SOAK UP WATER HAMMER IN LIQUID SYSTEMS

The pressure spike from a step change in flow velocity must be damped to save equipment from damage.

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Designing liquid filled pipes for steady state flow is easy; it is transient conditions that require careful thought and knowledge. The phenomena of water hammer, or more technically known as surge, can stress pipes, valves and fittings to the point of failure.

Surge is classified as an isolated event that occurs when flow conditions undergo a step change in velocity. Surge can occur without any noticeable or harmful effects when the velocity change is small. It becomes a problem, though, when the change is significant and high pressures are generated.

Surge is often the consequence of rapidly closing valves. Commonly known as water hammer, sudden pump failures can cause the same effect. It is also possible to create ‘negative surge’, that is a low-pressure spike during pump start-ups. Liquid systems can suffer damage just as much to low-pressure spikes as they can to high-pressure spikes.

All liquid systems pass through two transitional phases; start-up and shutdown. It is during these phases that pressure surges occur. One characteristic of water hammer is the metallic knocking often heard in the piping system. While the noise may be only a nuisance, various valve types can cause step changes in velocity which, when operated quickly, can produce devastating results. Quarter-turn valves, ball and butterfly valves and lever-operated knife valves are the most notorious.

This article will deal with the designer’s mathematics by reviewing the basic equations that quantify the effects of step changes in liquid flow. Then we will introduce ways of alleviating the impact of harmful pressure surges and offer a few practical examples. It deserves to be noted that the simplest means of surge avoidance is to slow down valve closing and opening times. But when this is not feasible, then a surge absorber can be fitted to the pipeline. In order to do this we must develop the sizing equations for a suitable surge absorber.

The various energies of a flowing liquid, assuming they are incompressible, constant temperature, and steady state or constant mass flow, are connected by Bernoulli’s equation, see Equation 1 below. When pipe elevation remains constant, any changes in velocity, and hence kinetic energy, are matched by changes in static head.

$$\frac{p_1}{rg}+\frac{v_1^2}{2g}+z_1 \quad = \quad \frac{p_2}{rg}+\frac{v_2^2}{2g}+z_2 \qquad \text{Eqn.1.}$$

where:-

p = static pressure
r = liquid density
v = liquid velocity
g = gravitational acceleration
z = height above datum

Investigators in the 19th century found that rapid changes in liquid velocity produced much larger head changes than predicted by Bernoulli. Many of the esteemed European scientists can claim an association with the water-hammer problem; Euler, Young, Savart, de la Tour, Wertheim, Helmholtz, Fourier, Poisson and Bernoulli; all became involved in developing wave theories. Water hammer, it seems, was not a problem of kinetic energy but of acoustics and pressure waves. Korteweg, in 1878, collated all the previous work and combined the elasticity of the fluid and the pipe to produce an accurate prediction of the velocity of sound (and pressure waves) in a confined fluid. However, it was Joukowsky in 1897 who produced the definitive equation for a pressure change associated with a sudden change in velocity. Joukowsky's work was extended by Allievi, in 1904 and in 1913, to include pressure changes produced by 'slow' valve closure.

The velocity of sound ' c ' in an unconfined liquid is given by the standard equation shown as Equation 2.

$$c = \sqrt{\frac{K}{r}} \quad or \quad c = \frac{1}{\sqrt{\frac{w}{\mathrm{g}K}}} \qquad \text{Eqn.2.}$$

'K' is the bulk modulus, which reflects the compressibility of the liquid. 'r' is the density and ' w ' is the specific weight. 'g' is not shown in italics as a variable although, strictly speaking, it is a variable. For those requiring very accurate results the local value of 'g' may be calculated from the ISO equation, Equation 3. Latitude is in degrees and altitude in meters.

$$g = 9.7803\left(1+0.0053\text{Sin}^2 j\right) - 3.1^{-6} z \qquad \text{Eqn.3.}$$

where:-

j = latitude

z = altitude

For cold water K= 2300Mpa and r =1000kg/m3, which produces an acoustic velocity of 1516m/s. Both $K$and r vary with temperature and pressure so that 'c' is a variable and not a constant. Wertheim found that the acoustic velocity of water confined in pipes was less than the theoretical unconfined value. Helmholtz concluded that the elasticity of the pipe wall reduces the acoustic velocity, hence the acoustic velocity of a confined liquid is given by Equation 4.

$$c = \frac{1}{\sqrt{\frac{w}{\mathrm{g}}\left(\frac{1}{K}+\frac{d}{tE}\right)}} \qquad \text{Eqn.4.}$$

