Globa Environmental Operations, Inc

Compression Waves (Water Hammer) Pipeline Failures and Pumping Stations

By David L. Russell, PE

On March 11, 2014, in the Linked In blog "American Water Works Association" there was a curious question posted by Riley Vittitoe, "When do most water main breaks occur?" One of the most interesting comments posted on the blog was that one respondent noticed that water main breaks in his system disappeared after he installed variable frequency drives on his system pumps.[i] While this answer was one item of many mentioned, it was interesting. Other causes listed in the blog indicated that improper bedding conditions, swelling or shrinking of the soils, and seasonal factors contributed to the frequency of breaks. Other commenters suggested that large changes in demand also contributed to the frequency of breaks.

Changes in demand, and the starting and stopping of system pumps can create pressure waves in all types of pipes. This article will look at some of the effects of pressure waves and how they can damage a piping system.

First, when we change the flow in a pipe, it creates a pressure wave in that pipe. Depending upon the diameter of the pipe, and the length of the pipeline, the pressure wave can, by itself, cause pipe ruptures, and can generate very large forces.

The basic equation of motion is from Newton's First Law: Force = mass * acceleration. Acceleration is the change in velocity, and the mass is the amount of liquid in the pipe. For long pipes, this can be a very great force because of the length of the pipe. A quick example follows:

Given a cast iron transmission main 12000' (3650 M) long 16"nominal Schedule 150 pipe[ii] (Actual Diameter is 16.32" and wall thickness is 0.54") (0.414528 M) diameter pipeline full of water, carrying 6500 gallons per minute (24 M^3/m) moving at 10.4 feet per second (3.171 M/s). Compute the pressure rise from valve closure or pump failure.

The force exerted is the sum of the density times the quantity times the change in velocity.

Note that this is simply the weight of the liquid in the section divided by the force of gravity. Written as an equation:

$$\Sigma F = \rho Q(\Delta V)$$

Where F is the force, and ρ is the density of the liquid, Q is the quantity, and ΔV is the change in velocity.

Looking at some terms are re-arranging and making some substitutions, we get:

$$-p'A = w * \frac{A * c}{g} * (0 - V)$$

Where –p' is the pressure force, w is the weight of the fluid, A is the area of the pipe and c is the velocity (celerity) of the pressure wave. The pressure wave reduces the velocity in the pipe to zero as it passes each section. This is

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much in the same way as a freight train slows down: The engine leads, and as it slows the resistance force is transmitted through each coupling until the entire train is slowed.

If the pipe is rigid, the velocity or celerity of the pressure wave can be calculated by some additional manipulation (not shown) to be $c = \sqrt{\frac{Ef}{\rho}}$

Where *Ef* is the bulk modulus of Elasticity of the Liquid (compressibility of the liquid), and *ρ* is the density. For Water, the bulk modulus of Elasticity is approximately 313000 psf, and the calculation, which assumes a totally rigid pipe wall is:

$c = \sqrt{(313000 * 144/1.94)}$ = 4820 Feet per second at 60°F or 1,469.5 M/s

But if the pipe is non-rigid, cast iron, steel or plastic, some of the energy is dissipated by pushing on the walls of the pipe and stretching it a bit. In steel and cast iron materials, this is small to negligible, but in PVC it can be significant. This stretching action also slows down the pressure wave.

The accurate formula for the velocity of a pressure wave in a non-rigid pipe including steel, cast iron, and plastic is shown below.

$$c = \sqrt{}(Ef/(\rho * \left[1 + Ef * \frac{d}{Ep * t}\right])$$

Where Ef is the bulk modulus of the liquid, Ep is the bulk modulus of the pipe, d is the diameter and t is the thickness. The density of the fluid is ρ. If we apply the actual values to our example above, the speed of the pressure wave becomes: 3,342 Ft/s or 1,019 M/s. The pressure wave will travel the length of our 12,000 ft pipe in 3.59 seconds. Any valve closure or pump failure which has a time less than 3.59 seconds will generate a pressure wave or water hammer in the pipe.

If a pipe has a length of L , the water hammer will reflect off of a reservoir or another closed valve, and the travel time for the return wave will be twice the length of the pipeline divided by the speed of the wave, or in this case 6.34 seconds. It is important to note that the return wave will be negative, and it will be reflected from the closed valve as a positive wave of slightly lesser magnitude, and travel back and forth as a positive and negative waveform until it finally dissipates.

For our pipeline example from above the increase in pressure will be given by

$$h = cV/g$$

and the resulting numbers are h= 3342 * 10.4/32.18 = 1080 feet of head or (449.6 PSI or 3100 kpa).

If we calculate the stress on the piping using the accepted hoop stress formula, the 469 psi increase will generate a stress (over and above the stress due to the existing pressure) in the pipe wall, of

Stress = pressure * radius/thickness

The additional stress is =469.6*8.18/0.54 = 9655 psi increase in tension on the pipe wall. The yield strength of cast iron, depending upon the type is between 25,000 psi and 50,000 psi. If the wall has been corroded and is thinner, the pressure at that point could exceed the tensile strength of the cast iron, resulting in a dramatic release.

Below are some values for the bulk modulus of liquids and solids used in piping systems.

