SOME CONSIDERATIONS IN SELECTION OF SURGE PROTECTION EQUIPMENT.

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SYNOPSIS

Most potential problems experienced on pipelines can be overcome by careful design and a knowledge of the appropriate methods to overcome these problems. Waterhammer has probably been the greatest cause of pipe failures over the years. With the latest computer software most of these problems can be identified and simulated and effective solutions provided. Even without computer analysis, better application decisions can be made by following some basic guidelines. An intimate knowledge of valve capabilities will ensure that most potential damages can be avoided and pipelines can provide long and efficient service.

INTRODUCTION

In any pumping or gravity line, the rapid start-up or shutdown of flow can result in a phenomena called waterhammer, which can cause serious damage to pipe components such as pumps and valves resulting in costly repairs, downtime and loss of water. Uncontrolled start-up and shutdown of pumps and isolating or control valves which close too quickly are the most common causes of these waterhammer events.

Another cause is air release valves which are allowed to blow out an excessive volume of air during pipe filling with resultant rapid closure.

It is the aim of this paper to investigate the correct application of control valves, air release valves, check valves and surge tanks, to eliminate the destructive forces of waterhammer and to ensure optimum operation of pipelines.

THE BASIC THEORY OF WATERHAMMER

In this paper, the comments regarding waterhammer serve only as an introduction to this complex subject. For an in depth study and analysis of any specific problem, it is suggested to use modern literature and state of the art computer programs of which a number are available.
If waterhammer is neither dampened nor reduced, the magnitude of the surge pressure caused by rapid changes in velocity can be calculated using the Joukowsky equation.

\[ \Delta h = \frac{a \Delta v}{g} \]

where

- \( \Delta h \) = Pressure surge (m)
- \( \Delta v \) = Change in velocity (m/s)
- \( a \) = Wave celerity (m/s). This is the speed at which a pressure surge is propagated in a pipeline with incompressible fluid.

The wave celerity depends, among others on the elasticity of both the fluid conveyed and the pipe itself and is calculated as follows:

\[ A = \frac{K}{\rho (1+dK/eE)} \]

Where:

- \( K \) = Bulk modulus of elasticity of the fluid conveyed
  (2,1x10^9 Pa for water)
- \( \rho \) = Density of fluid (kg/m³)
- \( d \) = Pipe diameter (mm)
- \( e \) = Pipe wall thickness (mm)
- \( E \) = Modulus of elasticity of piping material
  (25x10^9 Pa for Fibre Cement)

The Joukowsky equation is valid for “instantaneous” changes in flow velocity i.e. provided the change takes place within a time frame

\[ t < \frac{2L}{a} \]

where:

- \( t \) = Time over which the change in velocity takes place.
- \( L \) = Length of the pipeline (m)

If the change takes place beyond this time frame, the pressure surge is reduced to a large extent. The actual magnitude thereof, provided no damping takes place and no reduction measures are taken, can then be calculated as follows:

\[ \Delta h = \frac{m/2(1-T)^2 + m + 1 - m/2 (1-T)}{t} \]

Where:

- \( h \) = \( \frac{(Ho+h)}{Ho} \)
\[ \frac{\text{Ht}}{\text{Ho}} = \text{Initial internal pressure prior to surge (m)} \]
\[ \text{Ht} = \text{Total maximum pressure, i.e. initial internal pressure plus surge pressure (m)} \]
\[ m = \frac{\text{aVo}}{\text{gHo}} \]
\[ \text{Vo} = \text{Flow velocity before change (m/s)} \]
\[ T = \text{Critical time over which change in velocity can take place (s)} \]
\[ = \frac{2L}{a} \]
\[ t = \text{Actual time over which change in velocity takes place (s)} \]

**REMEDIAL DEVICES**

Besides some dampening which is inherent to a pipeline such as pipeline profile, elasticity of the pipe, types of coupling and pump inertia (if applicable), various additional reduction and/or protective devices can be incorporated into the system. These devices are mostly designed to reduce “instantaneous” stoppage and acceleration of water columns and can be summarised as follows:

- Control valves
- Check Valves (also known as non-return or reflux valves)
- Surge relief and surge anticipator valves
- Surge tanks
- Air release and intake valves

The above list of devices is not exhaustive but probably represents the more commonly used solutions to which we will limit ourselves in the rest of the paper.