' d ' is the pipe diameter and ' t ' the wall thickness. ' E' is Young's Modulus of Elasticity for the pipe material. The acoustic velocity varies with the pipe properties. Once the acoustic velocity is known the water-hammer head rise can be calculated from the Joukowsky equation, see Equation 5.

$$\Delta h_i = \frac{cv}{\mathrm{g}} \qquad \text{Eqn.5.}$$

The Joukowsky equation predicts the instantaneous head rise when the velocity of a moving body of fluid suddenly ceases. However, the liquid does not necessarily have to undergo an instantaneous stop in order for the effect to be noticeable. The calculated head rise lasts until a pressure wave, reflected from the far end of the pipe, returns to interact with the original event. This period of a pipeline is given by Equation 6.

$$T_{pp} = \frac{2l}{c} \qquad \text{Eqn.6.}$$

Once a surge problem is identified and the resulting pressure spike is determined by equation 5 above, the next step would be to select the appropriate type of surge relief mechanism. If the designer wishes to avoid the nuisance, the safety and environmental hazards and the costs associated with a rupture disc or a relief valve, then a gas-filled surge absorber can often be an inexpensive solution. Many such devices are pressure-rated vessels fitted with an internal flexible membrane that separates process fluid from a nitrogen gas pre-charge. Obeying the gas-laws, the contained nitrogen pre-charge reacts instantly to compress itself under reaction from a pressure spike.

Figure 1 illustrates a bladder-type device, where the compressed gas is contained within an elastomeric bladder. Other devices that feature flexible, Teflon diaphragms or bellows of either Teflon of alloy materials are also available. A variety of designs and material selections are available for process compatibility.

Sufficient gas volume is a prime requisite in order to fully protect against the worst-case scenario…i.e. rapid closure. Sizing for these purposes is accomplished by considering the energy change of the decelerated fluid and relating it to the adiabatic changes occurring to the gas condition. Typically the equations involved would be as follows:
The kinetic energy of a moving body of fluid of Q m3/second with a density of r kg/m3 travelling down a pipeline d metres diameter and length, l , metres is:

$$KE = \frac{1}{2} \times mass \times velocity^2$$

$$= \frac{1}{2} \times \frac{pd^2}{4} \times l \times r \left[\frac{Q}{\frac{pd^2}{4}} \right]^2$$

This becomes, after rearrangement:

$$KE = \frac{2\, r\, l\, Q^2}{p\, d^2}$$

If the velocity of the fluid is totally stopped, then the kinetic energy is converted to work done on the gas contained within the bladder under adiabatic compression.

$$W = p_1 V_1^g \int_{V_1}^{V_2} \frac{dV}{V^g}$$

$$= \frac{p_1 V_1}{(g-1)\left\{1-\left(\frac{V_1}{V_2}\right)^{g-1}\right\}}$$

$$= \frac{p_1 V_1 - p_2 V_2}{g-1}$$

Where 'g ' = ratio of specific heats of the gas (normally = 1.4 for diatomic gases such as Nitrogen and air).

Where p_1 and V_1 = initial volume and pressure, P2 and V_2 = final pressure and volume, but pV^g = constant, so…..

$$V_2 = V_1 \left(\frac{p_1}{p_2}\right)^{\frac{1}{g}}$$

Consequently…..

$$W(g-1) = p_1 V_1 - p_2 V_2$$

$$= p_1 V_1 - p_2 V_1 \left(\frac{p_1}{p_2}\right)^{\frac{1}{g}}$$

$$= V_1 \left(p_1 - p_2 \left(\frac{p_1}{p_2}\right)^{\frac{1}{g}}\right)$$

$$\therefore \quad V_1 = \frac{W(g-1)}{p_1 - p_2 \left(\frac{p_1}{p_2}\right)^{\frac{1}{g}}}$$

$$\text{and} \quad \mathrm{V}_1 = \frac{2\, r\, l\, Q^2 (g-1)}{p\, d^2 \left(p_1 - p_2 \left(\frac{p_1}{p_2}\right)^{\frac{1}{g}}\right)}$$

V_1 represents the volume of gas required at normal operating pressure, p_2 , in order to prevent the pressure spike of equation ⑤ under water hammer conditions occurring.

p_2 is the maximum allowable pressure set by the piping system designer, an hence is a known prerequisite.

However, there is one final small adjustment to be made before determining the size of a gas-filled surge absorber. It is generally recommended to slightly deflate the gas membrane to ensure that some process liquid is always present inside the chamber. A slightly reduced gas pre-charge pressure will enable the fluid port to be always open in order to accept the hydraulic transmission of a pressure spike travelling at the speed of sound. Normally, a gas pressure reduction to 90% of normal operating pressure is sufficient.

