Suppress Your Surges: Surge Suppression Fundamentals

April 13, 2017
'How Bad Can Waterhammer Really Be?'
Workshop Agenda

- What is waterhammer?
- Causes of waterhammer
- Instantaneous surge pressures
- Surges caused by cavitation
- Surge suppression
- Code compliance
- Reducing velocities with larger diameter pipes
- Valve closures
- Multiple valves in Parallel
- Surge Suppression Equipment
  - Gas Accumulators, Surge Tanks, Relief Valves, Vacuum Breaker Valves
- Q&A
What is Waterhammer?

- Waterhammer – transient phenomenon occurring in liquid pipe systems when an event causes steady-state departure
- Waterhammer is the process the piping system experiences as it adjusts to the new conditions
- Waterhammer can be caused by many events including
  - Valve closure or opening (in full or in part)
  - Pump speed change
  - Relief valves & check valves opening/closing
  - Control valves responding to system transients
  - Tank pressurization
  - Periodic pressure or flow conditions
- AFT Impulse models waterhammer due to mechanical transients
Types of Waterhammer

- Waterhammer can be caused by different physical mechanisms
  - There is no universal terminology for these mechanisms so the terminology here is for discussion purposes

1. “Thermodynamic” waterhammer
   - Liquid acceleration caused by local phase change

2. “Slug” waterhammer
   - Liquid flows into an evacuated pipe system or when there are distinct liquid slugs and gas pockets
   - When liquid contacts equipment or direction changes (elbows) pressure spikes can occur

3. “Mechanical” waterhammer
   - Caused by equipment or component operational changes
     - Pump trips, valves closed, etc.
   - This is the type of waterhammer that Impulse can model
Instantaneous Waterhammer

- The magnitude of a waterhammer transient is dependent on the wavespeed of the liquid.
- The wavespeed ($a$) is dependent on the:
  - liquid acoustic velocity
  - liquid density & liquid modulus of elasticity
  - pipe modulus of elasticity ($E$), wall thickness ($t$), and material Poisson Ratio ($\mu$)
  - pipe restraints
**Instantaneous Waterhammer**

- It can be shown that the theoretical maximum pressure surge is given by the instantaneous waterhammer equation

\[ \Delta P = -\rho a \Delta V \]

- Joukowsky Equation
- Example: Density is 62 lbm/ft\(^3\), Wavespeed is 2500 feet per second, Initial Velocity is 10 feet per second, Static Pressure is 50 psia.

\[
P_{\text{max}} = 62 \frac{\text{lbm}}{\text{ft}^3} \times 2500 \frac{\text{ft}}{\text{s}} \times 10 \frac{\text{ft}}{\text{s}} \times \frac{1 \text{ft}^2}{144 \text{ in}^2} \times \frac{1 \text{lbf} - \text{s}^2}{32.2 \text{ lbm - ft}} + 50 \text{ psia}
\]

\[
P_{\text{max}} = 334 + 50
\]

\[
P_{\text{max}} = 384 \text{ psia}
\]
Instantaneous Waterhammer

- AFT Impulse assumes constant properties during the simulation
  - Density
  - Wavespeed for each pipe

- As seen in the Joukowsky equation, a system’s pressure response during fluid transients is directly proportional to the change in velocity
Cavitation’s Role in Surge Analysis

- If the pressure of the fluid is less than the vapor pressure, a vapor cavity forms
  - This is sometimes referred to as liquid column separation

- When the local pressure increases above the vapor pressure, the vapor cavity will begin to shrink
  - When the cavity completely collapses, a large pressure impulse is caused

- Large amounts of cavitation can be extremely problematic for actual system operation
  - Cavitation should be avoided
Two Methods for Handling Cavitation
DVCM & DGCM

- **Discrete Vapor Cavity Model**
  - Has been available in AFT Impulse since 1996
  - Works well for short lived, minor, and localized cavitation
  - Has the potential to return chaotic/non-real results when cavitation becomes excessive

- **Discrete Gas Cavity Model**
  - Has been available in AFT Impulse since 2013
  - Has the potential to return more stable results than DVCM, especially in 2\textsuperscript{nd}, 3\textsuperscript{rd}, etc. pressure spikes.
  - If cavitation becomes excessive, model has harder time converging than DVCM
  - When cavitation is present, this method has the potential to significantly increase the transient solver run time
Limitations of Cavitation Methods

- Both DGCM and DVCM are mathematical methods designed to model cavitation under a specific set of assumptions
  - Localized
  - Discrete
  - Subtle
    - Usually 10%-15% of pipe section volume
- AFT Impulse cavitation models are great for identifying cavitation impact and location, within assumptions
- As cavitation volumes become excessive, the validity of results can become uncertain
  - Large vapor cavities would behave with slug flow or two-phase flow conditions
Comparing DVCM & DGCM – Exit Valve Pressure Profile

![Graph showing comparison between Published Data, Impulse DVCM, and Impulse DGCM with HGL (meters) on the y-axis and Time (seconds) on the x-axis.]

