ONE-DIMENSIONAL TRANSIENT MODEL OF A HEAT EXCHANGER TUBE RUPTURE USING THERMOPHYSICAL DATA: DISCHARGING A HIGH-PRESSURE LIQUID INTO A LOW-PRESSURE LIQUID-FILLED SHELL

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About AP Dynamics

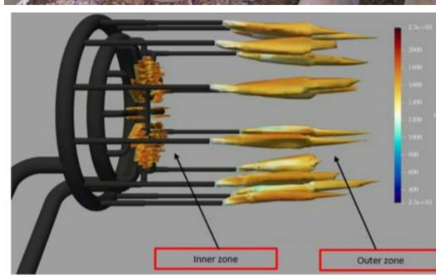
- Fully Integrated Engineering Service Company
- 20+ years in business
- Locations
  - Calgary, AB (Headquarters)
  - Houston, TX (US operations)
- Success Stories:

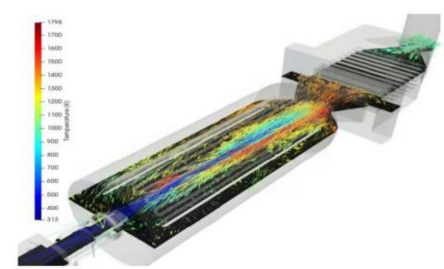
  TC Energy, Shell, Suncor Energy, Cenovus, Chevron, Kinder Morgan, ConocoPhillips, Air Liquide, Nutrien.
- Team of 200+ highly skilled engineers and PhDs
  - Many with 10+ years of experience

Our Priority

Help Clients minimize facility and equipment downtime and optimize productivity and revenue by performing:

- Fitness for Services (FFS) Assessments
- Asset integrity studies
- Field monitoring and troubleshooting
- Optimizing equipment throughput and environmental performance

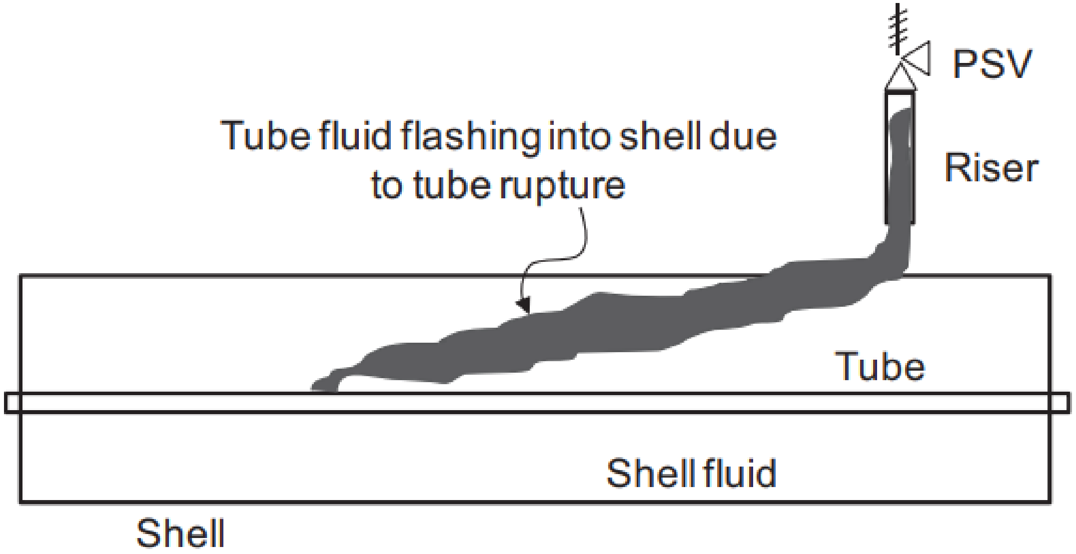


with reliable, innovative, value-effective solutions

using comprehensive, high tech on site testing and by

simulating reality through state of the art computer modeling

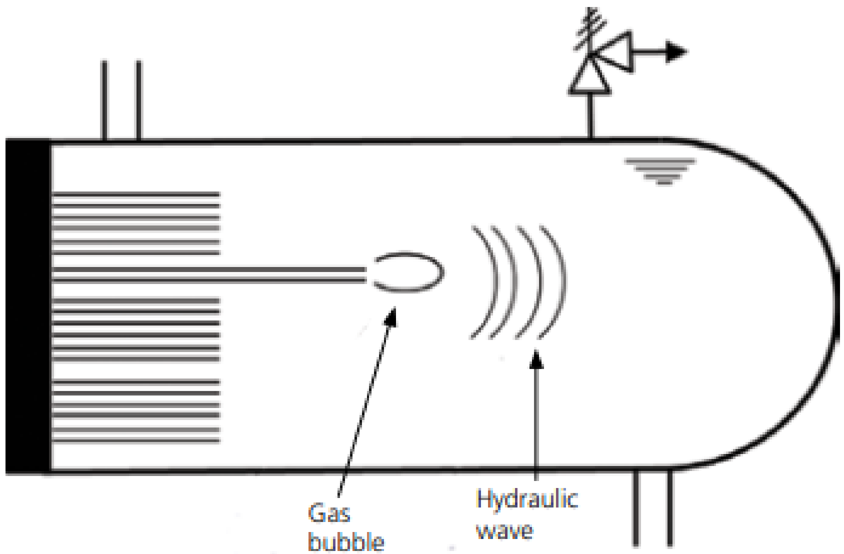
There is safety risk during Heat Exchanger operation when the flashing of the tube fluid occurs upon failure creating a significant pressure spike.



