Modeling of Priming Events Using GFSSP in Liquid Propulsion Systems

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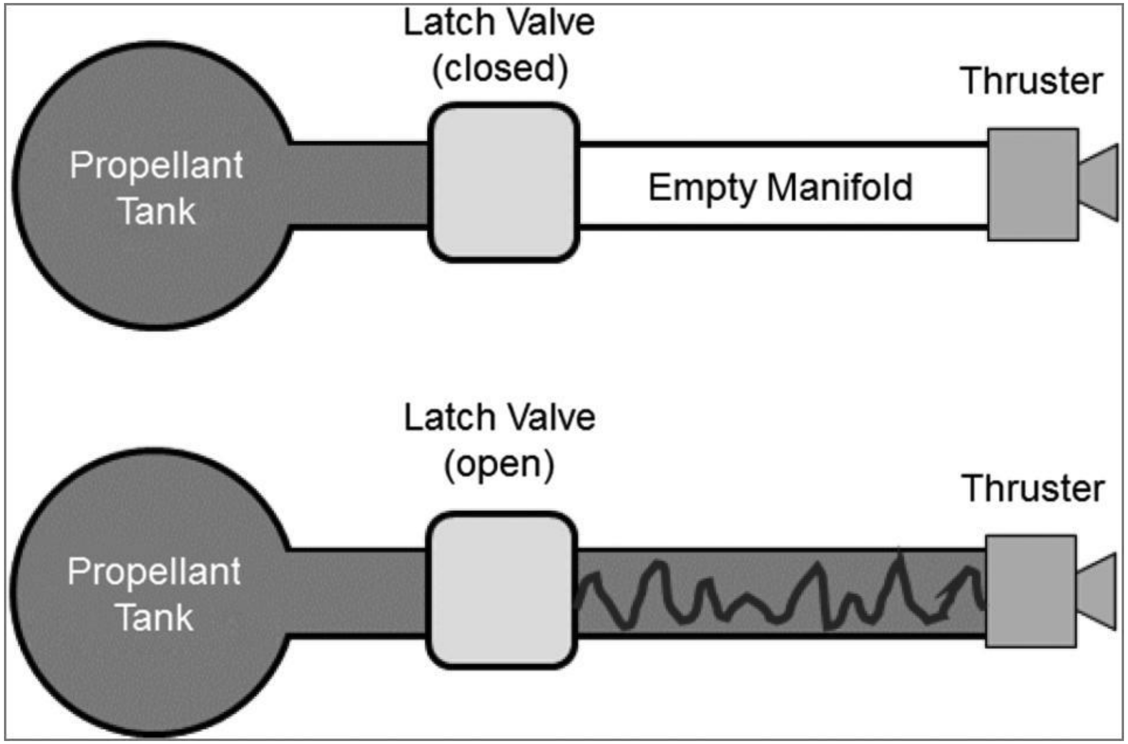
Background

- In aerospace propulsion, **priming** refers to filling evacuated or empty propellant feed lines.
- In the orbit, storable propellants are allowed to fill the evacuated line by opening the valve.



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:

$$\Delta P = \rho c \Delta V$$

  Where c is the sonic velocity.

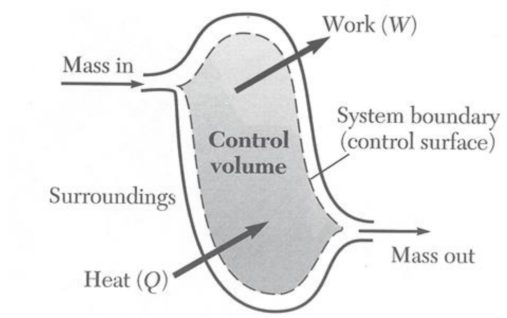
  - For example, if liquid water is suddenly stopped from 10 m/s, the pressure rise could be:

$$\Delta P = \left(1000\,\frac{kg}{m^3}\right)\left(1500\,\frac{m}{s}\right)\left(10\,\frac{m}{s}\right) = 15\,MPa$$

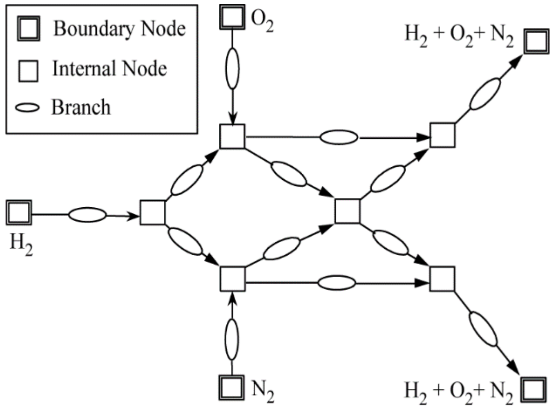
- Accurate prediction of maximum pressure aids in the design of a propulsion system

GFSSP

- 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.



Control Volume Analysis



Finite Volume Analysis

Study of Fluid Transients using GFSSP

- GFSSP has been successfully used earlier for solving multiple water hammer analysis: using both closing and opening of valves (1, 2, 4, 5)

- Some of the recent study for fluid transient analysis using GFSSP such as flow of water in entrapped air (2) and the results were validated against test data by Lee and Martin (3) of Georgia Tech.

