Water Hammer and Surge Tanks

Cive 401

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Water Hammer

Water Hammer is a pressure surge or wave that occurs when there is a sudden momentum change of a fluid (the motion of a fluid is abruptly forced to stop or change direction) within an enclosed space (*Water Hammer*). This commonly occurs in pipelines when a valve is closed suddenly at the end of a pipeline where the velocity of the fluid is high. The pressure wave created will propagate within the pipeline.

Cause and Effect

Water hammer is caused by a change in fluid momentum. The most common cause of this change in momentum is sudden closure of a valve on a pipeline. When this occurs, a loud hammer noise can be produced and vibrations can be sent through the pipe (*Water Hammer*). The pressure wave produced from this event can cause significant damage to pipe systems. The large increase in pressure can cause pipes to crack and in some cases burst. It also causes cavitation within pipe lines and if is severe enough can cause the pipe line to implode (*Water Hammer*). Figure 1and Figure 2 show a damage caused by water hammer.

Figure 1
http://www.cyclestopvalves.com/csvtechinfo_10.html

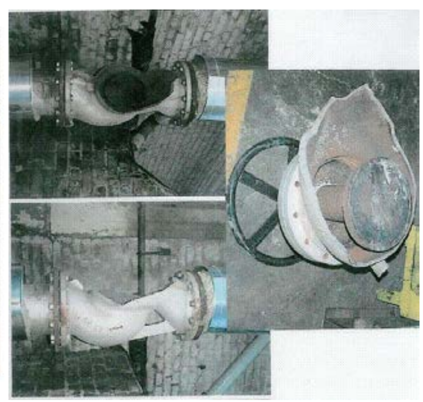

Figure 2
http://traction.armintl.com/db/attachments/docs/403/1/water%20hammer%20valve_2.jpg

Another instance that produces a water hammer effect is pump and turbine failure. When a pump fails, the sudden halt in flow will produce the momentum change causing the water hammer effect. This can also be seen in home plumbing systems when faucets are turned on and off suddenly. A loud hammer noise will be produced, and the plumbing will vibrate in most cases.

Water hammer can be induced intentionally for various applications. A hydraulic ram can be created using a water hammer, and is commonly used in mining practices to break through rock. In addition, the water hammer effect creates an increase in pressure within a pipe line and is then used to detected leaks within the pipe line. The increased pressure causes water to shoot out of the pipe at a leak site, which is then easily spotted.   Despite water hammer being useful at time, it is generally an undesired phenomenon that must be considered when designing pipe lines (*Water Hammer*).

Theory and Calculations

Through the application of the momentum equation (Equation 1),

$$\sum F = \rho Q(V_2 - V_1) \quad (1)$$

Where:

F = force, ρ = fluid density, V_1 = initial fluid velocity, V_2 = final fluid velocity

it can be seen that when V_2 falls below V_1, a negative force is created. This negative force forms a wave of increased pressure within a pipeline that propagates back toward the source of the flow and moves back and forth, to and from the source.

The wave speed, also known as celerity, is a function of the theoretical wave celerity, which is given by Equation 2 (Cruise).

$$c' = \sqrt{(\frac{E_v}{\rho})} \quad (2)$$

Where:

c' = theoretical wave celerity, E_v = bulk modulus of elasticity of fluid, ρ = fluid density

The wave speed is also a function of the composite modulus of elasticity of the pipe fluid pipe system, the pipe diameter, pipe wall thickness, and modulus of elasticity of the pipe. Equation 3 solves for the speed of the pressure wave within a pipe (Cruise).

$$c = \sqrt{\frac{c'^2}{1+(\frac{E_v d}{\varepsilon E_p})}} \quad (3)$$

Where:

c = celerity of pressure wave, E_v = bulk modulus of elasticity of fluid, d = pipe Diameter, ε = thickness of pipe walls, E_p = modulus of elasticity of pipe, c' = theoretical wave celerity

The maximum change in pressure created from water hammer in a pipeline is derived from the momentum equation and results in Equation 4. Equation 6 is for rapid valve closure, which occurs when the time of closure it less than the pipe length divided by the wave celerity $t < \frac{L}{c}$.

$$\Delta p = \rho c V_0 \quad (4)$$

Where:

Δp = change in pressure, c = wave celerity, V_0 = initial velocity

The maximum pressure that will occur in the pipe is the original pressure within the pipe plus the change in pressure, as shown in Equation 5 (Cruise).

$$p_{max} = p_0 + \Delta p \quad (5)$$

Where:

p_{max} = max pressure, p_0= initial pressure, Δp = change in pressure

This pressure variation will change in cycles at times equal to $t = (\frac{2L}{c})$ for a rapid interruption of the flow. Over time, the pressure wave will decrease due to friction losses. Figure below demonstrates the pressure wave cycles within a pipe.