Flow pattern from rupture to PSV [1]

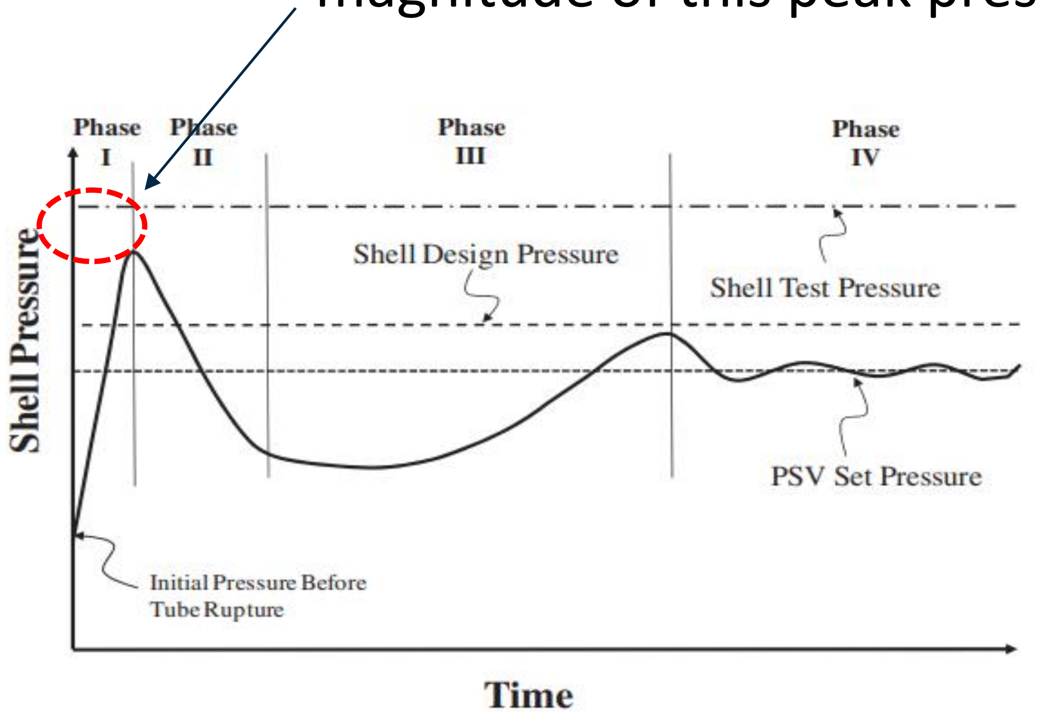
Ennis et al. J Loss Prevent Proc. 2011

API Std 521 recommends that a transient analysis should be performed to assess pressure surge and fluid dynamics between shell and PSV device when tube rupture occurs



Model Objective

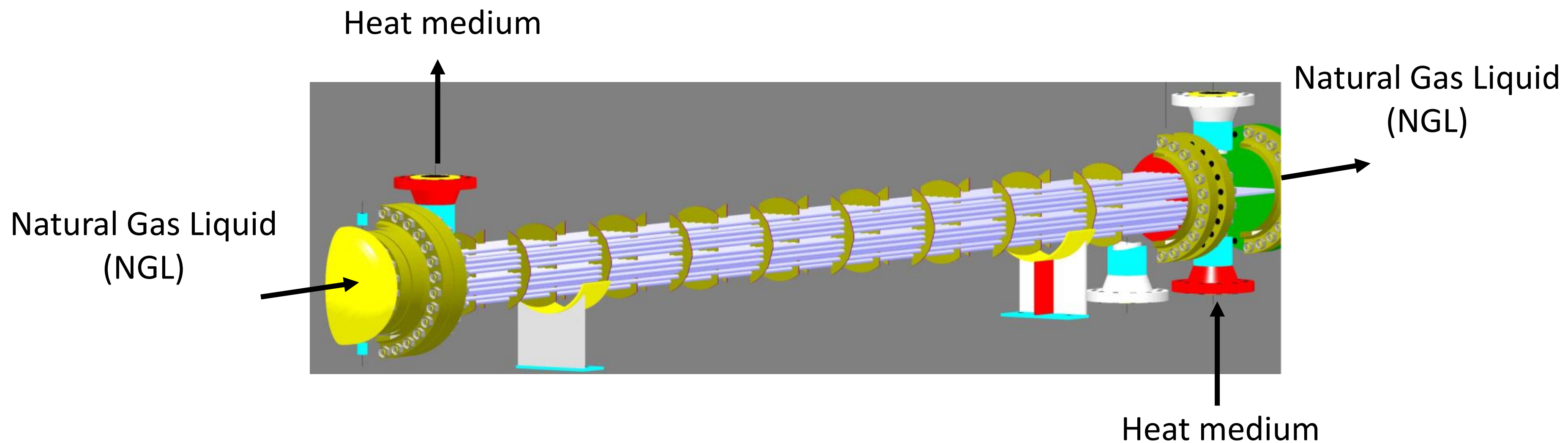
The goal is to determine the magnitude of this peak pressure



The phases following a tube rupture of high-pressure fluid into low pressure shell [1]

Ennis et al. J Loss Prevent Proc. 2011

Application



Flow Stream	Temperature [°C]	Pressure [barG]
NGL – Tube Side	85.4	35
Heat Medium – Shell Side	176	10.7

Peak Pressure Calculation Methods

- Method 1: Peak Pressure Calculations (EI Guideline)
- Method 2: Volume Model
- Method 3: Extended Model
- Method 4: Extended Model + Vaporization Effect

Peak Pressure Calculations (Method 1)

Volume change (arising from the regression of the liquid/gas interface due to the passage of hydraulic wave)