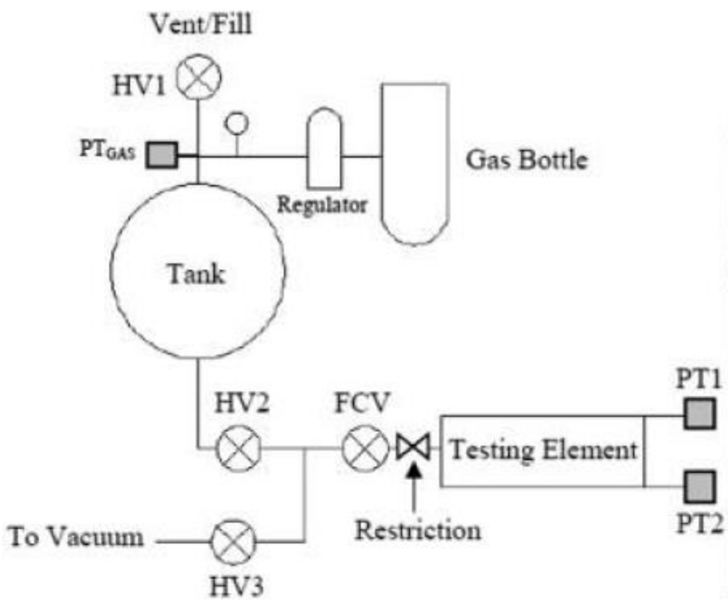
- Leclair et al. (5) have studied the Priming problem to validate GFSSP with Moore’s (6) experimental data.

Problem Statement

- The current study focusses on finding out the reasons of large differences of GFSSP simulation results with that of the test data of Moore (6) especially for the long pipe with high valve coefficients.
- Introduced an unsteady state friction factor in addition to standard steady state friction factor and the effect of the friction factor in the computation of pressure surges are studied on a multiple cases.

MOORE's Experimental Study

The figure below shows the schematic and actual picture of the experimental set up of Moore. The details of the test elements are shown at the bottom.



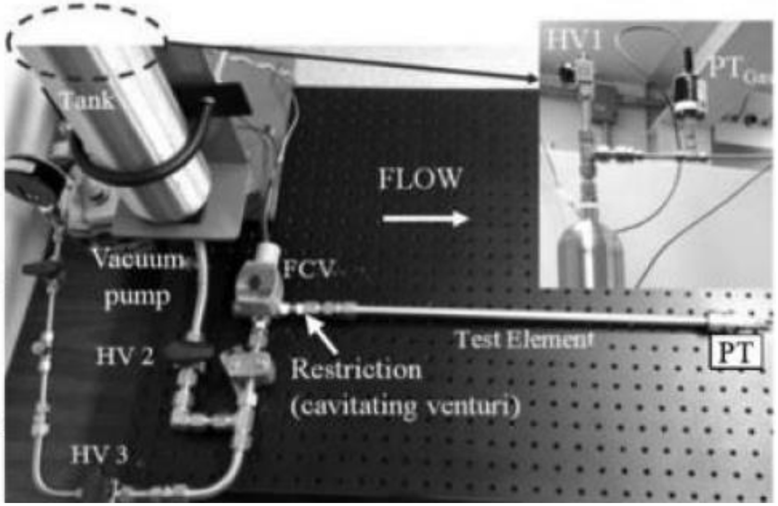


Fig 1(a). Moore's experimental set up

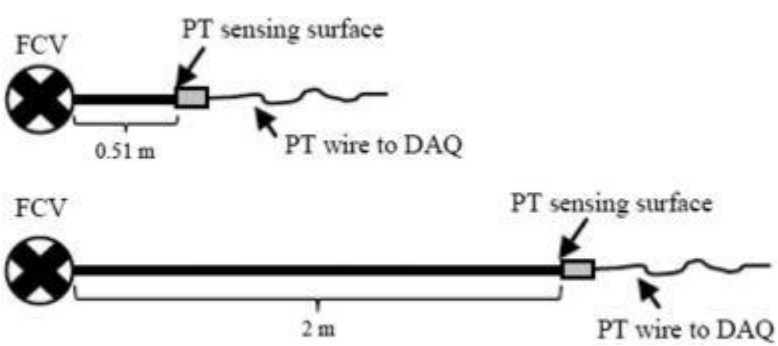


Fig. 1(b): Test elements

Operating Conditions

- 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

Moore's Experimental Data: Straight Pipe

For ease of understanding Moore's test data with operating conditions are given here.