- Published Data
- Impulse DVCM
- Impulse DGCM
Waterhammer Videos - Cavitation

- Instructor – show video files
  - waterhammer iihr.wmv (1:04)
    - Video of rapid, manual valve closure and column separation in a clear line
    - online version - http://www.iahrmedialibrary.net/db/i1/waterhammer.htm
  - GEFA Water Hammer GB.wmv
    - High speed movie of a cavitating valve
    - online version - http://www.youtube.com/watch?v=X9UbzcanuDk
  - check valve.wmv (0:44)
    - Video of check valve
    - online version – unavailable
Waterhammer Videos – Cavitation (2)

- Instructor – show video files
  - Waterhammer 2-0ms.wmv (0:58)
    - Video of column separation in a clear line
    - online version - http://www.youtube.com/watch?v=bmcOpuzemRU
  - How a Bladder Surge Tank can alleviate column separation1.wmv (1:38)
    - Pump trip and column separation
    - online version - http://www.youtube.com/watch?v=E6NIA4LxPPw
Surge Suppression

- Surge pressures that are excessively high can burst pipes and damage equipment.
- Surge pressures that reduce the local pressure can result in:
  - Crushed pipes
    - Due to atmospheric pressure exceeding the internal liquid pressure
  - Cavitation and liquid column separation
    - Can then cause large pressure spikes when the cavity collapses
  - Sub-atmospheric pressures that are unacceptable for drinking water pipelines
- Surge pressures can create imbalanced forces that move pipes, dislodge insulation and ultimately break supports.
Surge Suppression (2)

- Options for surge reduction include:
  - Reducing steady-state operating velocity (since surge is directly related to velocity changes)
  - Slowing the change in system operating conditions
  - Changing the profile of how equipment operates in transient mode
  - Installing surge suppression equipment
Code Compliance

- Codes such as ASME B31.3 and ASME B31.4 are in place to make sure that systems operate safely and are able to handle surge pressures.
- AFT Impulse will characterize and quantify maximum surge pressures.
  - Users can determine if system is code compliant.
  - Model possible surge suppression strategies.
ASME B31.3

ASME Code for pressure piping B31.3. Process Piping

- Surge pressure is included in the group of loads called occasional
- The piping design pressure shall take into account the maximum pressure that may occur in the system including surge pressure due to a transient event
- The maximum surge pressure shall not exceed the test pressure calculated for the pipe in any case
- The maximum stress produced by the loads created by the surge pressure shall not exceed: \( 1.33 \times S_h \) \( (S_h = \text{allowable stress for the operating temperature}) \).
- In order to meet the last requirement the AFT Impulse users shall calculate the forces originated on the bends of the system and feed this data to a pipe stress program (see Evaluating Dynamic Loads: [http://www.aft.com/technical-papers-alias/262-evaluating-dynamic-loads-in-piping-systems-caused-by-waterhammer](http://www.aft.com/technical-papers-alias/262-evaluating-dynamic-loads-in-piping-systems-caused-by-waterhammer))
Velocity Reduction

- Surge pressures can be reduced by using larger diameter pipes which thereby reduces velocity
  - Lower velocities lead to smaller changes in momentum
  - This is feasible when systems are in the design phase or when existing pipes are easily retro-fitted

![Diagram showing pressure changes at different locations](image)
Slowing System Operation Changes

- Slowing system operation changes usually means slowing the rate of valve position changes
  - Other operational changes are also valid
    - Pump trips
    - Pump start-ups
    - Flow changes
    - Etc.

- Ways to slow the rate of valve position changes
  - Increase closure time of valves
  - Single valve with dual closure rate actuator
  - Parallel valves with staggered closure times
    - Effective dual rate closure
Pressure Drop Across Valves

- Flow-coefficients have an inverse one-half order relationship to pressure drop

\[ C_v = \frac{Q \cdot SG}{\sqrt{\Delta P}} \]
Valve Closure Time Increase

- For linear closures, sometimes increasing the time needed for the valve to close can lower surge pressures
  - Surge pressures may still be too high to be code compliant
- Operating procedures may prevent increasing time needed to close valve
80-20 Rule