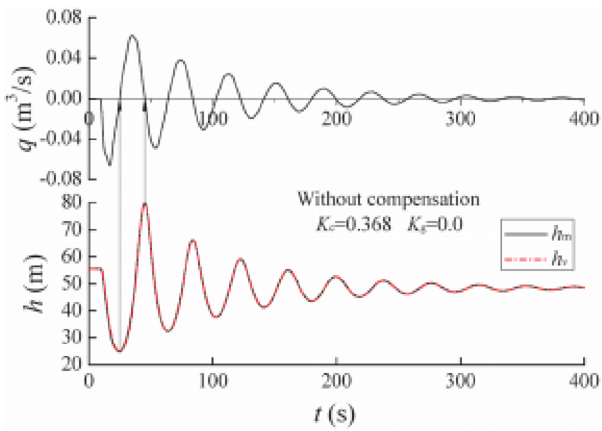

Figure 3

As shown in Figure 3, the pressure and velocity of the water at a given point within a pipe oscillate, while overall steadily decreasing as time passes.

For slow closure within a pipe $t > \frac{L}{c}$, the change in pressure can be found using Equation 6 (Cruise).

$$\Delta p = p_0\left(\frac{N}{2} + \sqrt{\frac{N^2}{4} + N}\right) \quad (6)$$

Where:

p_0 = initial pressure, $N = \frac{\rho L V_0}{p_0 T_v}$ (L= length of pipe, T_v = time to close), Δp = change pressure

Similar to when pipe flow is interrupted abruptly, the maximum pressure change is equal to the initial pressure, plus the change in pressure. The pressure wave caused by the slow closure of a valve also propagates throughout the pipe, decreasing in magnitude over time due to friction.

Surge Tanks

A surge tank, in its simplest design, is a supplementary reservoir within a pipe system subject to variable flow rates. Surge tanks are used to protect piping and turbines from pressure waves that occur when the flow rate quickly decreases. Most commonly surge tanks are used within hydroelectric power plants where large size piping is used at relatively high flow rates, however they can be applied to many other piping systems such as waste water management, water supplied for manufacturing, and even the automotive industry. Surge tanks for handling water flow come in a variety of styles ranging from 40 gallon pressurized units to thousands of gallon reservoirs open to the atmosphere. Surge tanks have been used for many years however it is still a topic that sees active research and improvements are frequently proposed. Figure 3 below shows The Elwha dam which was once located on the Elwha river in Olympic National Park. In the center of the picture a surge tank can be seen rising to the height of the dam before it.

Figure 3
(Elwha Dam)
http://www.nps.gov/olym/naturescience

Surge Tank Applications

Hydroelectric power plants are the most frequent benefiter of surge tanks, particularly those with long penstocks. Surge tanks can have a double benefit in this case, both by absorbing pressure waves as the system shuts down but also by providing extra water when the system starts up. There are a number of designs types that can be found to meet the particular needs of each use. Generally, the considerations fore design are as follows: A throttle valve must deliver water when needed and be able to dampen pressure waves, the reservoir must be large enough to supply necessary surplus water but small enough to effectively oscillate.

Applications of surge tanks can also be found in the automotive industry, particularly in specialty cars. In these situations the purpose is to supply fuel at times when the vehicle is under gravitational forces opposing the direction of fuel flow. In this case a small surge tank is able to supply fuel for a short period of time.

Finally, small pressurized surge tanks are often used in manufacturing or waste water treatment. In these applications the elevation head is often small however there is high pressure caused by the velocity head. In these situations a tank open to the atmosphere may not be feasible as it would have to be located high above the facility. On level ground pressurizing surge tanks can be an effective way to mitigate pressure waves. This design works by maintaining a high air pressure within a tank connected to the fluid line, effectively matching the air pressure to the pressure of the fluid is critical for this style of surge tank to work.