Table 2 **Results of priming event for atmospheric straight-tube test element pressure (0.101 MPa): no cavitating venturi**

Valve K_V, m^3/h bar	L, m	Line OD, mm	P_{TANK}, MPa	Peak surge time, ms	P_{WH}, MPa
0.032	0.51	9.53	2.85	436 ± 7	2.82 ± 0.01
0.032	2.00	9.53	2.84	1617 ± 8	3.02 ± 0.01
1.298	0.51	12.70	2.87	54 ± 1	12.33 ± 0.59
1.298	0.51	12.70	2.18	59 ± 1	6.41 ± 0.46
1.298	0.51	12.70	1.49	69 ± 1	2.61 ± 0.09
1.298	0.51	9.53	2.90	37 ± 1	28.24 ± 1.08
1.298	0.51	9.53	2.19	40 ± 1	18.04 ± 1.57
1.298	0.51	9.53	1.49	46 ± 1	8.40 ± 0.66
1.298	0.51	6.35	2.91	31 ± 1	38.42 ± 0.18
1.298	2.00	12.70	2.87	172 ± 2	4.51 ± 0.05
1.298	2.00	9.53	2.88	105 ± 1	10.90 ± 0.46
1.298	2.00	6.35	2.86	99 ± 1	12.37 ± 0.14
3.460	0.51	12.70	2.84	70 ± 1	9.97 ± 0.40
3.460	0.51	9.53	2.89	47 ± 1	17.69 ± 0.03
3.460	0.51	9.53	2.19	55 ± 1	11.29 ± 0.99
3.460	0.51	9.53	1.49	64 ± 1	4.45 ± 0.10
3.460	0.51	6.35	2.82	83 ± 2	11.70 ± 0.79
3.460	2.00	12.70	2.90	173 ± 1	5.63 ± 0.14
3.460	2.00	9.53	2.87	114 ± 1	6.04 ± 0.08
3.460	2.00	9.53	2.18	130 ± 1	3.25 ± 0.03
3.460	2.00	9.53	1.47	157 ± 1	1.49 ± 0.08
3.460	2.00	6.35	2.84	238 ± 2	9.93 ± 0.02

Moore's Experimental Data: Straight Pipe

Table 2 (test element initial pressure = 15 kPa)

Table 3 Results of priming event for subatmospheric straight-tube test element pressure (0.015 MPa): no cavitating venturi

Valve K_V, m^3/h bar	L, m	Line OD, mm	P_{TANK}, MPa	Peak surge time, ms	P_{WH}, MPa
1.298	0.51	12.70	2.89	50 ± 1	25.03 ± 0.73
1.298	0.51	12.70	2.20	56 ± 1	21.64 ± 1.84
1.298	0.51	12.70	1.47	67 ± 2	14.38 ± 0.90
1.298	0.51	9.53	2.87	35 ± 1	36.98 ± 2.18
1.298	0.51	9.53	2.18	35 ± 5	28.55 ± 2.88
1.298	0.51	9.53	1.49	45 ± 1	18.88 ± 1.48
1.298	0.51	6.35	2.89	28 ± 3	48.58 ± 2.74
1.298	0.51	6.35	2.20	30 ± 2	41.50 ± 2.04
1.298	0.51	6.35	1.49	31 ± 2	31.66 ± 0.72
1.298	2.00	12.70	2.85	164 ± 1	16.67 ± 1.27
1.298	2.00	12.70	2.20	188 ± 4	13.58 ± 1.01
1.298	2.00	12.70	1.49	229 ± 1	7.34 ± 0.63
1.298	2.00	9.53	2.87	93 ± 1	32.17 ± 0.17
1.298	2.00	9.53	2.18	106 ± 1	28.14 ± 1.61
1.298	2.00	9.53	1.50	126 ± 2	21.38 ± 0.14
1.298	2.00	6.35	2.87	83 ± 3	34.38 ± 0.82
1.298	2.00	6.35	2.20	93 ± 1	28.90 ± 0.12
1.298	2.00	6.35	1.48	112 ± 2	21.88 ± 0.02
3.460	0.51	9.53	2.89	40 ± 1	34.34 ± 0.79
3.460	0.51	9.53	2.19	42 ± 1	28.21 ± 1.07
3.460	0.51	9.53	1.48	50 ± 3	18.42 ± 1.19
3.460	2.00	9.53	2.88	103 ± 1	16.67 ± 0.03
3.460	2.00	9.53	2.18	112 ± 7	14.08 ± 0.08
3.460	2.00	9.53	1.48	138 ± 1	10.82 ± 0.15

Valve Area Computation from CV value in GFSSP

Flow through restriction, the friction coefficient, K_f is obtained by using (Refer to GFSSP manual, 3.1.7.2)

$$K_f = \frac{1}{2 g_c \rho_u C_L^2 A^2}$$

Valve with a given loss coefficient (branch option 16) (section 3.1.7.16)

$$K_f = \frac{4.68 \times 10^5}{\rho_u C_v^2}$$

Equating these two expressions gives, the equivalent area computation for a given C_V as:

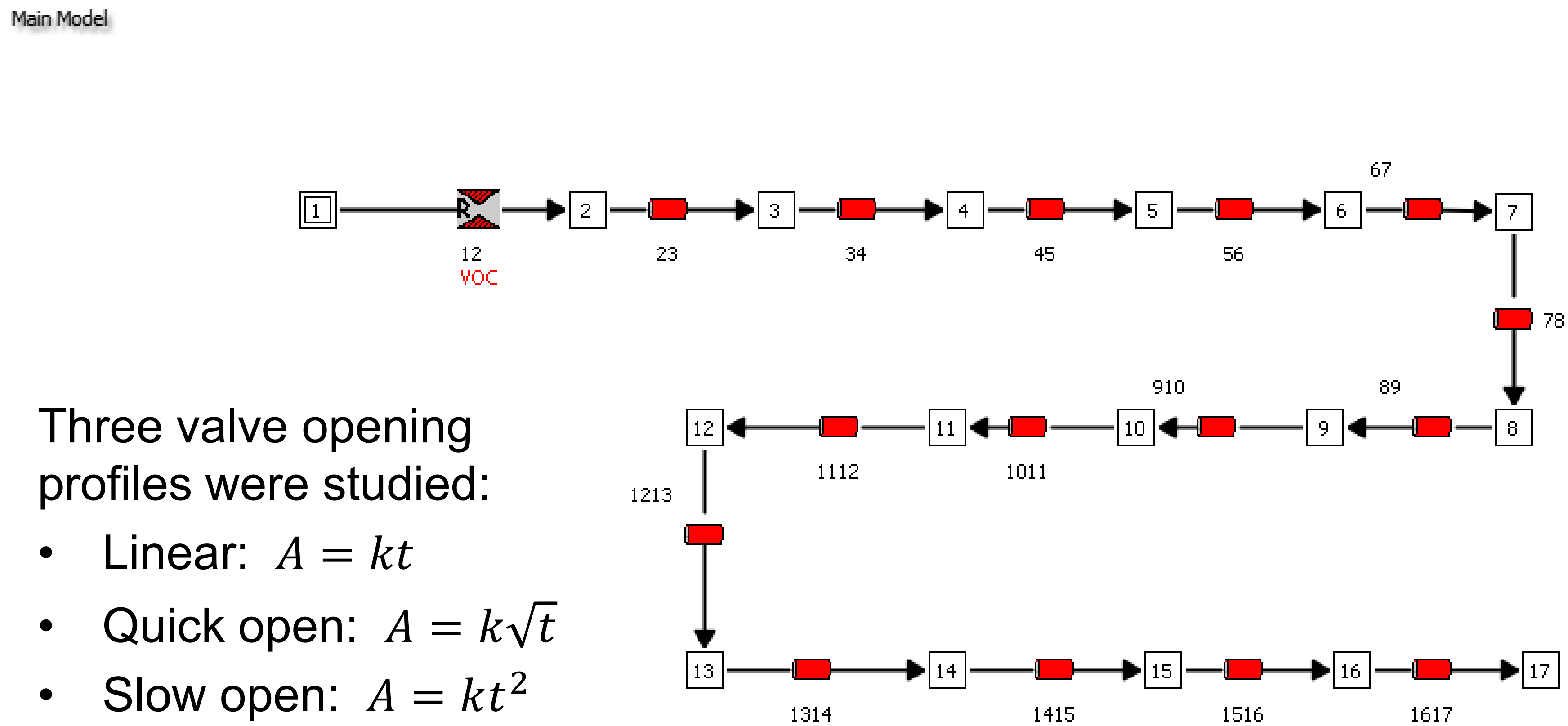
A = $\frac{C_v}{967.4606\sqrt{g_c}}$ **(ft^2) = 1.69305e-5 * C_V m^2 (using g_c = 32.17)**

Modeling the control valve (Boehm, 2026)

The valve coefficient and valve opening times as stated in Moore's experiments are given as below

Kv (m^3 /hr)	Cv	Valve Opening (ms)
0.032	0.037	150
1.3	1.5	8
3.4	4.0	75

GFSSP Model

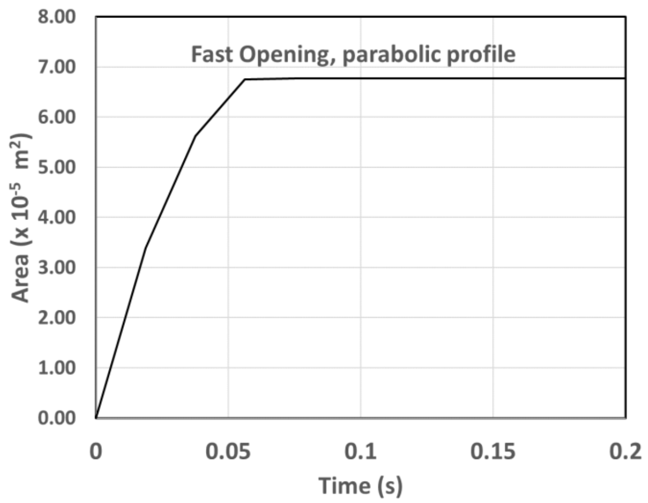


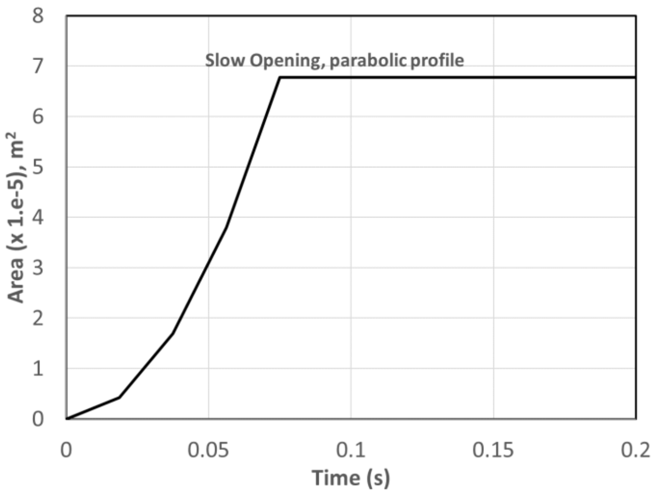
Three valve opening profiles were studied:

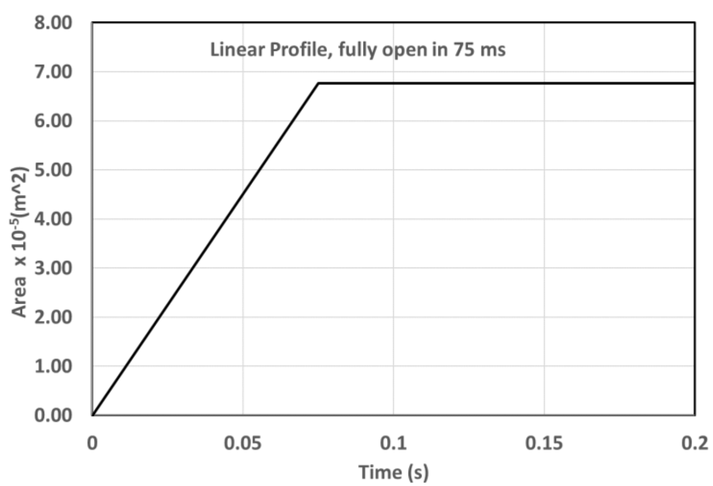
- Linear: $A = kt$
- Quick open: $A = k\sqrt{t}$
- Slow open: $A = kt^2$

Valve Opening History Files

Three different profiles are tried for valve opening; Linear, fast (parabolic) and slow (parabolic) with opening time being same

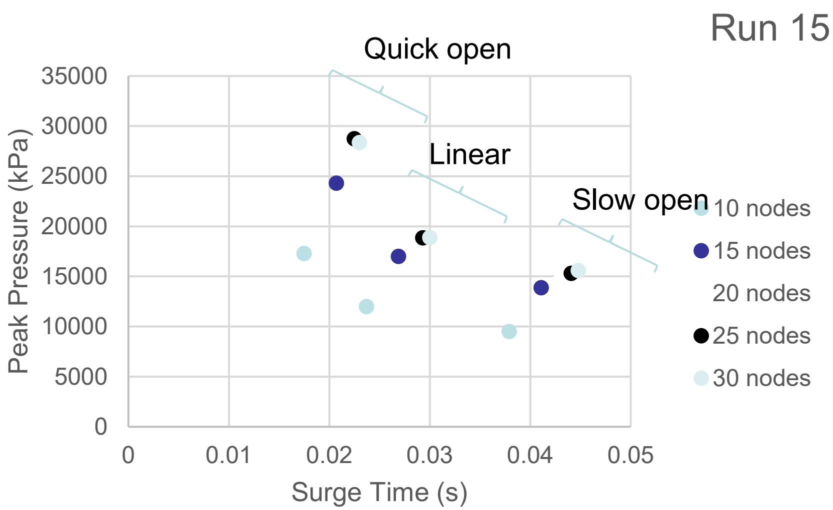


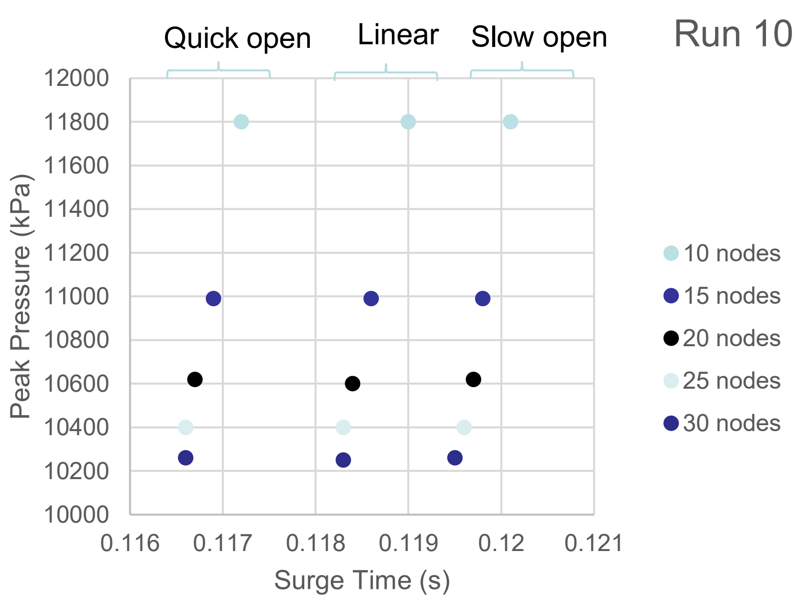




Grid Independence Study

Grid Independence Study: Selected both short and long pipes with different Cvs





Results: Comparisons with test data (6)