=

Volume inflow gas at the rupture

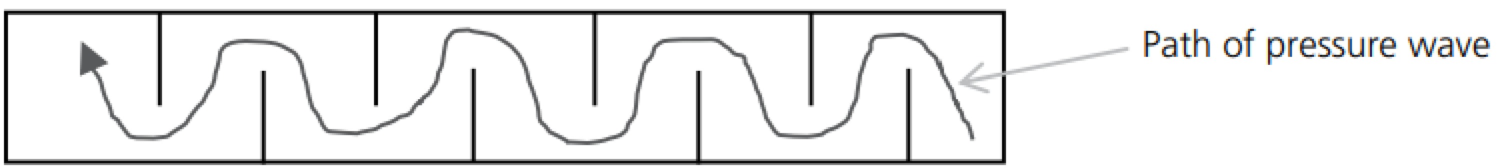
$$P_{is}(P_{is} - P_r)^{\gamma} = \left(\frac{2}{(\gamma+1)}\right)^{(\gamma/(\gamma-1))} P_0 \left(\frac{C_D a\, \rho_L c A_t}{A_s}\right)^{\gamma}$$

where

c is the wave speed in the liquid (m/s)
P_r is the operating pressure of the Low Pressure (LP) liquid (Pa)
P_{is} is the gas impact induced initial step in pressure (Pa)
ρ_L is liquid density (kg/m^3)
γ is the ratio of specific heats of the High Pressure (HP) gas
C_D is the coefficient of discharge for the tube
a is the velocity of sound for the discharging gas at the choke (m/s)
A_t is the twice the total cross-sectional area of the tube (m^2)
A_s is the characteristic shell area (m^2)
P_0 is the source pressure of High Pressure (HP) gas

Peak Pressure Calculations (Method 1)

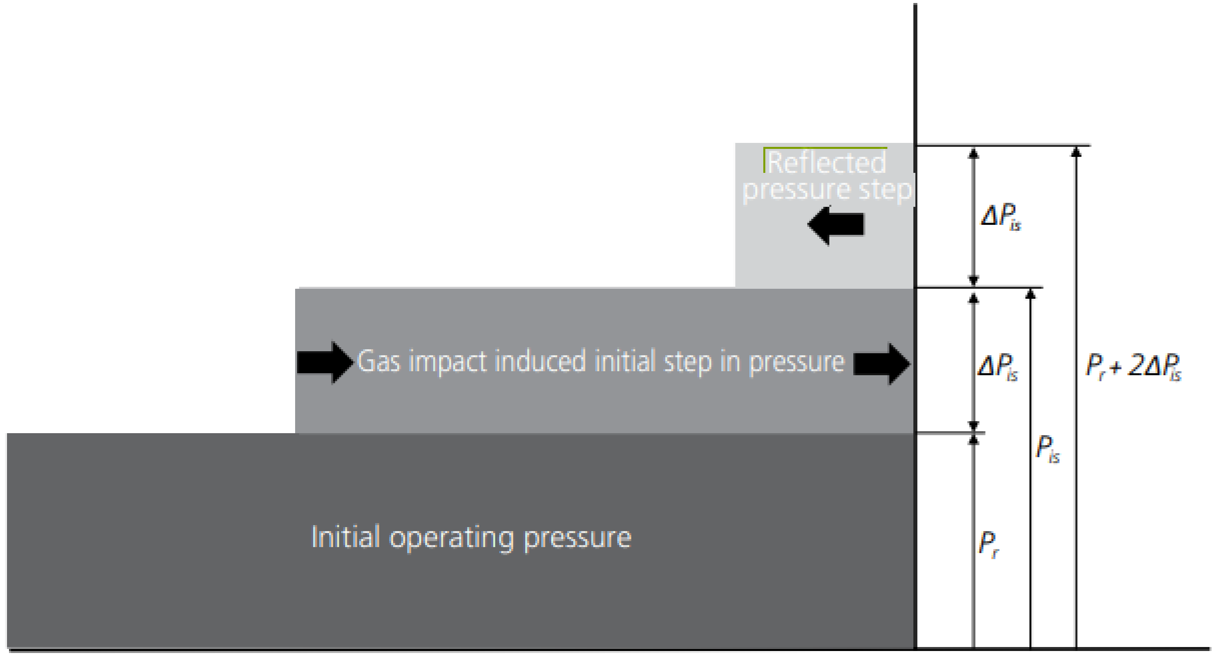
- Path of Pressure Wave is required to determine the **Characteristic Shell Area (A_s)** :



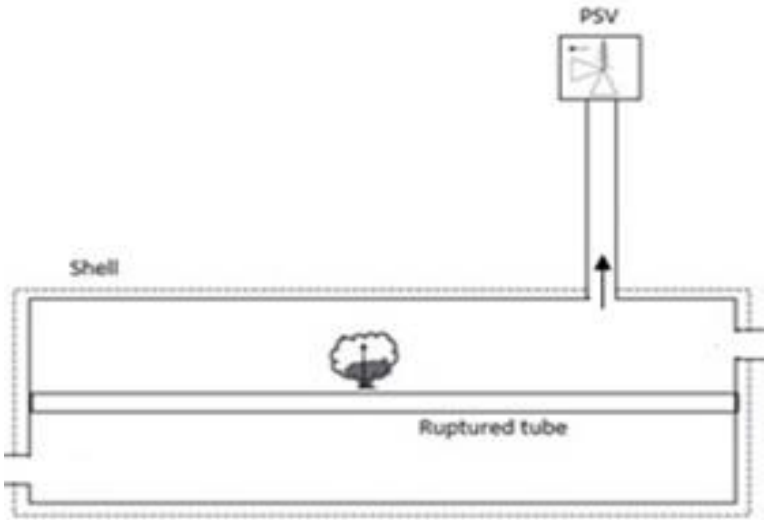
Actual distance the pressure wave travels from the tube rupture around each baffle