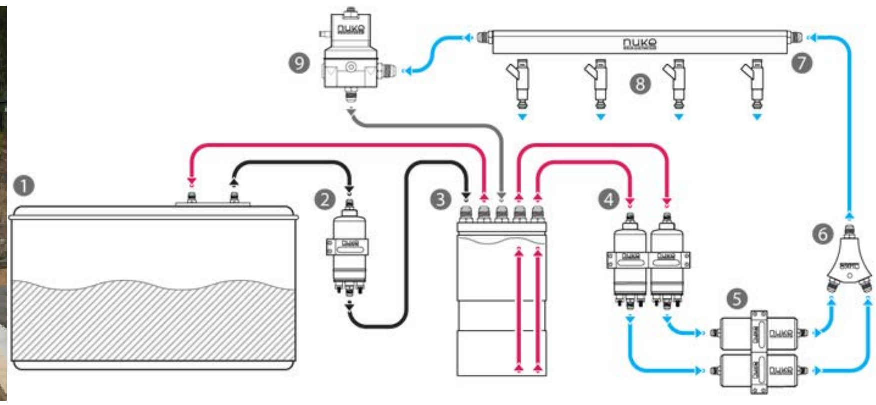

Figure 4 & 5

(Bladder Surge Tanks used in manufacturing compared to an automotive surge tank system)

www.youngeng.com, (Engineering, 2013)

Surge Tank Design

Automotive surge tanks range from complex networks of controllers and pumps to simple reservoirs placed within the fuel line. Manufactures advertise “Providing a constant level of fuel increases your chance to take advantage of all the power your engine delivers” (nuke performance). These surge tanks are placed within a fuel line and are sold to performance drivers. Automobile surge tanks are technically not surge tanks as there is no surge of pressure to be absorbed, in reality they are more similar to a secondary gas tanks. Hydroelectric surge tanks and automobile surge tanks do have one benefit in common, that is they provide additional flow when it is required. True surge tanks must also dampen the high pressure waves that form when a turbine is shut off rapidly.

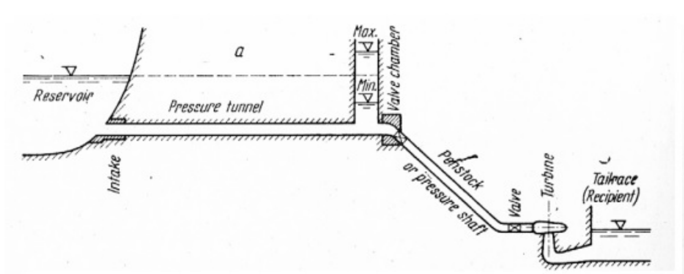

Figure 6

(Typical Surge Tank Set-Up)
(Bulu)

A typical surge tank is shown in figure 6 as it would be used with a hydroelectric power plant. In this design the surge tank is located far from the turbine so that the elevation of the surge tank matches the elevation of the reservoir. All surge tanks open to the atmosphere must be designed higher than the reservoir that supplies it, additional elevation beyond the height of the reservoir allows for oscillations to occur without spilling. Hydroelectric surge tanks require a great deal of engineering to be designed effectively. These surge tanks must quickly dampen strong pressure waves caused by restricting the flow of water. Typically, this will be done with (Bulu) specialty openings, or throttle valves. The target of a throttle valve is to allow water to easily enter the surge tank but expend much more energy to leave the tank. This energy is lost due to friction and turbulence within the tank and throttle body. Many patterns of openings are used from multiple small holes to single large ones. Additional design options come from the shape of the tank itself. There are dozens of configurations available although they can be broken down in to three categories, simple surge tanks, surge shafts with expansion chambers, and restricted-orifice type surge tanks. Examples of simple surge tanks can be seen in figure 4.

