ConocoPhillips

Water Hammer in Upstream Production

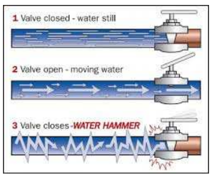
Thomas J. Danielson
March 23, 2017

Presentation Overview

- Water Hammer Definition
- Joukowsky Equation
  - Force Balance
  - Bernoulli Equation
- Fast and Slow Valve Closure
- Water Hammer
  - Inelastic Pipe
  - Elastic Pipe
  - Two-Phase Flow
  - Condensation-Induced
- Conclusions

Water Hammer - Definition

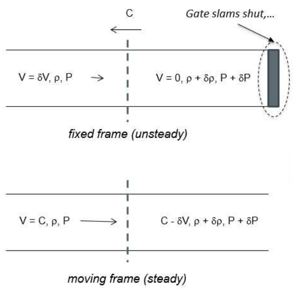
- Water Hammer
  - The result of a sudden stop of flow. The kinetic energy stored in the pipeline is converted to potential energy which manifests as an increase in line pressure.
  - Water hammer pressure spikes are much higher than any other operational event, and pipeline pressure cannot go above MAOP – otherwise, the pipe can burst.
- Sonic Wave
  - The pressure surge created by a water hammer event moves backwards through the pipe at the speed of sound.
  - The draining away of pressure energy by the sound wave sets an upper limit on the magnitude of the pressure surge.



http://www.structuretech1.com/2012/06/water-hammer/

http://63.135.98.40/trainwreck02.jpg/

Force Balance (Inelastic Pipe)

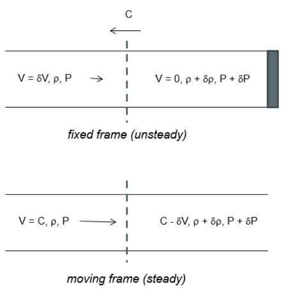


Joukowsky Equation

$$\boxed{\delta P = -\rho C \delta V}$$

$$F = \delta P A = \dot{m}(V_{OUT} - V_{IN}) = (\rho A C)[(C - \delta V) - C] = -(\rho A C)\delta V$$

Can We Apply Bernoulli?



$$P + \frac{\rho(\delta V)^2}{2} = P + \delta P + \frac{(\rho+\delta\rho)(0)^2}{2}$$

$$\delta P = \cancel{\frac{\rho(\delta V)^2}{2}}$$ *Very wrong!*

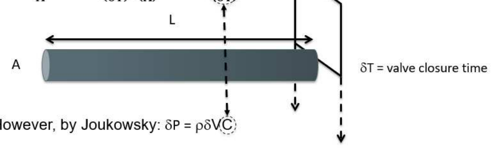
$$P + \frac{\rho(C)^2}{2} = P + \delta P + \frac{(\rho+\delta\rho)(C-\delta V)^2}{2}$$

$$\delta P \approx \frac{2\rho C(\delta V)}{2} = \rho C \delta V$$

Works because Bernoulli was correctly applied in steady-state

Fast and Slow Closure - Definition

$$\delta P = \frac{F}{A} = \rho L A\left(\frac{\delta V}{\delta T}\right)\left(\frac{1}{A}\right) = \rho \delta V\left(\frac{L}{\delta T}\right)$$



However, by Joukowsky: $\delta P = \rho \delta V C$

Conventional wisdom states that $2L/\delta T < C$ constitutes a slow valve closure (fluid behaves as incompressible)