Peak Pressure Calculations (Method 1)

Pressure	Value, [bar]
P_{is} (peak pressure)	34.28
$P_r + 2\Delta P_{is} = P_r + 2 \times (P_{is} - P_r)$ (shell design pressure)	56.85



Volume Model (Method 2)



$$\frac{dP}{dt} = \frac{\frac{\dot{m}_{tv}}{\rho_{tv}} + \frac{\dot{m}_{tl}}{\rho_{tl}} - \frac{\dot{m}_{psv}}{\rho_{sl}}}{\frac{V_{tv}}{c^2{}_{tv0}\,\rho_{tv}} + \frac{V_{tl}}{B_{tl}} + \frac{V_{sl}}{B_{sl}} + \frac{V_{shell}}{B_{shell}}}$$

fluid

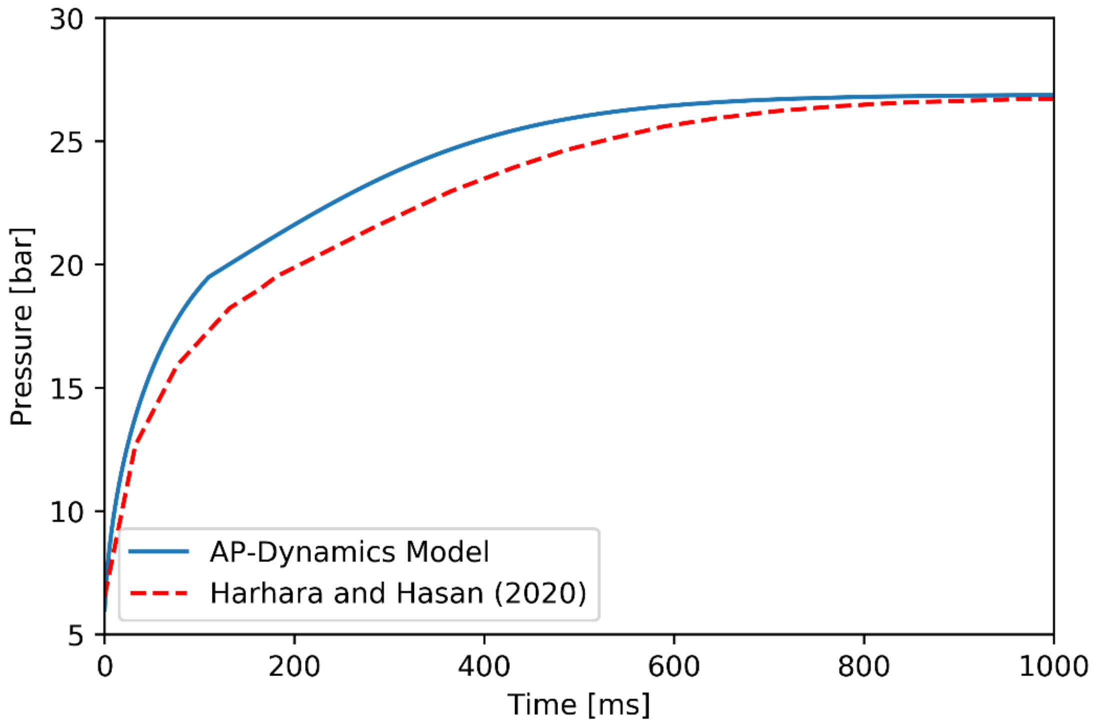
shell geometry

where:

$\dot{m}_{tv}$ and ρ_{tv} are the tube-side vapor mass flow rate [kg/s] and density [kg/m^3]
$\dot{m}_{tl}$ and ρ_{tl} are the tube-side vapor liquid flow rate [kg/s] and density [kg/m^3]
$\dot{m}_{psv}$ and ρ_{sl} are the PSV mass flow rate [kg/s] and shell-side liquid density [kg/m^3]
V_{tv} and $c^2{}_{tv0}$ are the volume of tube-side vapor that has entered the shell-side [m^3] and tube-side vapor's speed of sound [m/s]
V_{tl} and B_{tl} are the volume of tube-side liquid that has entered the shell-side [m^3] and tube-side liquid's bulk modulus [Pa]
V_{sl} and B_{sl} are the volume of shell-side liquid [m^3] remaining in the shell-side and tube-side liquid's bulk modulus [Pa]
V_{shell} and B_{shell} are the volume [m^3] and bulk modulus [Pa] of the shell material of construction (e.g., carbon steel)