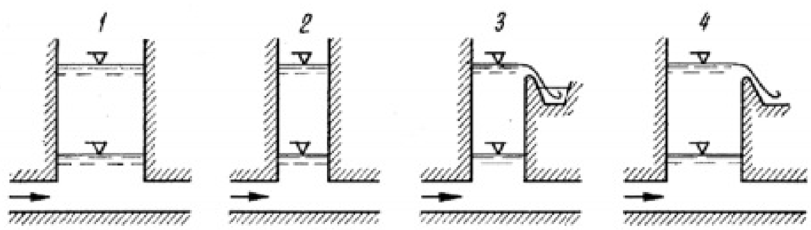

Figure 7
(Simple Surge Tank Design)
(Bulu)

Current Research

Current research applying to surge tank design ranges from modeling techniques to throttle design. Even simple analysis of surge tank behavior can be difficult to model due to the non-linearity of the friction term in the differential equation of the system (Moghaddam, 2003). Techniques such as genetic algorithms are presented to find accurate solutions to general surge tank designs. Specific cases such as "Design of throttled surge tanks for high head plants, reflection at a T-Junction with an orifice in the lateral pipe" are also under investigation.

Example Problem: Water Hammer and Surge Tank design

A surge tank aims reduce the effect of water hammer to protect a pipeline. For a surge tank to be effective, the maximum height of a surge must be found, then the surge tank can be properly sized for the system. This example system consists of a reservoir connected to a pipe line at the upstream end. At the end of the pipe there is a valve. Under standard operating conditions, the water flows from the reservoir to the pipe and is discharged through the control valve into a collection reservoir. The pipeline is built with 45 cm diameter cast iron pipe. The pipe has cylindrical surge tank with a diameter of 122 cm. The length of the pipe is 3,120 m. The steady flow rate is Q = 0.001723 m^3/s. What is the maximum elevation on that surge tank? Now, if there is no surge tank and the valve is closed in 2.5s, what will be the pressure surge in the line? And for 5s? Assume the initial pressure of 200 kN/m^2 and use $E_{v} =$ 2.0 x 10^9 N/m^2. Figure 8 shows a schematic of the problem.

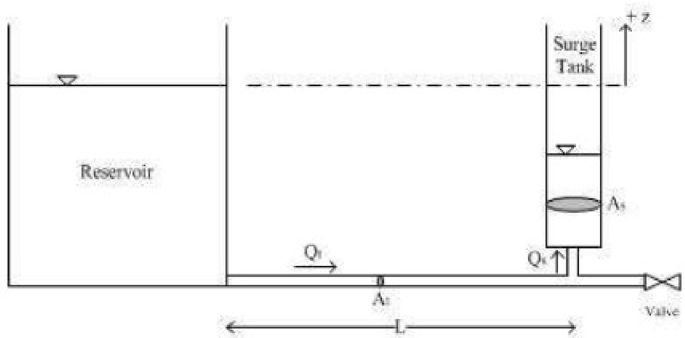

Figure 8

To find the maximum elevation within the surge tank, the initial flow velocity within the pipe line must be determined. To find the velocity the flow rate must be divided by the cross sections area of the pipe line. These two steps are listed below.

$$A = \pi r^2$$
$$= \pi\ (0.225)^2 = 0.16 \text{ m}$$
$$V = Q/A$$
$$= 0.1723 / 0.16 = 1.08 \text{ m/s}$$

Next, the area of the surge tank must be determined, as seen below.

$$At = \pi r^2$$
$$= \pi\ (0.61)^2 = 1.17 \text{ m}^2$$

Equation 7 solves for the maximum elevation within a cylindrical surge tank.

$$L = 3120 \text{ m},\ g = 9.81 \text{ m/s}$$
$$S = V\sqrt{\frac{AL}{Atg}} \quad (7)$$
$$= 1.08\sqrt{(0.16 \text{x} 3120)/(1.17 \text{x} 9.81)} = 7.12 \text{ m}$$

The maximum elevation for the given conditions is equal to 7.12 meters.

Next, assuming there is no surge tank present, the water hammer effect will occur. To determine the change in pressure, the theoretical wave celerity, actual wave celerity and time of closure must first be determined. Equation 8 solves for the theoretical wave celerity, as shown below.

$$c' = \sqrt{\frac{Ev}{\rho}} \quad (8)$$

$$= \sqrt{}\ (2.0\text{x}10^9)/1000)) = 1414.21 \text{ m/s}$$

The actual wave celerity is a function of the theoretical wave celerity, pipe diameter, modulus of elastic of the pipe, and bulk modulus of elasticity of fluid. The celerity is found below with Equation 9.