- **From the previous study, reported the following best and worst GFSSP results as compared to test data**

a) Absolute best:

Paper Run #	Valve Cv	Test Element Pressure (kPa)	Test Element Length (m)	Test Element Diameter (mm)	Tank Pressure (kPa)	Penn State Peak Pressure (kPa)	GFSSP Peak Pressure (kPa)
24	1.5	15	0.51	12.7	2200	21640	21530
7	1.5	101	0.51	9.53	2190	18040	17920
8	1.5	101	0.51	9.53	1490	8400	8256.667

b) Relative Best

Paper Run #	Valve Cv	Test Element Pressure (kPa)	Test Element Length (m)	Test Element Diameter (mm)	Tank Pressure (kPa)	Penn State Peak Pressure (kPa)	GFSSP Peak Pressure (kPa)
24	1.5	15	0.51	12.7	2200	21640	21530
7	1.5	101	0.51	9.53	2190	18040	17920
52	1.5	3.7	2	6.35	2850	36080	35640

Results: Comparisons with test data

a) Absolute worst:

Paper Run #	Valve Cv	Test Element Pressure (kPa)	Test Element Length (m)	Test Element Diameter (mm)	Tank Pressure (kPa)	Penn State Peak Pressure (kPa)	GFSSP Peak Pressure (kPa)
44	4	15	2	9.53	2880	16670	47176.67
19	4	101	2	9.53	2870	6040	33923.33
18	4	101	2	12.7	2900	5630	33146.67

b) Relative worst:

Paper Run #	Valve Cv	Test Element Pressure (kPa)	Test Element Length (m)	Test Element Diameter (mm)	Tank Pressure (kPa)	Penn State Peak Pressure (kPa)	GFSSP Peak Pressure (kPa)
20	4	101	2	9.53	2180	3250	21646.67
21	4	101	2	9.53	1470	1490	9331
18	4	101	0.51	12.7	2900	5630	33146.67

Current Study

- As observed from the previous study that Cv = 4.0 cases show maximum differences between GFSSP and test data.
- Errors are more in case of long pipes as compared to the short pipes.
- In the current study, the cases with maximum discrepancies of GFSSP simulations with test data are revisited and grid independence and time step independence is established first.
- The unsteady friction factor is introduced and implemented into the code and effect of unsteady state friction factor is studied.

Unsteady State Friction Factor

- Fluid friction during rapid transient events (like valve closures or pump startups) is higher than steady-state predictions.
- Wall shear stress depends on both instantaneous flow velocity and past flow acceleration history, requiring dynamic time-dependent adjustments rather than standard Moody diagram values.

Major Modeling Approaches

- **Brunone's Model (Instantaneous Acceleration):**Adds a correction term based on local and convective fluid acceleration.

- **Weighting Function Models (Vardy-Brown / Convolution Integral):**Uses a convolution integral of past velocity changes weighted against time domains.

Brunone

$$f = f_q + \frac{kD}{V|V|}\left(\frac{\partial V}{\partial t} - c\frac{\partial V}{\partial x}\right)$$

Where, k = Brunone's coefficient = $\frac{\sqrt{C^*}}{2}$
with C^* = 0.00476 for laminar flow
For turbulent flow:

$$C^* = \frac{7.41}{\mathrm{Re}^{\log\left(14.3/\mathrm{Re}^{0.05}\right)}}$$

Vitkovsky (modified Bruno)

Vítkovský proposed a new formulation of Eq. (8):

$$f = f_q + \frac{kD}{V|V|}\left[\frac{\partial V}{\partial t} + c\,sign(V)\left|\frac{\partial V}{\partial x}\right|\right]$$

In which sign(V) = (+1 for $V \geq 0$ or -1 for $V < 0$).

Time Step Selection based on Courant Condition

- Courant number for fluid transient problem is defined as: C = $a\frac{\Delta t}{\Delta x}$, where Δt is the time step and Δx = 2L/N

  is the step size, where L is pipe length and N is number of pipe segments. The constant a is the sound velocity in the medium (taken as water),
- The CFL (Courant–Friedrichs–Lewy) condition requires for stable transient solution, C <= 1 and this puts a restriction on time step as below:

$$\Delta t <= \frac{2L}{N*a}$$

L (m)	N	delta_tMax (s)
0.51	15	4.59459E-05
0.51	8	8.61486E-05
2	15	0.00018018
2	30	9.00901E-05
2	40	6.75676E-05

Time step used for short pipe: 5e-5 s
Long pipe: 0.0001 s

Grid and Time Step Independence study

- First conducted Grid Independent and then time independent study.
- Case 20 with Cv = 4, **L = 2 m**, test-element pressure of 101 kPa, OD 9.53 is used for base study as this case shows maximum error between GFSSP and test data (558%).
- Used time step of 0.0001 s