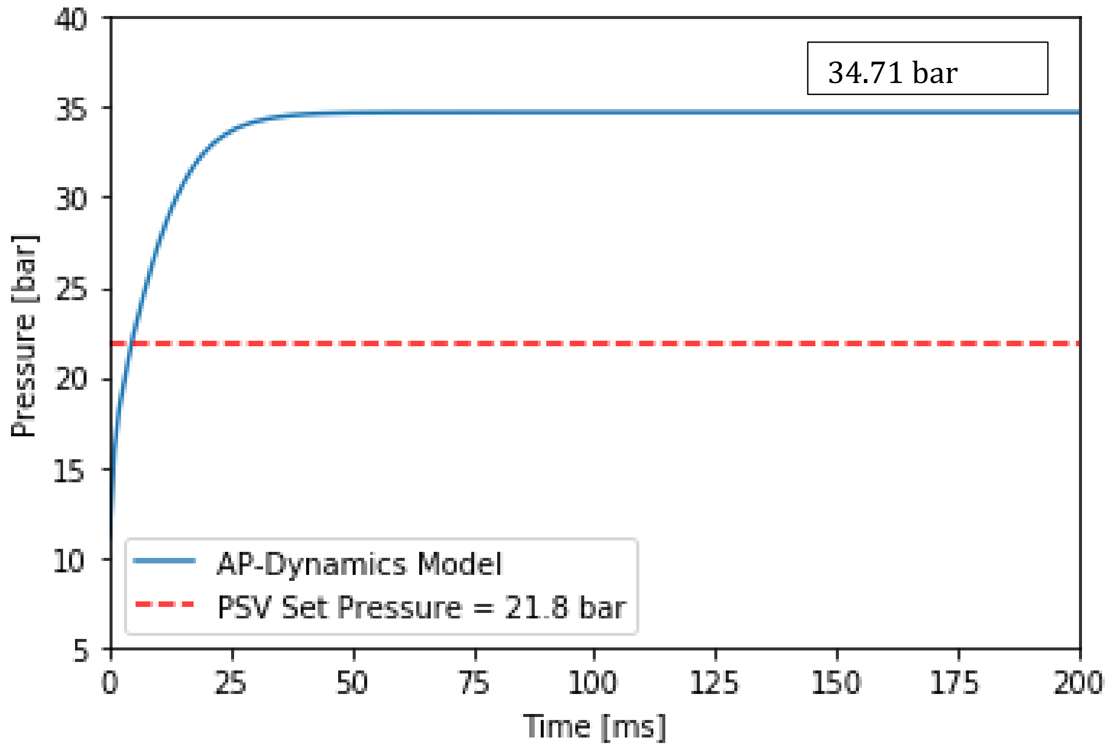
$A_{psv}C_0$ is assumed to be 0.71 cm^2 ("D" PSV orifice size)

Volume Model (Method 2) - Validation



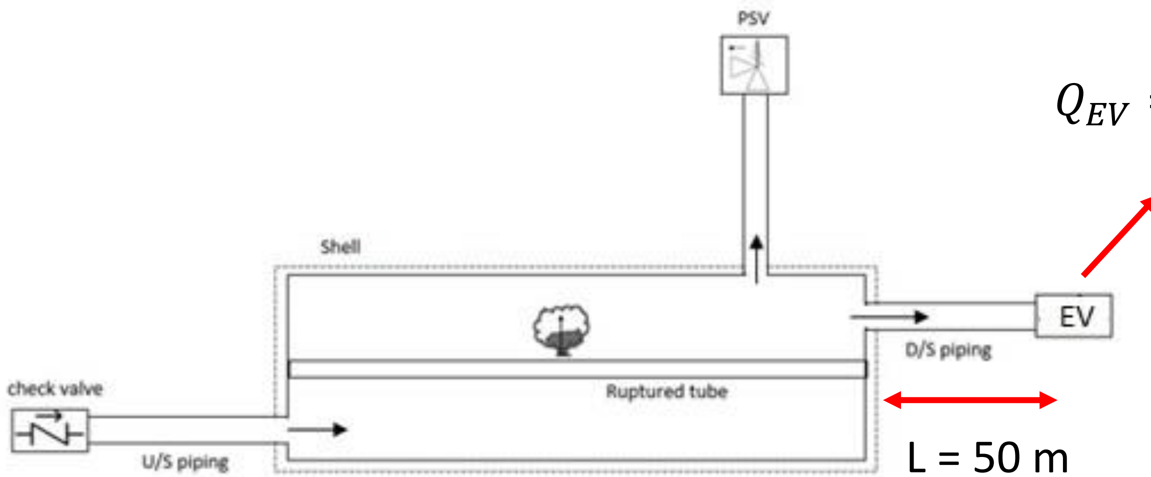
Harhara and Hasan *BMC Chemical Engineering* (2020) 2:5

Volume Model (Method 2)



Shell Only
"D" PSV orifice size

Extended Model (Method 3)



$$Q_{EV} = \begin{cases} \frac{\dot{m}_{sl}}{\rho_{sl}}, & t < 6 \\ 0, & t \geq 6 \end{cases}$$

L = 50 m
ID = 152 mm

L = 50 m
ID = 152 mm

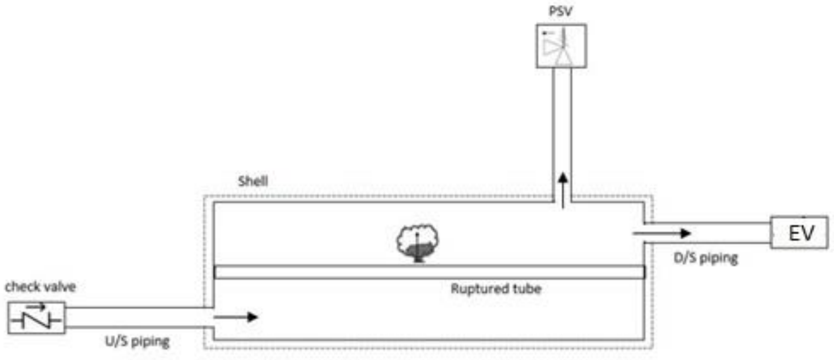
Governing equations for U/S and D/S piping:

$$\frac{\partial V}{\partial t} + V\frac{\partial V}{\partial x} + g\frac{\partial H}{\partial x} + \frac{fV|V|}{2D} = 0$$

$$\frac{\partial H}{\partial t} + V\frac{\partial H}{\partial x} + \frac{a^2}{g}\frac{\partial V}{\partial x} = 0$$