- Swaffield* discusses how closing valves more quickly at first and then more slowly at the end can result in significant surge reduction
  - Examples are given where the first 80% of closure occurs over the first 20% of closure time, with the final 20% closure occurring over the remaining 80% of the time
  - Known in other applications as Pareto’s Principle (“80-20 rule”)
- It should be noted that obtaining accurate transient valve data can be difficult

* Swaffield and Boldy, "Pressure Surges in Pipe and Duct Systems"
Multiple Rate Closure Profiles for Single Valves

- Swaffield’s suggestion can be applied to single valve junctions
  - AFT Impulse transient profiles will linearly interpolate between data points
  - Valves are not limited to only dual closure rates
  - As many as able to fit into the transient profile tables

- Dual closure rate valve equipment is available on the market

- Large savings are possible
  - Can eliminate the need for additional surge suppression equipment
  - The cost of a new motor actuator is inexpensive compared to equipment like surge tanks
Dual Rate Single Valve

- Reduce 80% of the full open Cv over 20% of the full closure time
- Close the remaining 20% of the full open Cv over the rest of the time
Parallel Valves with Staggered Closures Profiles

- Staggering valve closures of parallel valves can lower surge pressures by replicating dual rate closures
  - One valve has a larger Cv profile and closes rapidly
  - The other valve has a smaller Cv profile and closes more slowly
  - System follows an effective Cv that is a composite of both Cv profiles
    - Includes additional piping losses in the new effective Cv
Effective Flow Coefficient

- The resistance characteristics of the parallel lines form an overall effective \( Cv \) for this section of the system
  - Acts like a single dual rate closure valve
Parallel Valve Surge Reduction

- The system, as a whole, experiences lower surge pressures compared to a single valve closing over 100 seconds with a $C_v = 25,000$

**Linear Closure**

**Dual-Rate Closure**
Notes on Parallel Valve Closures

- Economic calculations should be performed regarding the additional piping, valve equipment, and installation expenses
  - Typically still more cost effective than adding large surge equipment
- Experience shows that material costs can be lowered with existing equipment if present
- Solution may not be suitable for existing systems
  - Difficulty of system expansion
Surge Suppression Equipment

- Surge suppression equipment is equipment designed specifically for reducing surge pressures.
- Options for surge suppression equipment depend on steady-state pressure levels and whether one is protecting for high pressure or low.
- Common choices include:
  - Gas Accumulators
  - Surge Tanks
  - Relief Valves
  - Vacuum Breaker Valves
Instructor – show video files

- How a Bladder Surge Tank can alleviate column separation2.wmv (1:16)
  - Gas bladder accumulator upstream of valve which closes
  - online version - http://www.youtube.com/watch?v=E6NIA4LxPPw

- accumulator after pump trip.wmv (1:23)
  - Gas bladder accumulator close to pump - after pump trip
  - online version - http://www.youtube.com/watch?v=kiTzez0x6aQ
Gas Accumulators

- Enclosed vessels pre-charged with gas such as air or nitrogen
- Gas compresses or expands to allow liquid in or out of vessel
  - Can reduce surge pressure
  - Changes the frequency response of the pipe system
- Important parameters: Polytropic constant & initial gas volume
- Can also model flow restrictor (such as an orifice) or short connecting pipe
  - These change how the accumulator interacts with the system
- Max & Min Volumes prevent volumes from exceeding certain sizes
Add Accumulator to Pump Model

- **Size and locate an accumulator to prevent sub-atmospheric pressure**
- The accumulator will be connected to the system through an integral short connector pipe with data as shown below
  - Assume a polytropic coefficient of 1.2
Surge Tanks

- Surge tanks are similar to gas accumulators, but are open to the atmosphere.
- When a surge pressure reaches the surge tank, the liquid in the tank rises or falls:
  - This has the tendency to reduce the surge pressure.
  - It also changes the frequency response of the pipe system.
Surge Tanks (2)

- Surge tanks are more commonly used for low pressure water systems
  - If the steady-state pressure is high, the surge tank will need to be very tall
  - Surge Tanks are more commonly used in civil engineering systems such as hydroelectric facilities

- Surge Tanks are similar to Reservoirs in Impulse
  - Reservoirs do not change liquid level automatically, and are thus more massive liquid sources
Modeling Surge Tanks

- Surge Tanks can drain in reality, but Impulse does not model this
  - This allows air into adjacent pipes
- Surge Tanks can spill over the top when the Tank Height is entered
- Geometries other than pure cylinders can be modeled by entering the tank accumulated volume as a function of height
- Short connector pipes and orifices can be modeled
- Surface pressure transients can be modeled to represent known pressures in an enclosed tank
  - These can be time or event based
Modeling Surge Tanks (2)

- A hybrid accumulator/surge tank can be modeled called a "Dipping Tube Vessel" using features on the Tank Model tab.
- During steady-state conditions, surge tanks behave like branch junctions:
  - Impulse solves for the liquid height.
Modeling Surge Tanks (3)

- The surge tank can be used as a reference pressure during steady-state
  - It then acts just like a reservoir junction
  - The liquid height is input by the user (in the Initial Liquid Height field)
  - The surge tank no longer represents a point of mass balance
Surge Tank Mitigation

- A valve closes while a pump continues to run. The surge caused by the closure is determined to be problematic for the system and needs to be addressed. There is an existing tank at the facility not in use. Economic concerns restrict purchasing any new equipment.