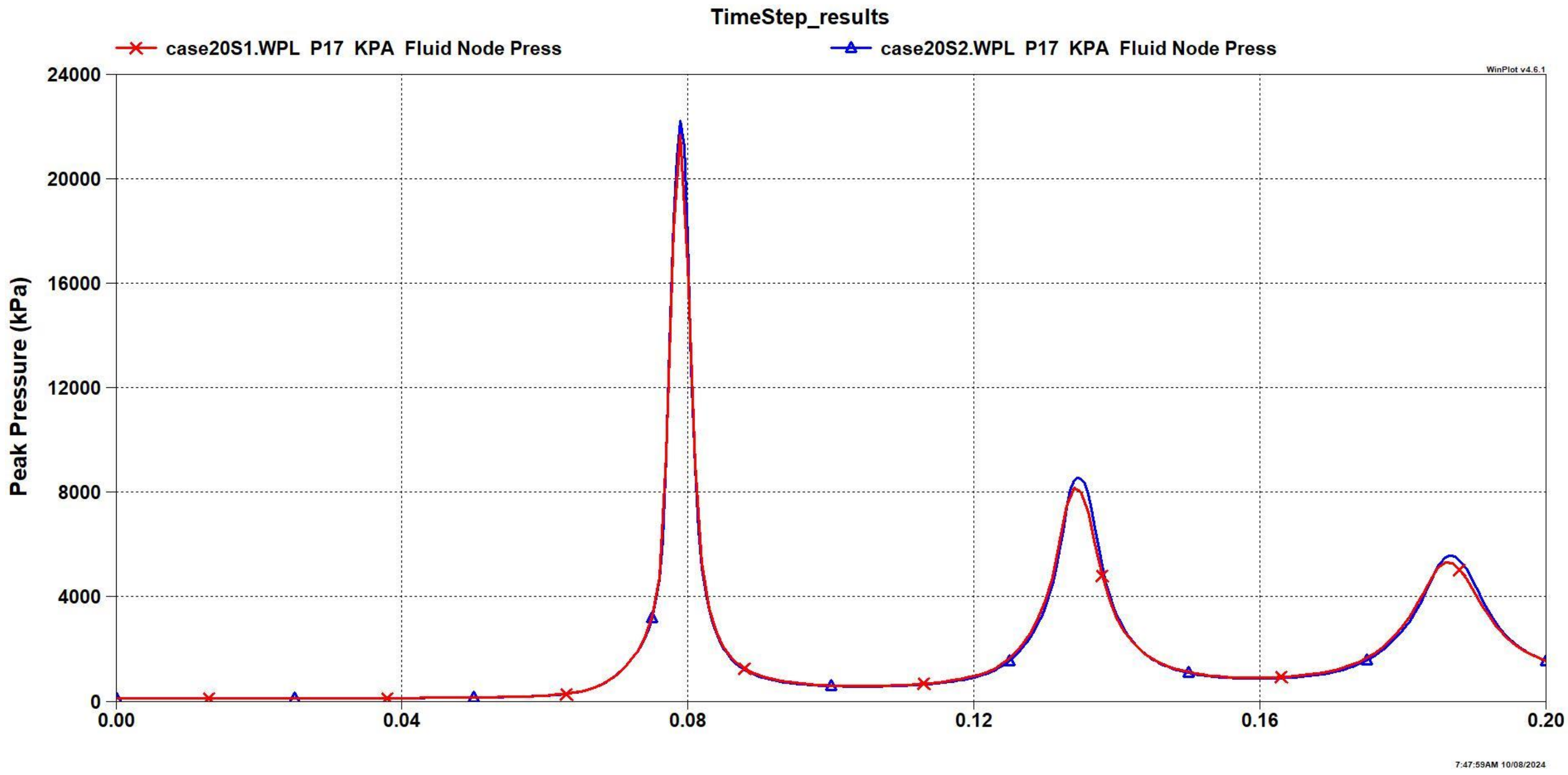
N	peak_p	response time	expt peak
15	21673	0.08	3250
30	21667	0.09	

Short Pipe (case 15)

N	peak_p	response time	expt peak
8	20416	0.033	11290
15	21016	0.033	

Time step Independence

- For all long pipe case with high Cv (=4) has been tested for time step independence, and delta_t = 0.0001 s produces almost time step independent results.