Extended Model (Method 3)

$$\frac{dP}{`t} = \frac{\frac{\dot{m}_{tv}}{\rho_{tv}} + \frac{\dot{m}_{tl}}{\rho_{tl}} - \frac{\dot{m}_{psv}}{\rho_{sl}} + \frac{\dot{m}_{s-in}}{\rho_{sl}} - \frac{\dot{m}_{s-out}}{\rho_{sl}}}{\frac{V_{tv}}{c^2{}_{tv0}\,\rho_{tv}} + \frac{V_{tl}}{B_{tl}} + \frac{V_{sl}}{B_{sl}} + \frac{V_{shell}}{B_{shell}}}$$

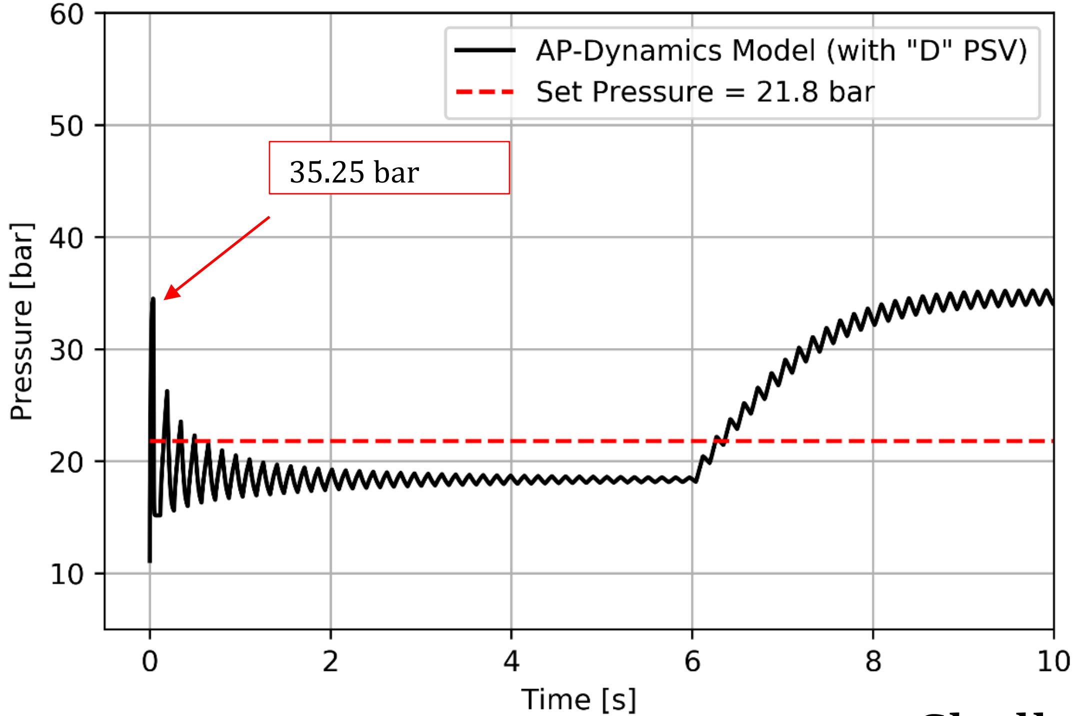


where:

$\dot{m}_{s-in}$ is the shell inlet mass flow rate [kg/s]
$\dot{m}_{s-out}$ is the shell outlet mass flow rate [kg/s]

$A_{psv}C_0$ is assumed to be 0.71 cm² ("D" PSV orifice size)

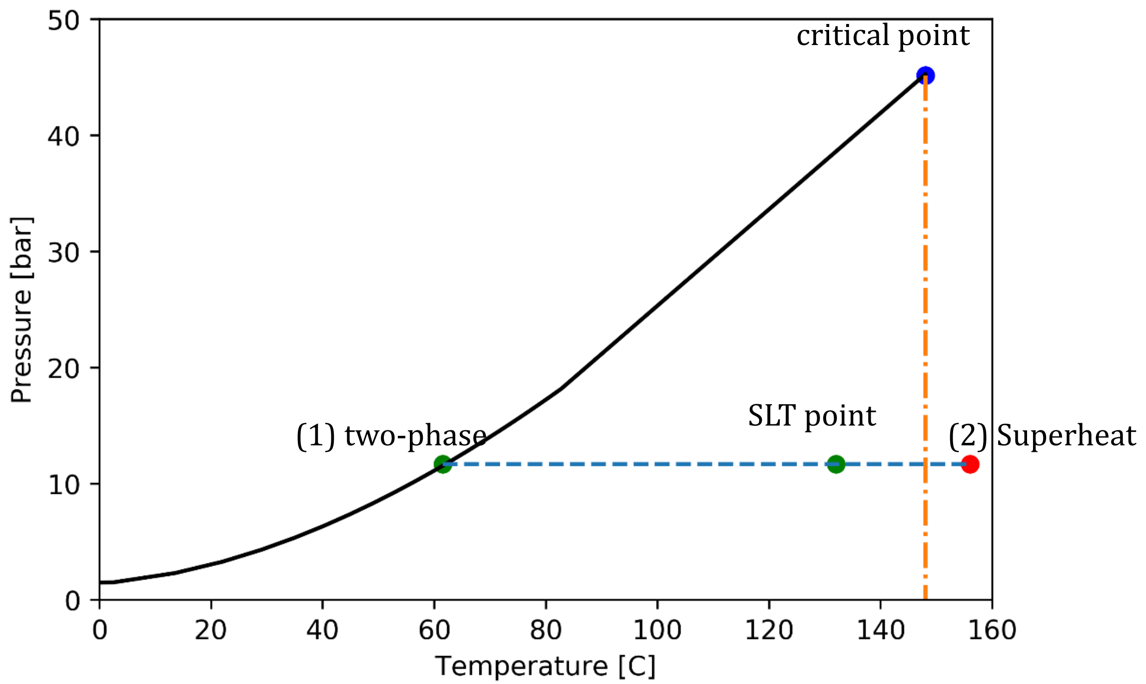
Extended Model (Method 3)