- The tank is 15 feet in diameter and 10 feet tall and can be easily fitted to the system 600 feet upstream from the valve.

- Surge Pressure may NOT exceed 50 psia.

- What is the maximum pressure with the tank in place? How does this compare to not using the tank?

- Is the tank large enough to prevent overflowing after 20 seconds, long enough for the pump to begin to shutdown?
Surge Tank Mitigation (2)

- The system is pumping water along a pipeline to a user delivery point.
- The tank is to be installed 600 feet upstream of the valve if effective.
Relief Valves

- Relief valves are a common equipment type used to mitigate surge pressures.
- Surge pressures are reduced by allowing flow to other parts of system:
  - Relief lines
  - Recirc. Lines
  - Atmosphere
  - Etc.
Pump Trip Accident

- It is recently discovered that during a pump trip, an isolation valve can fail and close faster than expected. A proposed relief valve needs to be validated to ensure the system will still shutdown safely.
- **Determine the maximum surge pressure in the discharge header using the proposed relief valve installed.**
- **Compare this to the maximum surge pressures without the relief valve.**
Pump Trip Accident (2)

- The proposed relief line for this oil transfer line is as shown below.
- Note, J105 is the valve assumed to fail.
Vacuum Breaker Valves

- Vacuum breaker valves (also known as air valves) are primarily used to protect against low pressure conditions.
- When the liquid pressure drops below some set pressure (usually atmospheric), air (or any gas you choose) is allowed in to maintain near atmospheric pressure at that location.
- Vacuum breakers are typically located at high points in the system which are most vulnerable to low pressure transients.
Vacuum Breaker Valves (2)

- Typical designs allow air to flow in and out
- Five conditions can exist:
  - Valve closed
    - Behaves like a branch junction
  - Valve open with subsonic flow in
  - Valve open with sonic flow in
  - Valve open with subsonic flow out
  - Valve open with sonic flow out
Modeling Vacuum Breaker Valves

- Important input are the inflow and outflow CdA values
  - These are the air flow areas
- The inflow CdA is usually as large as possible to allow rapid air flow in
- The outflow CdA is usually much smaller than the inflow to let the air out slowly and prevent rapid collapse of the liquid columns which can cause pressure surge
- Transients can start with air already in the system
  - These valves can be modeled as "air eliminators"
- Air flow is assumed to be adiabatic
Three Stage Air Release Valves

- AFT Impulse allows users to model three stage “Anti-shock” air release and vacuum break valves
  - This is a particular type of air release valve sold by Vent-O-Mat valves
- Three stage valves work the same as regular valves when gas is flowing in, but they have two orifice sizes when gas flows out
- Pressure difference or volumetric flowrate criteria specify which orifice to use
  - When the actual value is less than the specified value, the normal Outflow CdA is used
  - When the actual value is greater than the specified value, the intermediate orifice CdA is used
Three Stage Air Release Valves (2)

- Intermediate orifice CdA values are typically much smaller than the normal outflow CdA
  - This slows the rate of release of the last amounts of gas in the system, and results in slower fluid velocities as the valve closes
  - This translates into greatly reduced surge pressures than those caused by rapidly closing air release valves
Three Stage Air Release Valves (3)

- Important input are the inflow, outflow, and intermediate CdA values
  - These are the air flow areas
- The intermediate outflow CdA is typically very small in relation to the outflow CdA
  - This slows the rate of discharge as the last of the air is expelled
Low Pressure Protection

- The system shown below simulates a pump trip with a concurrent pump start up. During this transient the pressure at the high point in the system falls below atmospheric pressure.
- Using a vacuum breaker valve, prevent the pressure in the main header from falling below -1 psig.

![Diagram of Low Pressure Protection System]
Low Pressure Protection (2)

- As mentioned previously, large outflow CdA's for vacuum breaker valves can have adverse affects on piping networks.
- Increase the vacuum breaker valve outflow CdA from 0.6 to 6 and compare the pressure response to the original CdA.
- What are the maximum and minimum pressures the system will experience in each configuration?
Questions?