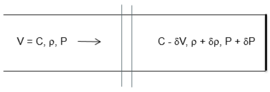
Mass Balance (Inelastic Pipe)

$$\delta V = \frac{C\delta\rho}{(\rho + \delta\rho)}$$

Mass Conservation

ρAC = A(ρ + δρ)(C - δV)

$$\delta P = \frac{\rho C^2 \delta\rho}{(\rho+\delta\rho)} \approx \rho C^2\left(\frac{\delta\rho}{\rho}\right) = C^2\delta\rho$$



change of frame to wave

$$C^2 = \left(\frac{\delta P}{\delta\rho}\right) = \frac{K}{\rho}$$

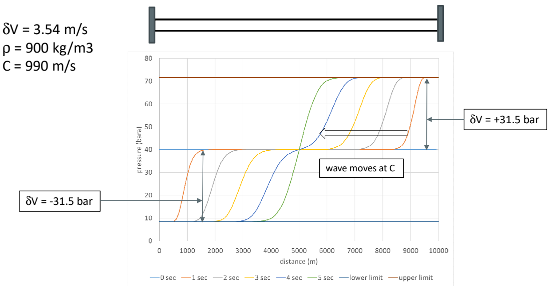
Equation can be used in conjunction with PVT look-up table to determine sound speed from fluid properties: C = [1/(∂ρ/∂P)]$^{1/2}$

ConocoPhillips

Water Hammer Surge for Nearly-Frictionless Flow & Inelastic Pipe

δP = ρCδV = 31.5 bar (3.15·10^6 Pa)

δV = 3.54 m/s
ρ = 900 kg/m3
C = 990 m/s

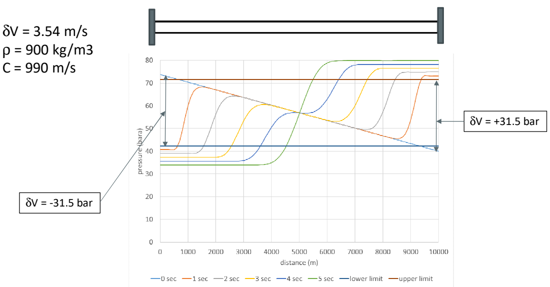


 ConocoPhillips

Water Hammer Surge for Flow with Friction & Inelastic Pipe

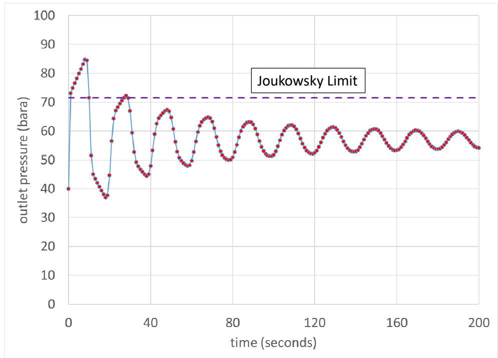
δP = ρCδV = 31.5 bar (3.15·10^6 Pa)

δV = 3.54 m/s
ρ = 900 kg/m3
C = 990 m/s



 ConocoPhillips

Water Hammer Surge for Flow with Friction & Inelastic Pipe



Using the Mass Equation to Derive the Effect of Elasticity

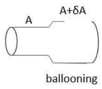
- Mass Equation / No Elasticity (Area A is constant)

$$dz \cdot A\frac{d\rho}{dt} = dz \cdot A\left(\frac{\delta\rho}{\delta P}\right)\frac{dP}{dt} = dz \cdot A\left(\frac{1}{C^2}\right)\frac{dP}{dt} = \dot{m}_{IN} - \dot{m}_{OUT}$$

- Mass Equation / Elasticity (A is varying with pressure)

$$dz \cdot \frac{d(A\rho)}{dt} = dz \cdot \left(A\frac{d\rho}{dt} + \rho\frac{dA}{dt}\right) = dz \cdot \left(A\left(\frac{\delta\rho}{\delta P}\right) + \rho\left(\frac{\delta A}{\delta P}\right)\right)\frac{dP}{dt}$$

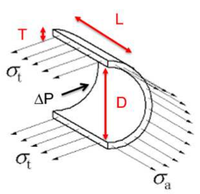
$$= dz \cdot A\left(\frac{1}{C'^2}\right)\frac{dP}{dt} = \dot{m}_{IN} - \dot{m}_{OUT}$$



