Fluid Transient Analysis of Propellant Feedlines during a Priming Event

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Background

• Priming is the process of filling an evacuated pipe line.
  – For safety reasons, storable propellants such as hydrazine are separated from thrusters by one or more valves.
  – Once in orbit, the valve is opened, and the evacuated line is filled with propellant.

Picture Credit: Moore et al., JSR, 2018.
Background

• The velocity change when the fluid hits the dead end can cause a brief pressure surge.
  – The pressure rise can be as high as:
    \[ \Delta P = \rho c \Delta V \]
  – For example, if liquid water is suddenly stopped from 10 m/s, the pressure rise could be:
    \[ \Delta P = \left( 1000 \frac{kg}{m^3} \right) \left( 1500 \frac{m}{s} \right) \left( 10 \frac{m}{s} \right) = 15 \text{ MPa} \]

• Accurate prediction of maximum pressure aids in the design of a propulsion system that is not too conservatively heavy.
The Generalized Fluid System Simulation Program (GFSSP) is a general-purpose computer program to calculate pressures, temperatures, and flow rates in a fluid network.

Fluid networks are discretized into nodes and branches.
- Mass and energy equations are solved in the nodes.
- Momentum equation is solved in the branches.
Ph.D. dissertation by N. H. Lee, 2005

Test series varied:
• Reservoir pressure: 2 to 7 atm
• Gas volume proportion: \( \alpha = \frac{L_g}{L_T} \)
• Nodes 1-11 initially contain liquid water at 102.9 psia.
• Nodes 12-20 initially contain air (as an ideal gas) at 14.7 psia.
• A Fortran user subroutine fixes all temperatures in model at 60°F. Air temperature increase by compression is neglected.
• Predicted peak pressure is 20% higher than experimental.
• Maximum pressure increases when trapped air length is decreased:
  • $\alpha = 0.448$, $P_{\text{max}} = 250$ psia
  • $\alpha = 0.195$, $P_{\text{max}} = 450$ psia
Prickett et al., 1992

- Test series varied reservoir pressure: 30 to 120 psia
- Pipe diameter: 0.25 in.
- Pipe downstream of latch valve (LV) is initially evacuated.
• GFSSP does not understand “empty”, so the evacuated line is initially filled with ideal gas air at low pressure.
• Reported maximum pressure is 2350 psia in the dead end at 0.17 sec.
• GFSSP predicts 2279 psia at 0.176 sec.
• Decreasing initial air pressure of evacuated lines increased the maximum pressure, although there was little change when $P_{\text{air}} < 1$ psia.
Reservoir pressure: 240 psia
Pipe diameter: 0.25 in.
R1 is the suddenly opening valve.
R2 is a pair of valves that close quickly during priming event.
• Evacuated nodes are modeled as ideal gas air initially at 1 psia.
• Pressure data available at nodes 15 and 28.
• Maximum pressure in lower branch is 1837 psia at node 28. Measured pressure at this location is 1800 psia.
• Maximum pressure in upper branch is 3500 psia at node 9. No test data were reported for this location.
Moore et al., JSR, 2019

- Reservoir pressure: 1.5, 2.2, or 2.9 MPa
- Line lengths: 0.51 or 2.0 m
- Line diameters: 6.5, 9.5, or 12.7 mm
- Flow Control Valve $C_v$: 0.037, 1.5, or 4.0
- Initial air pressure in line: 4, 15, 101 kPa
Three valve opening profiles were studied:

- Linear: \( A = kt \)
- Quick open: \( A = k\sqrt{t} \)
- Slow open: \( A = kt^2 \)
Predictions are reasonable for cases with FCV $C_v = 0.037$ and 1.5.
For cases with $C_v = 4.0$, GFSSSP consistently over-predicts peak pressure.
No clear relationship seen between GFSSP prediction accuracy and tank pressure or initial line pressure.
Discretization study found that predicted peak pressure values slowly converged as more nodes were added to model.

Valve history profile (linear or parabolic) usually had little effect on the peak pressure, and only a small effect on predicted time of peak pressure.

\[
\begin{align*}
\text{Cv} &= 1.5, \quad D = 12.7 \text{ mm}, \quad L = 2 \text{ m} \\
\text{P}_{\text{tank}} &= 2.9 \text{ MPa}, \quad \text{P}_{\text{init}} = 101 \text{ kPa} \\
\text{P}_{\text{meas}} &= 4510 \text{ kPa at 0.172 sec} \\
\end{align*}
\]

\[
\begin{align*}
\text{Cv} &= 1.5, \quad D = 9.53 \text{ mm}, \quad L = 2 \text{ m} \\
\text{P}_{\text{tank}} &= 2.2 \text{ MPa}, \quad \text{P}_{\text{init}} = 15 \text{ kPa} \\
\text{P}_{\text{meas}} &= 28,140 \text{ kPa at 0.106 sec} \\
\end{align*}
\]
• However, choice of valve opening profile did have an effect on those runs where the valve was not completely open before the pressure surge time.
  • Shorter line with narrow-or-medium diameter.
  • Moderate-or-high tank pressure
  • High Cv valve with slow opening time (0.075 s)

Cv = 4, D = 9.53 mm, L = 0.51 m
P_{tank} = 2.2 MPa, P_{init} = 101 kPa
P_{meas} = 11,290 kPa at 0.055 sec
• Penn State paper did not provide line length and minor losses between tank and flow control valve.

• Adding an arbitrary line length between the boundary and the valve decreased peak pressure, but not enough to match data.

\[ y = -4510x + 39890 \]

\[
\begin{align*}
C_v &= 4, \quad D = 9.53 \text{ mm}, \quad L = 2 \text{ m} \\
P_{\text{tank}} &= 2.2 \text{ MPa}, \quad P_{\text{init}} = 15 \text{ kPa} \\
P_{\text{meas}} &= 14,080 \text{ kPa}
\end{align*}
\]

Moore et al., JSR, 2019
Discussion

- GFSSP’s predictions of peak pressure during a priming event are usually either accurate or too high.
- Models of the Penn State Experiments stress the importance of the valve opening time and profile shape to the peak pressure prediction when a slow-opening valve is matched with a small volume to be filled.
- Future work:
  - More complex fluid networks
  - Effect of a cavitating venturi in the line
  - Implicit vs. explicit solution of the conservations equations
References