In order to relate all the waterhammer-causing events to a typical system, we investigate a pumping system transferring water from a river to a reservoir (see fig 1).
Fig 1

**Pump Control Valves**

In most pumping systems it is advisable to start and stop the pump in a controlled fashion to ensure that:

1. The acceleration and deceleration is achieved gradually to reduce the effects of waterhammer.
2. The pump does not operate outside its efficient design parameters.
3. Pump cavitation is avoided.

The latter causes damage to pump components as well as increasing the release of detrimental air into pumping columns.

Almost any valve can be made into an automatic pump control valve by the addition of an electric, pneumatic or hydraulic actuator. Over the years Gate, Globe, Ball and Butterfly valves have been used with various forms of actuators as Pump Control valves.

Some **Selection Criteria for Pump Control Valves** are:

- Pressure drop in fully open position. Low pressure drop is always a benefit as energy is expensive.
- Ability to withstand the arduous conditions of slow opening causing potential damage to valve seats.
- Cost

Actuators are chosen on the basis of:

- Availability of Electric, Pneumatic or hydraulic power.
- Speed of operation required
- Dependability of above sources of power.
A valve that has gained in popularity as a Pump Control valve over the years is the self actuated, diaphragm operated Globe control valve which uses the water pressure in the pipeline as the hydraulic power source.

![Diagram of Ultra ACV](fig2.png)

This valve is extremely flexible whereby various functions such as a Pressure Sustaining or Flow Rate Control and Check valve feature can be added at little extra cost. *Many different types of Pump Control Valve designs are available today* (visit [www.ultravalves.co.za](http://www.ultravalves.co.za) and see product profile).

**Check Valves**

Check valves are generally installed on Pump delivery manifolds to prevent return flow when the pump is stopped. When used in conjunction with a pump control valve, their performance during normal operation is not critical as all the work is performed by the pump control valve. However, during a pump trip-out due to electrical failure or in installations where pump control valves are not used, they perform a critical duty and can have a great effect on waterhammer reduction. The worst check valves are those that are forced closed by reverse flow (which creates “instantaneous” closure under high velocity), whereas the best check valves are those that close under their own force during the short time span between forward and reverse flow after pump trip-out. The following is a brief listing of the most common types of check valves with their relevant benefits:

**Swing Check Valves**

In its most basic form as a wafer pattern swing check valve (see fig 3), this valve depends on reverse flow to close, resulting in severe waterhammer. Another disadvantage of this valve is that its opening forces created by flow velocity decreases to a very low value when in the fully open position, resulting in unstable operation.
Over the years the swing check valve has been re-designed into different formats i.e.

a) With an external shaft to enable a counterweight to be fitted to speed up closure and to provide a greater closing force. (See fig 4). A further use of the external shaft is to fit a hydraulic damper to soften the final closure.

b) Tilting disc arrangement (see fig 5). This design balances the forces on the disc to allow for more compact designs for the larger size valves. The offset shaft also ensures that the disc itself has a closing force which can reduce the weight required in a counterweight.
c) Double Door check valves (see fig 6). These are normally spring actuated to increase speed of operation aided by the lower inertia of the doors.

Diaphragm Check Valves (see fig 7)
This valve has a good reputation for reducing waterhammer due to the spring force in the rubber diaphragm causing the valve to close before return flow occurs as well as the dampening effect of the rubber diaphragm after closure has taken place.
Silent (Piston) Check Valves
This valve consists of a piston with a spring behind it to increase closing speed (see fig 8). This type of valve is the best known design to reduce waterhammer as its spring can be made of sufficient force to ensure the required closure speed and it has a short stroke length to ensure very fast and “slam-free” closure.