- Divide the second equation by the first,…

$$\frac{\frac{1}{C'^2}}{\frac{1}{C^2}} = \frac{C^2}{C'^2} = \frac{\left(A\left(\frac{\delta\rho}{\delta P}\right)+\rho\left(\frac{\delta A}{\delta P}\right)\right)}{A\left(\frac{\delta\rho}{\delta P}\right)} = \left(1 + \frac{\delta A}{A}\frac{\rho}{\delta\rho}\right)$$

An Aside: Force Balance (Elastic Pipe)



$$\frac{C^2}{C'^2} = \left(1 + \frac{\delta A}{A}\frac{\rho}{\delta\rho}\right)$$

$$\delta P = \frac{2T}{D}\sigma_t = \frac{2T}{D}\left(\frac{E\delta D}{D}\right)$$

$$\frac{\rho}{\delta\rho} = \frac{K}{\delta P} = \frac{KD^2}{2TE\delta D}$$

$$\frac{\delta A}{A} = \frac{2D\delta D}{D^2} = \frac{2\delta D}{D}$$

$$\frac{C^2}{C'^2} = \left(1 + \frac{D}{T}\frac{K}{E}\right)$$

Barlow's Equation: $\delta PDL = 2TL\sigma_t$

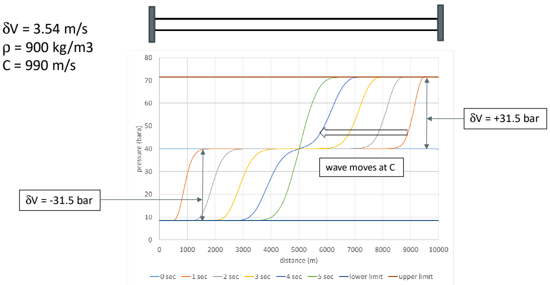
Bulk Modulus: $K = \rho C^2$

Pipe Elastic Modulus: E

Water Hammer Surge for Nearly-Frictionless Flow & Inelastic Pipe

δP = ρCδV = 31.5 bar (3.15·10⁶ Pa)

δV = 3.54 m/s
ρ = 900 kg/m3
C = 990 m/s



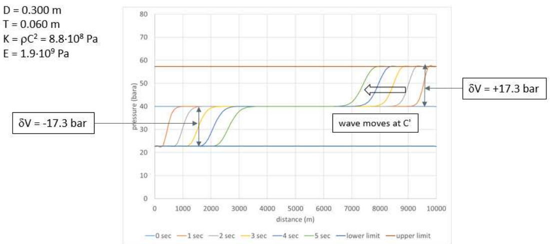
Water Hammer Surge for Nearly-Frictionless Flow & Elastic Pipe

δV = 3.54 m/s
ρ = 900 kg/m3
C = 990 m/s

$$\frac{C^2}{C'^2} = \left(1 + \frac{0.30\ \mathrm{m}}{0.06\ \mathrm{m}}\frac{8.8\cdot10^8\ \mathrm{Pa}}{1.9\cdot10^9\ \mathrm{Pa}}\right) = 3.32$$

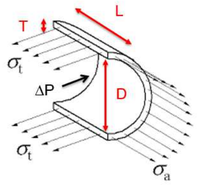
δP = ρC'δV = 17.3 bar (1.73·10⁶ Pa)

D = 0.300 m
T = 0.060 m
K = ρC² = 8.8·10⁸ Pa
E = 1.9·10⁹ Pa



Water Hammer Damage

An Aside: Why do sausages split parallel to their length?



$$\pi D T \sigma_a = \delta P\left(\frac{\pi D^2}{4}\right)$$

$$\sigma_t = \frac{\delta P D}{2T} \qquad \sigma_a = \frac{\delta P D}{4T} = \frac{\sigma_t}{2}$$

Fun fact: The sausage example is used by many German students as a mnemonic helping to remember which of the stresses is larger. As a result, the formulas are often called "Bockwurstformeln" (sausage formulas).