Time step Independence Table

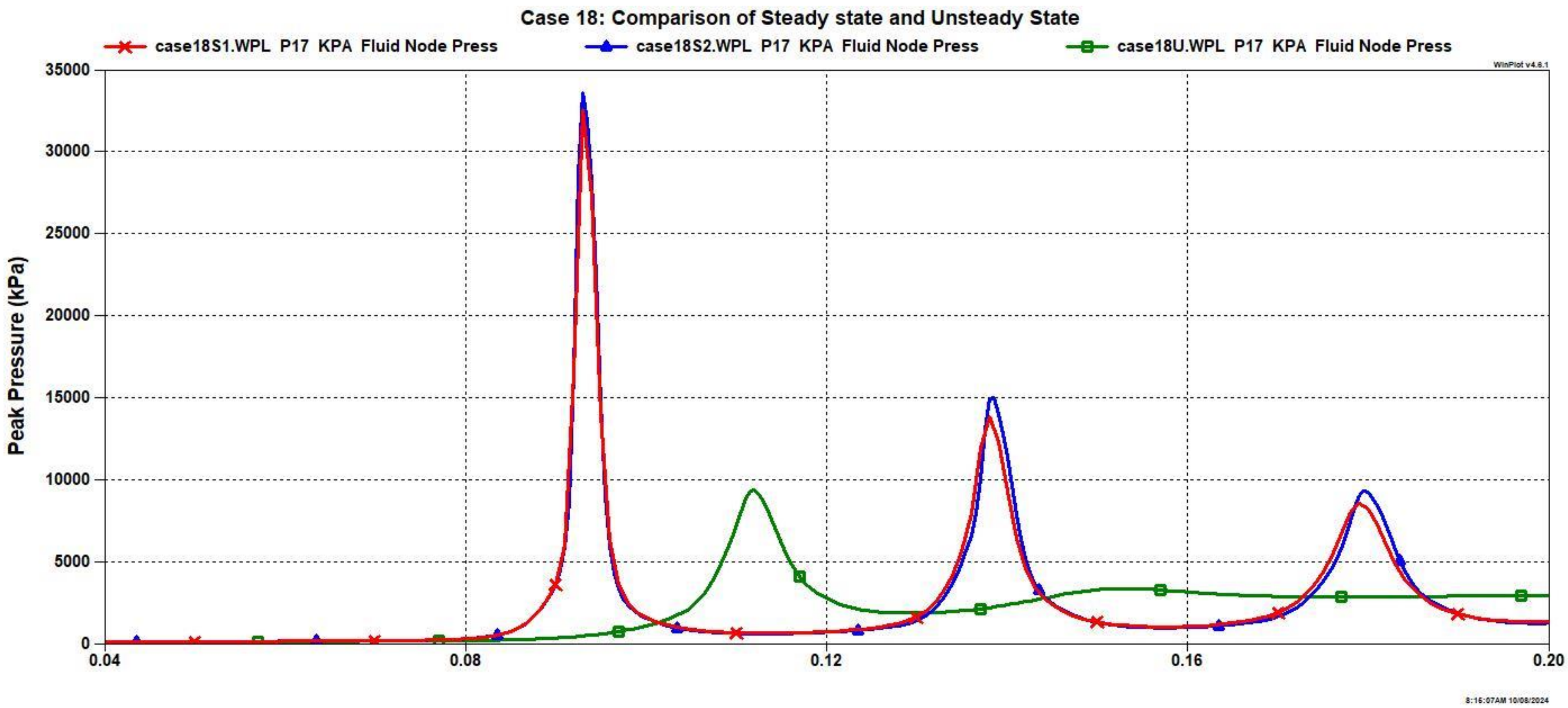
	Peak Pressure					Response Time				
TimeStep	**Case18**	**Case19**	**Case20**	**Case21**	**Case22**	**Case18**	**Case19**	**Case20**	**Case21**	**Case22**
0.0001	32597	33382	21684	9070	20568	0.093	0.079	0.079	0.107	0.075
0.0005	33607	34138	22191	9312	20942	0.093	0.08	0.079	0.107	0.075

Effect of unsteady state friction factor

The GFSSP simulations have been conducted using both (a) steady-state and (b) unsteady state friction factor model.
The table below lists the cases with long pipe and high valve coefficient

case	pamb	CV	L	OD	Ptank	p_expt	GFSSP_steady	GFSSP_unsteady	t_expt	t_gfsspS	t_GFSSPU
case 18	101	4	2	12.7	2900	**5630**	33585	9394	0.173	0.093	0.112
case 19	101	4	2	9.53	2870	6040	33384	7565	0.114	0.079	0.101
Case 20	101	4	2	9.53	2180	3250	21385	3424	0.13	0.079	0.114
case 21	101	4	2	9.53	1470	1490	9070	**1471**	0.13	0.107	0.185
case 22	101	4	2	6.35	2840	9930	20007	4425	0.238	0.075	0.107
case 44	15	4	2	9.53	2880	16670	50507	27670	0.103	0.078	0.096
case 45	15	4	2	9.53	2180	14080	40855	18743	0.112	0.087	0.113
case 46	15	4	2	9.53	1480	10820	32967	6552	0.138	0.101	0.15
case 56	3.7	4	2	12.7	2850	20340	45383	27878	0.15	0.092	0.107
case 57	3.7	4	2	9.53	2870	38100	45551	26762	0.114	0.078	0.095
case 58	3.7	4	2	6.35	2860	35310	36672	20826	0.093	0.073	0.097

Effect of Steady-State vs Unsteady State friction



Discussion

- GFSSP Numerical computation with standard friction factor model predicts very well with experimental data of Moore et al (6) for short pipes with low valve coefficient.
- However, flow with long pipes and large valve coefficients need to apply the unsteady state friction factor model.
- The unsteady state friction factor model need to be tested more rigorously, and applications of that need to be investigated for both valve opening and valve closing cases.

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