Fig 8 Ultra Silent Check Valve

Nozzle Check Valves
This is the “ultimate” check valve which combines the benefit of a very fast closing valve with a Nozzle flow path which ensures a very low pressure drop in the valve. (See Fig 9)

Fig 9 Nozzle Check Valve
Check valves play a vital role in waterhammer reduction. Besides being used on a pump discharge they can be utilised as follows:

- On a pump by-pass to allow water from the pump suction to the delivery line to fill the low pressure void (vapour cavity) created during a pump trip-out.
- In long pipelines with many gradient changes, strategically placed check valves could reduce waterhammer caused by column separation and also separate the “momentum” in the pipeline into smaller parts.

**Surge Relief Valves**

These valves are available in different formats to remove high pressure “Spikes” caused by waterhammer from the pipeline. Two most commonly used are as follows:

**Surge Anticipating Valves**

These self-actuated control valves are designed to react to the low pressure wave generated during a pump trip, causing the valve to open. The low pressure wave reflects off the open end of the pipeline (at the reservoir) as a high pressure wave. By the time this wave returns to the pump, the surge anticipating valve is already open and will relieve the high pressure wave to atmosphere, thereby protecting the pump and Check Valve. (see fig 10)

![Fig 10 Ultra ACV Surge Anticipator Valve](image)

**Fast acting relief valves**

A self actuated control valve can be made to react fast (within 1 second) to a high pressure caused through a slamming check valve or rapid
Closure of say the reservoir control valve in our example. If this speed is not fast enough a gas loaded surge relief valve has to be used. These valves are known to react within a micro second. (see fig 11)

Fig 11 Gas Loaded Surge Relief Valves
Reservoir Control Valves
Reservoir Level Control valves are critical to the reduction of waterhammer as the required speed of closure plays such a significant role. Slow closure leading to shortened valve life due to the destructive forces from high velocities and cavitation are in conflict and should receive careful consideration from the design engineer.

As shown in our typical pumping layout, it is customary to install an automatic level control valve at the reservoir. The most common type is again the self-actuated type (see fig 12), due to the fact that power is seldom available at reservoirs. These valves also have the highest resistance to cavitation of all valve types which is an important benefit as cavitation is very prevalent with reservoir control valves. Even though they have a “relatively” high resistance to cavitation, a normal maximum pressure drop ratio which can be tolerated is 4:1, so if the back pressure from the reservoir is 10m (or 1 bar), the maximum dynamic head which can be tolerated upstream of the valve is 4 bar. Various artificial back pressure devices could be installed which are all dependent on energy losses from a fixed flow rate, but the problem arises during the opening and closing cycles of the reservoir valve when the benefit from the backpressure device no longer applies.

Closure time of the reservoir control valve is critical in order to limit the extent of the waterhammer pressure generated. The longer the pipeline, the slower the valve has to close to prevent “instantaneous” closure as governed by the formula \( t = \frac{2L}{a} \) (Pipe period). The valve can be slowed down by the inclusion of a needle valve on the control circuitry, but care has to be taken that this needle valve is not set so closed that it becomes vulnerable to clogging up. The problem becomes quite severe if the valve
has to close very slowly (sometimes up to 10 minutes) and cavitation conditions exist, as this would reduce valve life quite severely. Sometimes such problems can only be effectively solved by the installation of a pressure reducing valve upstream of the reservoir level control valve at great cost.

Fig 12 Ultra ACV Level Control Valve
A “new” valve concept is available where the Axial flow path provides a 10:1 pressure drop capability as well as inherent soft closure. (see fig 13).