ConocoPhillips

Using the Mass Equation to Derive the Effect of Gas-Liquid Flow

$$dz \cdot A \frac{dH_L\rho_L}{dt} = dz \cdot A\left(H_L \frac{d\rho_L}{dt} + \rho_L \frac{dH_L}{dt}\right) = \dot{m}_{L,\,IN} - \dot{m}_{L,\,OUT}$$

$$dz\left(\left(\frac{H_G}{\rho_G}\right)\frac{d\rho_G}{dt} + \frac{dH_G}{dt}\right) = U_{SG,\,IN} - U_{SG,\,OUT} \qquad dz\left(\left(\frac{H_L}{\rho_L}\right)\frac{d\rho_L}{dt} + \frac{dH_L}{dt}\right) = U_{SL,\,IN} - U_{SL,\,OUT}$$

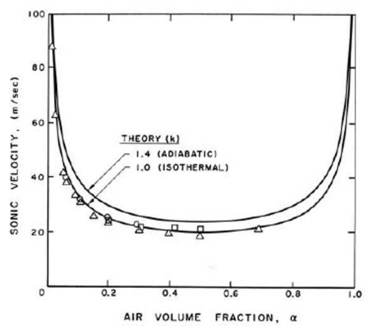
$$dz\left(\left(\frac{\delta\rho_G}{\delta P}\right)\left(\frac{H_G}{\rho_G}\right) + \left(\frac{\delta\rho_L}{\delta P}\right)\left(\frac{H_L}{\rho_L}\right)\right)\frac{dP}{dt} = U_{M,\,IN} - U_{M,\,OUT}$$

$$dz\left(\left(\frac{H_G}{\rho_G C_G^2}\right) + \left(\frac{H_L}{\rho_L C_L^2}\right)\right)\frac{dP}{dt} = U_{M,\,IN} - U_{M,\,OUT}$$

$$\frac{1}{\rho_M C_M^2} = \frac{H_G}{\rho_G C_G^2} + \frac{H_L}{\rho_L C_L^2}$$

ConocoPhillips

Experimental Data for Speed of Sound in Air-Water



- Bulk Modulus

  $$\frac{1}{K_M} = \frac{H_G}{K_G} + \frac{H_L}{K_L}$$

- Mixture Density

  $$\rho_M = \rho_G H_G + \rho_L H_L$$

- Mixture Speed of Sound

  $$C_M = \left(\frac{K_M}{\rho_M}\right)^{1/2}$$

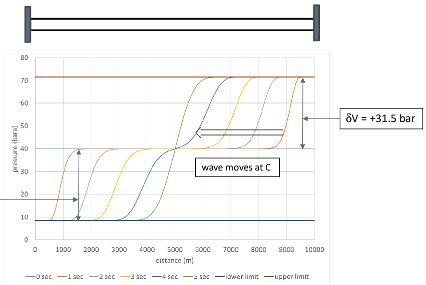
- Properties
  - C_{AIR} = 343 m/s
  - C_{WATER} = 1500 m/s
  - ρ_{AIR} = 1 kg/m^3
  - ρ_{WATER} = 1000 kg/m^3

ConocoPhillips

Water Hammer Surge for Nearly-Frictionless Flow & Inelastic Pipe

$\delta P = \rho C \delta V$ = 31.5 bar ($3.15 \cdot 10^6$ Pa)

δV = 3.54 m/s
ρ = 900 kg/m3
C = 990 m/s



δV = -31.5 bar

Water Hammer Surge for Nearly-Frictionless Two-Phase Flow

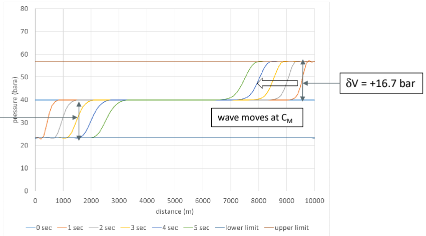
δV = 3.54 m/s

ρ_L = 900 kg/m3
C_L = 990 m/s
K_L = $8.82 \cdot 10^8$ Pa

ρ_G = 18 kg/m3
C_G = 440 m/s
K_G = $3.48 \cdot 10^6$ Pa

<u>1% gas</u>
ρ_M = 891 kg/m3
K_M = 2.51108 Pa
C_M = 530 m/s

δP (1% gas) = $\rho_M C_M \delta V$ = 16.7 bar ($1.67 \cdot 10^6$ Pa)