The final selection of the volume required for the gas filled surge alleviator is:

$$V_{required} = \frac{p_1}{0.9\, p_1}$$

A schematic of a typical gas filled damper is shown in Figure 1…..

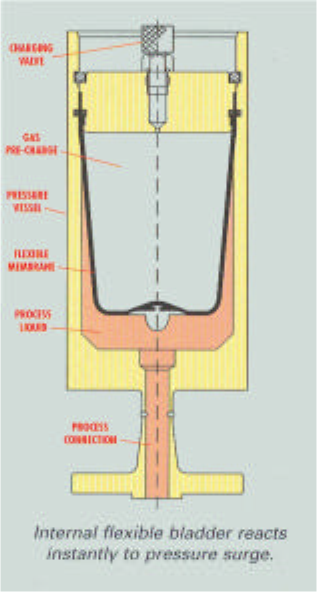

Fig 1…
Schematic of a gas filled bladder style
Surge Absorber

Slow, valve-closure times on very long pipelines may have to last for several minutes in order to dissipate the energy of the moving mass without harm. Power actuated isolating valves should have speed adjustment to allow fine-tuning at site. Non-return valves used on long pipelines should be of the controlled closure type rather than simple swing-disc style, which have a tendency to slam shut.

As noted, water hammer is often associated with valve closure. Quarter-turn ball and butterfly valves can close in 0.5 seconds and less. Low-pressure cold water systems may operate with velocities up to 15 m/s. Given these two conditions, if we ignore the effects of pipe elasticity on the acoustic velocity, then the Joukowsky equation predicts an instantaneous pressure rise of 227 bar applicable to all pipe lengths up to 379m, based upon a 0.5 sec closure time. Butterfly valves very often are used on systems that operate below 40 Bar (g). It is highly unlikely that designers would include for a 560% safety margin.

Just like quarter turn valves, lever-operated knife gate valves can also be closed very quickly. They are usually rated at 25 Bar (g), but even a modest 3 m/s water flow, suddenly stopped, will create a surge of 45 Bar. Some low velocity applications, particularly those dealing with slurries that cause sediment deposits, may eventually produce such surges. A clogged piping system that results in a suddenly choked velocity during a flushing cycle can result in water hammer. A 45-Bar spike on a 5Bar (g) flushing system would be very detrimental.

Check valves are very popular in pumping systems. They protect the pump against reverse flow. They need to be fitted very close to the pump, though, in order to be effective. When circumstances dictate otherwise, e.g. when fitted at surface level, as in the case of submerged pumps, and sudden power failures stop the pump, reverse flow under gravity can slam the check valve closed and produce surge pressures destructive to the valve and to the pump casing.

Positive displacement pump systems are not immune to water hammer. Reciprocating pumps are used in metal manufacturing to generate hydraulic power or for high-pressure water de-scaling. These pumps are often blamed for 'control' problems. These applications are characterised by an irregular flow demand. High flow rates are required for short periods. The pumps are used to pressurise accumulators, which in turn are used for 'peak-lopping'. One popular method of pump control is 'load/unload' or bypass control. Fixed speed pumps run continuously. When the accumulator pressure is high and there is no demand for water, the pumps operate at very low pressure through a bypass line back to the suction tank. When the process demands water, the bypass valve closes and pump flow is diverted to the high-pressure accumulators.

Water is a difficult liquid to control because it is very erosive. Valves that are subject to throttling tend to wear quickly. Bypass valves are usually fitted with hydraulic, pilot operated control devices that use the same water for actuation. The bypass valve's opening and closing times are controlled by an orifice or a needle valve in the pilot. When the orifice wears, the bypass valve action speeds up and surge or water hammer is produced.

Systems with positive displacement pumps often require protection from excessive pressures. Special spring-loaded relief valves are very popular as they are simple and failsafe. These devices can be seriously damaged by the effects of water hammer, though, due to the suddenness by which the pressure spike comes and goes. The spring opens and closes the valve very rapidly and with a large impulse thus damaging the lift stops, discs, nozzles and springs. The suction side of the pump is equally susceptible to surge pressures, particularly at start-up and shut down. Surges can be avoided by the careful use of suction unloaders or by the inclusion of a properly sized surge alleviator.