$$C = \sqrt{\frac{c'^2}{1+\frac{dE_v}{\varepsilon E_p}}} \quad (9)$$

$$= \sqrt{}\ (1414.21)^2/\ (1 + 0.05625) = 1376.04 \text{ m/s}$$

To determine if the valve closure is considered to be rapid, the closure time must be less than two times the length divided by the wave celerity. This is seen in Equation 10,

$$T = \frac{2L}{c} \quad (10)$$

$$= (2\text{x}3120)/1376.04 = 4.53\text{s}$$

$$2.5 \text{ s} < 4.53 \text{ s}$$

Because the valve closure is considered rapid, Equation 11 is used to determine the pressure change created.

$$\Delta p = \rho c V \quad (11)$$

$$= 1000\text{x}1376.04\text{x}1.08 = 1486123.2 \text{ N/m}^2 \text{ or } 1486.12 \text{ kN/m}^2$$

$$H = \Delta p/\gamma \quad (12)$$

$$1486.12/\ 9.81 = 151.5 \text{ m}$$

Next, the change in pressure caused by a 5 second closure time must be found. Because 5 seconds is greater than 4.53 seconds, as previously calculated, it is considered to be a slow closure. Equation 13 and 14 solve for the change in pressure for a slow closure.

$$N = (\rho LV)/\ (p_0T) \quad (13)$$

$$= (1000\text{x}3120\text{x}1.08)/\ (200000\text{x}5) = 3.37$$

$$\Delta p = p_0 \left(\frac{N}{2} + \sqrt{\frac{N^2}{4} + N} \right) \quad (14)$$

$$= 200000 \times ((3.37/2) + \sqrt{((3.37)^2/4) + 3.37}) = 1348 \text{ kN/m}^2$$

$$H = \Delta p/\gamma$$

$$= 1348/9.81 = 137.41\text{m}$$

Surge Tank Case Study

Surge tanks, which are used to dissipate water hammer pressure, are available in many designs. Dr. Ghulam Nabi, from the University of Engineering and Technology, Lahore, analyzed 3 types of surge tanks under the conditions of complete closure and complete opening of a turbine. Three different surge tanks were studied: one without chamber, a surge tank with a lower chamber and surge tank with two lower chambers. The goal of the study was to analyze the surge wave height within the surge tanks, and the time to dissipate.

The project is located on Golen Gol Nullah. The design discharge is 30 m^3/s and the turbine was shutdown in 120s. "The simulation was carried out for 2000s with a computational time interval of 0.5s" (Nabil). To the left in Figure 9 are the exact surge tank parameters that were used in the studied.

The results of the experiment shown in Figures 10 and 11 indicate that the most efficient surge tank design tested was the surge tank with two lower chambers.

Descriptions of data	Data
Location of surge tank	Upstream
Water level of upper reservoir	2052.00m
Water level of lower reservoir	1612.00 m
Friction coefficient reach upper reservoir- surge chamber	80
Friction coefficient reach surge chamber – plant	80
Friction coefficient reach plant – lower reservoir	70
Tunnel length reach reservoir –surge chamber	3810.00m
Tunnel diameter reach reservoir – surge chamber	3.20m
Tunnel length reach surge chamber – plant	650.00 m
Tunnel diameter reach surge chamber- plant	3.00 m
Tunnel length reach plant- lower reservoir	80.00
Tunnel diameter reach plant- lower reservoir	5.00 m
Diameter of surge shaft	9 m
Height of surge shaft	30 m
Diameter of vertical shaft below orifice	3.00 m
Diameter of vertical shaft above orifice	9.00m
Diameter of orifice	3.25m
Design discharge	30 m^3/sec
Installed capacity	106 M watt
Total efficiency of power station	0.85

Figure 9
(Initial Conditions)

Sr. No.	Type of surge tank	Maximum up surge (m)
1	Surge tank without chambers	2070.00
2	Surge tank with lower chamber	2069.80
3	Surge tank with two chamber	2062.00

Figure 10
(Complete Closure Results)

Sr. No.	Type of surge tank	Max. down surge (m)
1	Surge tank without chambers	2044.50
2	Surge tank with lower chamber	2044.20
3	Surge tank with two chamber	2044.50

Figure 11
(Complete Opening Results)

The surge tank with two lower chambers produced the lowest maximum surge of the three tanks tested. In addition, all three surge tanks had equal maximum up surges.

Based on this study, it can be concluded that a surge tank containing two lower chamber produces the lowest maximum water upsurge height.

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