δV = -16.7 bar

Water Hammer Surge for Nearly-Frictionless Two-Phase Flow

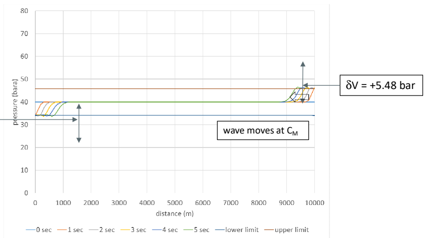
δV = 3.54 m/s

ρ_L = 900 kg/m3
C_L = 990 m/s
K_L = $8.82 \cdot 10^8$ Pa

ρ_G = 18 kg/m3
C_G = 440 m/s
K_G = $3.48 \cdot 10^6$ Pa

<u>10% gas</u>
ρ_M = 812 kg/m3
K_M = $2.51 \cdot 10^8$ Pa
C_M = 204 m/s

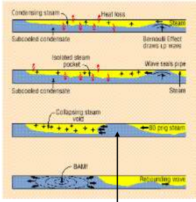
δP (10% gas) = $\rho_M C_M \delta V$ = 5.84 bar ($5.84 \cdot 10^5$ Pa)



δV = -5.84 bar

Condensation-Induced Water Hammer

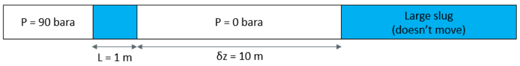
MEG Energy Incident, May 5, 2007
(Steam Line Rupture)



This slug is pushed by pressure difference, and can reach *very high speeds* (δV can become *very high*)

Condensation-Induced Water Hammer

Burst pressure = 150 bara



U_{GAS} = 478 m/s

$$\frac{d^2z}{dt^2}\rho AL = \delta PA$$

$$U_{CRASH} = \left(\frac{2\delta z\delta P}{\rho L}\right)^{1/2} = 505 \text{ m/s (!)}$$

L = 1 m
δz = 10 m
$\delta P = 90 \cdot 10^5$ Pa

C_{WATER} (90 bara) = 891 m/s
ρ_{WATER} (90 bara) = 705 kg/m3

$$\delta P = \frac{\rho C U_{CRASH}}{2} = 1590 \text{ bar!}$$

Conclusions

- Water Hammer
  - Due to system transients brought about by pump or valve operations
  - Also by collapse of vapor pockets (condensation-induced water hammer)
  - Accurate prediction of fluid speed of sound is critical to correct prediction of water hammer
  - In the event of high rates (high pressure gradients) initial surge pressure can be exceeded
- Pencil and Paper calculations can give you
  - Joukowsky limit for surge pressure
  - Accommodation of elastic hose effects
  - Accommodation of gas entrainment
  - Estimates of condensation-induced water hammer
- In many instances, transient simulations can be supplemented and even replaced by these simpler methods
  - Methods can also give quick check of transient results

Acknowledgements / Thank You / Questions

The author wishes to acknowledge ConocoPhillips for permission to publish this presentation.

Abstract

- When a fluid in motion is suddenly stopped, a pressure surge wave is generated which propagates back through the fluid. This effect is commonly referred to as 'water hammer'.
- This presentation gives an overview of water hammer in Upstream Production. The Joukowsky Equation for pressure surge is derived analytically from first principles for inelastic pipe, and the impact of slow closure and frictional effects is considered. The Joukowsky expression is then modified to account for pipe elasticity, again derived from first principles. The Joukowsky Equation is modified still further to account for the presence of gas. Finally, an analytic estimate of condensation-induced water hammer – the most severe form of water hammer - is given.
- The main point of the presentation is that a great deal of analysis of water hammer can be done using simple pencil-and-paper methods.