The problems described thus far are fairly obvious to experienced system designers. Those that follow are not quite so obvious. For instance, on completion of construction or after servicing long pipelines, those lines are full of air. Before normal pumping can commence the pipeline must be vented and filled. Automatic air release valves can be mounted at strategic locations on top of the pipe. During the filling process, air release valves allow all of the gases to escape as they are displaced by liquid. The air release valves close automatically when the float chamber fills with liquid. The filling operation is done using high-flow, low-pressure centrifugal pumps rather than the normal pipeline pumps. High-pressure is unnecessary because friction losses are very low. Water hammer can arise, though, when the automatic air release valve closes. Relatively large bore valves must be fitted to allow fast exhaust of the gases. If valve closure is abrupt then the probability of water hammer exists.

Negative surge pressure or negative water hammer can occur when pumps are installed with long suction pipes. A fixed speed pump is either 'On' or 'Off'. When the pump is switched 'On' the flow at the pump suction connection tries to change from zero to rated flow, or even from zero to a very high flow for some centrifugal pumps. This sudden change in liquid velocity creates a pressure depression in the pipe work local to the pump. If that depression is low enough, then the liquid locally can boil and produce vapor bubbles (cavitation).

If the process fluid contains dissolved or entrained gas, then even a slight depression could allow that gas to separate and form gas bubbles. When the system pressure is reapplied, the gas will return to solution and create pseudo-cavitiaton. Cavitation and pseudo-cavitation can be very damaging to equipment and pipe work. Both cause surface and metal removal. Cavitation and pseudo-cavitation can produce very rapid failures in components; components may fail without warning if characteristic indications have been ignored or not observed.

All of the problems described are the result of rapid changes in liquid velocity. Very high pressures can be generated by the sudden deceleration of a liquid column. Low pressures can be created by the sudden acceleration of a liquid column. Both of these problems can be alleviated if the sudden changes can be smoothed out into much gentler changes. Surge arresters or shock absorbers change the system characteristic to eliminate the sudden velocity changes of the liquid column.

Most of the foregoing is based on clean pure liquids as already stated. Liquids in normal processes are usually not very clean and very rarely pure. Solids entrained in the liquid tend to reduce the acoustic velocity. Dissolved gas and entrained gas bubbles have the same effect. Reducing the acoustic velocity is beneficial in that it reduces the maximum instantaneous head rise. Unfortunately, reducing the acoustic velocity also increases the pipe period so that valve closures might have to be much longer than expected to prevent dangerous pressure rises. Consequently, designers need to consider all of these parameters in order to alleviate the effects of surge when designing their piping systems. The provision of surge absorbers up front may be a component of prudent planning.

Pumps and piping systems are at times modified for reasons of upgrade or for modernisation. The same rules apply and should be considered beforehand. Newly installed control and feedback mechanisms can interact with each other such that valves close unexpectedly or pumps stop suddenly. To the unaware, the resultant problems can manifest themselves in the unanticipated activation of relief valves or rupture discs. If negative surge occurs, then rupture discs have been known to implode. Engineers who have not experienced water hammer can be at a disadvantage in recognising these symptoms when they occur. The incidence of failure might span a considerable period before finally noted. We have seen instances, for example, where motors of greater size have replaced pump drive motors and shafts are sheared upon start-up. Appropriately positioned surge alleviators can be used to cushion the initial start-up energy to induce a ‘soft-start’ and hence protect the drive shaft. The moral here is to talk to an experienced surge alleviation designer who will help to diagnose whether or not the potential for surge problems exists.

All in all, pressure surges are realistic phenomena frequently experienced in fluid systems. It is important to recognise these symptoms quickly to avoid the risk of spillage, contamination and costly downtimes. The effects of both positive and negative surge pressures should not be underestimated, as they can be costly and dramatic.

The system designer should examine and investigate all of the operating regimes of his piping system and evaluate the potential for surge and water hammer occurrences, so that appropriate alleviation plans can be implemented in advance. The gas-charged type of surge absorber is usually a simple, reliable and cost effective solution – one that requires little routine maintenance

Reference:-
Water-hammer head...or the Joukowsky equation…is as derived by Moody, ASME-ASCE Symposium on Water Hammer, pp 25 – 28, American Society of Mechanical Engineers, New York, 1933.

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TABLE OF SYMBOLS			
p_1, p_2	pressure: barA	t	pipe wall thickness: m
V_1 V_2	volume: m^3	d	pipe diameter: m
ρ	density:kg/m^3		
v_1, v_2	liquid velocity: m/sec	l	pipe length: m
g	gravity acceleration : m/sec²	Dh_i	incremental ”head”; m
z_1, z_2	liquid head height: m	T_{pp}	pipe period: seconds
c	velocity of sound: m/sec	Q	liquid volume flow: m^3/sec
K	bulk modulus:N/m^2	KE	kinetic energy: Joules
w	specific weight: N/m^3	g	ratio of specific heats: dimensionless