Bulk Modulus - *E*	Imperial Units - BG (10^5 psi, lb_f/in^2)	SI Units (10^9 Pa, N/m^2)
Acetone	1.34	0.92
Benzene	1.5	1.05
Carbon Tetrachloride	1.91	1.32
Ethyl Alcohol	1.54	1.06
Gasoline	1.9	1.3
Glycerin	6.31	4.35
ISO 32 mineral oil	2.6	1.8
Kerosene	1.9	1.3
Mercury	41.4	28.5
Paraffin Oil	2.41	1.66
Petrol	1.55 - 2.16	1.07 - 1.49
Phosphate ester	4.4	3
SAE 30 Oil	2.2	1.5
Seawater	3.39	2.34
Sulfuric Acid	4.3	3.0
Water	3.12	2.15
Water - glycol	5	3.4
Water in oil emulsion	3.3	2.3

Material	Bulk Modulus	
	(10^6 psi)	*(GPa)*
Aluminum, various alloys	9.9 - 10.2	68 – 70
Brass, 70-30	15.7	108
Brass, cast	16.8	116
Copper	17.9	123
Iron, cast	8.4 - 15.5	58 – 107
Iron, malleable	17.2	119
Magnesium alloy	4.8	33.1
Monel metal	22.5	155
Phosphor bronze	16.3	112
Stainless Steels 18-8	23.6	163
Steel, cast	20.2	139
Steel, cold rolled	23.1	159
Steel, various	22.6 - 24.0	156 – 165

The above tables were reproduced from http://www.engineeringtoolbox.com/bulk-modulus-elasticity-d_585.htm and http://www.engineeringtoolbox.com/bulk-modulus-metals-d_1351.html

A question and some answers:

The sudden stopping of a fluid in a pipeline can cause high pressure waves. OK, so how do we prevent water hammer?

Increase the valve closing times will help. An initial calculation suggested above where the valve closing time is greater than twice the length of the pipe divided by the celerity of the wave will greatly reduce the incidence of water hammer. Similarly, providing pumping stations with variable speed drives and standby generators to reduce sudden starts and stops of the fluid will also help prevent water hammer.

For long pipelines, a surge tank is recommended to help reduce water hammer. Even in some houses, this can be as simple as a tee and a pipe stub filled with air near the faucet or valve subject to sudden closure. The stub should be vertical, and may or may not contain an air valve to allow it to be filled with air from an external pressure tank. Similarly, a pressure tank which is filled with air in small water systems located immediately following a pump can easily reduce water hammer from the starting and stopping of the pump while it maintains overall system pressure. But it won’t reduce water hammer occurring on the system pipes leading from the tank to distribution points.

Analytical Solutions Abound

There are a number of computer programs which model piping systems and can model water hammer and help one to figure out how to reduce it. Some of these programs will work together, others are commercially available, and some are freeware.

Freeware:

EPANET from the USEPA. http://www.epa.gov/nrmrl/wswrd/dw/epanet.html

The program will handle a wide variety of conditions in water systems, and an unlimited number of pipes, reservoirs and pumps. The program is flexible, but it is difficult to use. It comes with a complete manual, and a reasonably good demo for learning it's use. Data input into the system is often difficult, but once input, the program is quite powerful and can track contaminants and age of water as well as chemical contamination. The program will not compute water hammer.

SWMM from the USEPA. http://www.epa.gov/athens/wwqtsc/html/swmm.html It is a stormwater management model. The program has been around in various generations since 1971, and contains a number of models and routines which allow GIS Data, water quality data, and even one dimensional river modeling. It is a complete package, and allows good graphical outputs with postprocessing of the data. The latest version was developed by CDM, Inc., and the system runs under Windows.

ITM (Illinois Transient Model) from http://web.engr.oregonstate.edu/~leon/ITM.htm . The program is a finite volume model which is designed to analyze transient flows in closed conduit systems over a wide range of conditions, including flows with free surfaces as well as flows under pressure. The ITM model uses the SWMM? EPANET interface, so it is not the easiest to use, and for a condition such as that mentioned above, for a single pipe, hand calculations are faster.

Not Freeware

KYPipe from http://www.KYPipe.com is an advanced variant of the SWMM model. The program was developed by Drs. Don J. Wood, and Sria Lingireddy. The description indicates that it can handle stedy state, surges, gas, steam and it will work with SWMM as well. The systems do perform water hammer and transient and surge analyses, and will perform steam and gas distribution and collection system analyses, and can be used to help design sprinkler systems as well. The program is commercially available.

MikeUrban by DHI from http://mikebydhi.com is a software suite which includes water distribution systems, water collection (sewer) systems, and wastewater treatment modeling systems. The software will perform transient and water hammer analyses. The software is commercially available and is widely used outside the US. It is an integrated suite where water supply, sewer collection, stormwater, and wastewater treatment systems all work together on a single platform.

Water CAD and HAMMER by Bentley systems. http://www.bentley.com/en-US/Products/Water+and+Wastewater+Network+Analysis+and+Design/ is a series of programs which were formerly marketed under the name Haestad, and the Water Cad program is significantly easier to use than EPANET, but provides much of the same information. The Hammer program has been successfully used by a number of municipal systems to analyze water hammer in pipelines.

[i] http://www.linkedin.com/groupItem?view=&srchtype=discussedNews&gid=733277&item=5848387471896752130&type=member&trk=eml-anet_dig-b_mc-ttl-cn&fromEmail=&ut=1jc542X9NHIS81

[ii] Actual dimensions from the Mueller catalog are: ID: 16.32”, wall thickness 0.54”, (metric diameter 0.414528 M, thickness is 1.3716 cm)