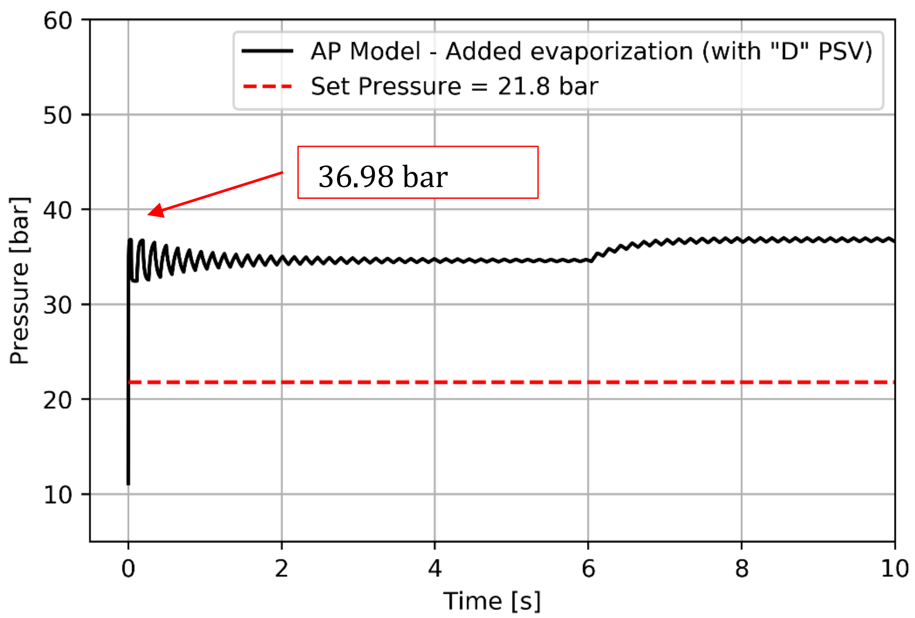
Shell + Piping
“D” PSV orifice size
EV Closes Suddenly

Method 4 (Method 3 + Vaporization Effect)

$$\frac{dP}{dt} = \frac{\frac{\dot{m}_{tv} + \dot{m}_{tl}}{\rho_{tv}} - \frac{\dot{m}_{psv}}{\rho_{sl}} + \frac{\dot{m}_{s-in}}{\rho_{sl}} - \frac{\dot{m}_{s-out}}{\rho_{sl}}}{\frac{V_{tv}}{c^2{}_{tv0}\,\rho_{tv}} + \frac{V_{tl}}{B_{tl}} + \frac{V_{sl}}{B_{sl}} + \frac{V_{shell}}{B_{shell}}}$$

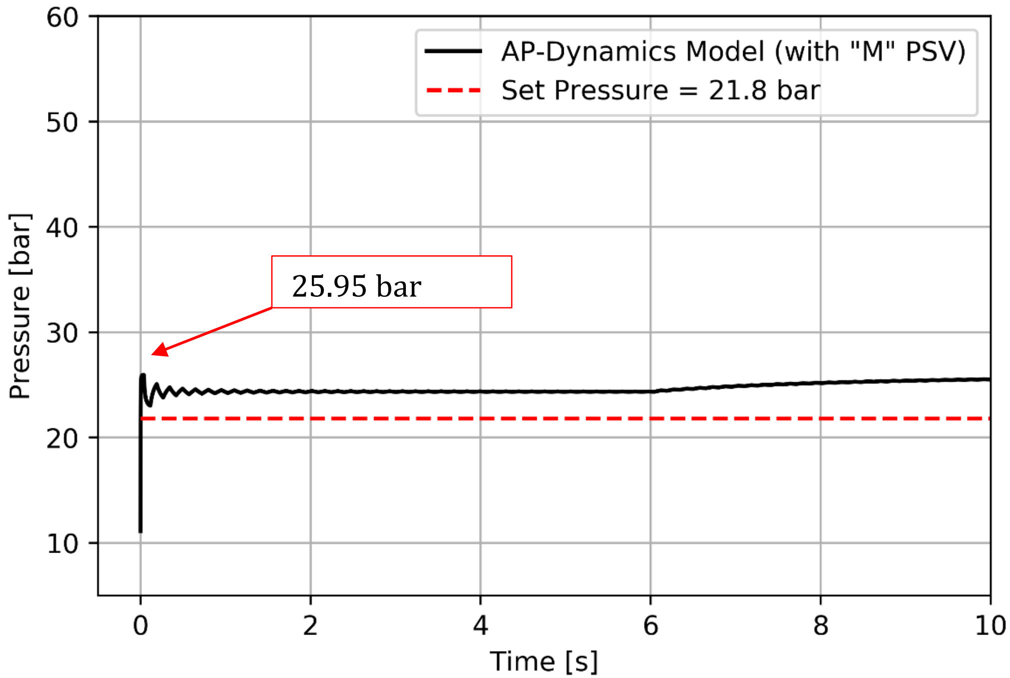


Method 4 (Method 3 + Vaporization Effect)



