i+1/2} = h_{i-1/2} \exp \left( \pi / \sqrt{n} \right), \quad h_i = \sqrt{h_{i+1/2} h_{i-1/2}}.
\]

\[
\frac{\exp (\pi \sqrt{n}) - 1}{\exp (\pi / \sqrt{n}) - 1} > \sqrt{\frac{t_{\text{max}}}{t_{\text{min}}} \geq 100} \quad \text{for} \quad n \approx 8
\]

To detect heat and mass leaks in the GN2 vehicle (storage) tank, we propose to use/modify/upgrade standard techniques verified and validated for LH2 and LO2 tanks.

The technique involves introducing calibrated pulses of hot gas into the pressurized tank every time the pressure goes below a preset limit.

Validation of the model:
- The top figure shows a comparison of model predictions (blue) with experimental data (green) for LO2 tank during countdown before the physics model is improved and validated.
- The middle figure displays a high-fidelity model used for validation.
- The bottom figure shows the performance of the model after validation and correction using improved material properties, GHe pressurization pulse dynamics, and free convection correlations at the wall.

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Model validation using LO2 Shuttle data
Model validation using Shuttle data for LH2 ET
This test demonstrates that the model (blue) can accurately reproduce both experimental (green) pressure and temperature time series data for
- Prepress
- Pulse dynamics during prepress
- Repress
- Earlier in flight dynamics

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Heat leak in the tank

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Tank volume 2000 Gal;
Temperature of GN2 flow is 572R;
GN2 pulses had duration 0.5s,
flow rate 0.5lb/s, shark fin shape

- In this test we first check the dispersion of the pulses frequency as a function of the pulses mass flow dispersion. It is shown that to detect 1 extra pulse the deviation of the mass flow rate should be kept within few %

- In the next test a continuous heat leaks of various level are applied to the patch with area 1m². It is shown that the heat leak 1kW can be detected (given condition above on the deviation of the pulse mass flow rate)
Gas and Liquid Leaks in the Tank

Ekaterina Ponizhovskaya

Tank volume 2000 Gal; Temperature of GN2 flow is 572R; GN2 pulses had duration 0.5s, flow rate 0.5lb/s, shark fin shape

- In the 3rd test we demonstrate liquid leaks with mass flow rate 0.5 kg/s (0.116 Gal/s) can be detected
- In the final test it is shown that the gas leak with mass flow rate 0.01 kg/s can be detected
Stratification and Chilldown (Nodes)

10-30 nodes for the ET ullage space according to # of baffles

100 nodes for the ST wall

100 nodes for the ET wall

100 nodes for the ST wall

7-100 nodes in the pipe line to model chilldown

1 node for the vaporizer wall

230 nodes for the pipe wall

1 node for the vaporizer wall

10-30 nodes for the ET ullage space according to # of baffles

Pipe losses 9 constraints

Release valve

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Conclusions

○ Model of the LH2 loading operation was developed and validated
  ▪ Pressure oscillations and losses in transfer line can be accurately reproduced

○ The model capability of detecting multiple faults were demonstrated including:
  ▪ Vaporizer Pressure Control faults
  ▪ Simultaneous valve clogging in transfer Line
  ▪ Mass and Heat Leaks in the Vehicle tank

○ Work in progress:
  ▪ Chilldown model of the transfer line coupled to stratification model of the vehicle tank