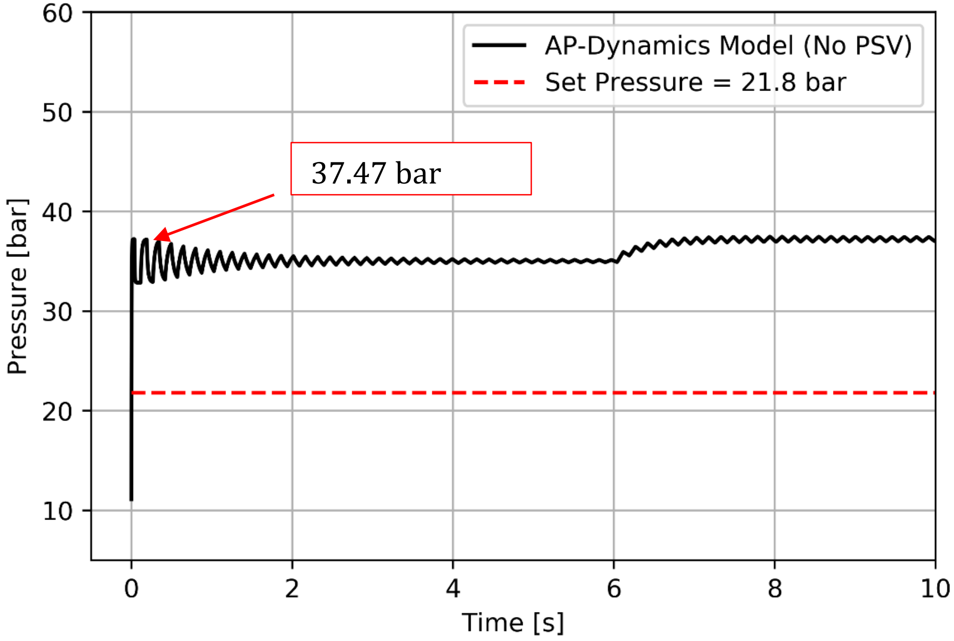
Shell + Piping
"D" PSV orifice size
EV Closes Suddenly

Method 4 (Method 3 + Vaporization Effect)



Shell + Piping
“M” PSV orifice size
EV Closes Suddenly

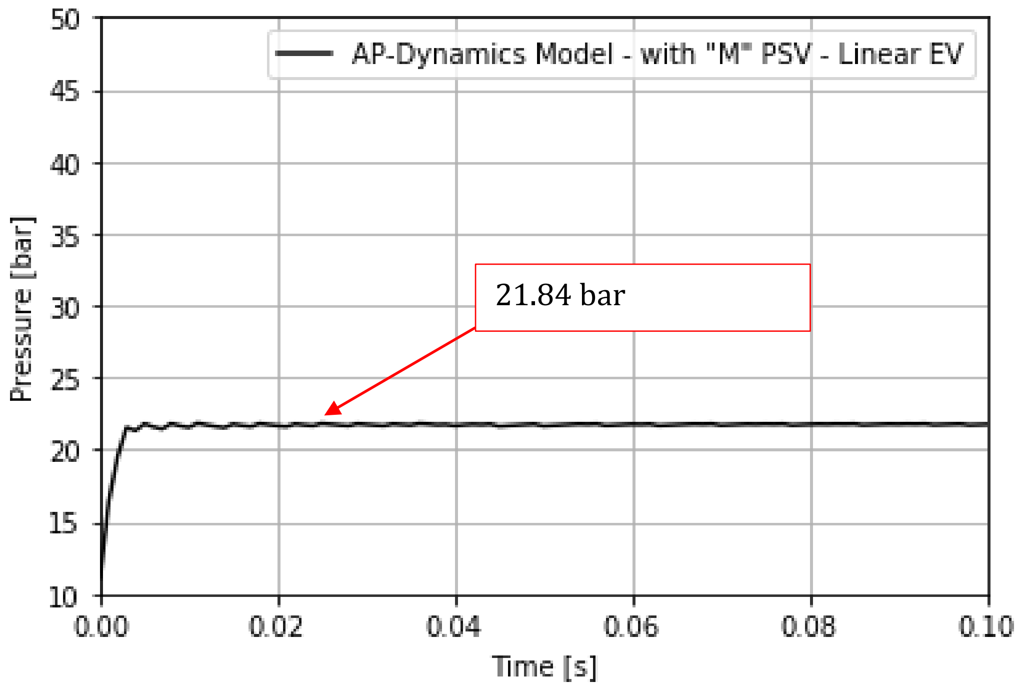
Method 4 (Method 3 + Vaporization Effect)



Shell + Piping
No PSV
EV Closes Suddenly

Method 4 (Method 3 + Vaporization Effect)

$$Q_{EV} = \begin{cases} \frac{\dot{m}_{sl}}{\rho_{sl}} \times \left(1 - \frac{t}{6\,[s]}\right), & t \leq 6 \\ 0, & t > 6 \end{cases}$$



Shell + Piping
“M” PSV orifice size
EV Closes gradually

Summary of Results

Method	Shell Overpressure (bar)
P_{is} (EI Guideline)	34.28
Volume Model	34.71
Extended Model	35.25
Extended Model + Vaporization Effect	36.98

The shell overpressure calculated with the Method 4 are as follows:

Method	Shell Overpressure (bar)
Extended Model + Vaporization Effect (“M” PSV Orifice Size)	25.95
Extended Model + Vaporization Effect (No PSV)	37.47
Extended Model + Vaporization Effect (Closure Linear Function of EV + “M” PSV Orifice Size)	21.84

Conclusions and Recommendations

- Overpressure Dynamic/Transient analysis should be performed to identify an accurate overpressure
- Overpressure greatly depends on PSV orifice size
- Upstream and Downstream piping and associated devices should be considered in the transient model
- Vaporization effect should be addressed in cases that two-phase condition cannot be maintained and superheat conditions are reached

THANK YOU FOR YOUR ATTENTION!

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