Fig 13 C-Valve manifoldered Control valve
Air Release Valves

Air enters pipelines from various sources i.e.
• Air intake from open sources and pump stations
• Release of dissolved air due to pressure and temperature changes
• Incomplete discharge of air during filling of empty pipes
• Controlled air penetration to prevent negative pressures

The presence of air in pipelines can cause serious problems such as:
• Reduced capacity of pipelines resulting in increased energy consumption.
• Increased corrosion of internal pipe surfaces
• Inaccuracies in flow metering and damage to such equipment
• Sudden changes in velocity will be magnified by air due to its compressibility and increase the magnitude of waterhammer

Even though in certain instances air can be beneficial in slowing down the pressure wave caused by waterhammer, the overall effect of air in pipelines is very detrimental and should be avoided at all costs, with the entrance and exit of air controlled by high performance and quality air valves.

Removal of air from pipelines
There are two ways in which air can be removed from pipelines and normally they should work together to ensure effective de-aeration of pipelines i.e.
• Hydraulic movement. To move air to points in the pipeline where it can be bled from the pipe, a certain flow velocity is required which depends on the slope and internal diameter of the pipe.

The minimum flow velocity necessary to move entrapped air along the pipeline can be calculated using Wisner’s formula:

\[ V \geq (0.25 \sin \varphi + 0.825) \cdot gd \]

Where:
\( V \) = Minimum velocity required to transport air along the pipe (m/s)
\( \varphi \) = Gradient of section of pipeline under consideration (degrees)
\( g \) = Gravity acceleration (m/s^2)
\( d \) = Internal pipe diameter (m)
This equation should be applied between air valves on the flatest sections and decreasing slopes of the pipe so as to determine whether trapped air will in fact be transported to the points where the air will be bled out.

- **Mechanical Removal.** This is the removal of accumulated air from the pipeline through either manually operated valves or the more common method of using automatic air release valves placed at points where air would naturally accumulate. It is very important that accumulators are provided at these points to ensure that air is indeed trapped at these points and does not merely flow past the air valve. These accumulators are simply Equal Tee’s. (See fig 14)

![Fig 14 Correct Installation of Air valve](image)

Formulas exist for the correct placement and sizing of air release valves, but some manufacturers have developed computer programs which have made this task a lot more accurate and easy to do. It is outside the scope of this paper to go into more detail about the correct sizing of air valves, but the author can be contacted for this information and particularly the availability of sizing programs.

Modern air valves (see fig 15) normally include three functions into one valve i.e.

- Release of large quantities of air whilst filling the pipeline.
- Intake of large quantities of air during evacuation or draining of the pipeline.
- Release of pressurised air which accumulates at the air valve during normal operation of the pipeline.
All three functions have their inherent problems which were particularly prevalent in the older designs and have been overcome through some innovative engineering in new designs. Some of these factors are described as follows:

**Blow shut.** Some designs blow shut when the pipe is being filled too fast thereby rendering the valve inoperable. In order to overcome this phenomena, valves were designed with a “kinetic” shield which allowed a suction effect to keep the float open under high velocity air flow. This allowed designers to produce more compact and competitive designs but which also resulted in other problems i.e. too rapid closure of the float when water reaches the air valve, causing serious damage due to waterhammer.

**Non-slam designs**

In order to overcome the “slamming “ effect caused by the closure of Kinetic air valves, engineers used to install check valves on air valve inlets. This allows the valve to operate normally during pipe filling, but as soon as water arrives at the valve, the check valve closes and reduced flow is allowed to fill the air valve through a small bypass.

In latter years some manufacturers have incorporated this feature into their air valves (see fig 16) to reduce cost and size of the installation.

These valves can serve to reduce waterhammer on pump discharge whereby the fast intake of air after a pump trip and the slow release of air after the event can replace the function of surge tanks in a lot of installations. Most Design Engineers have adopted this design as it provides comfort in the belief that any waterhammer problems are now solved.

*It is the author’s opinion that non-slam designs should not just become the norm in all installations as serious restrictions in release capacity
during pipe filling can cause other problems where large “bubbles” of air are left in the pipe after filling, resulting in all the problems associated with air in pipelines. **Correct sizing and selection of air valves should receive more attention from Design Engineers.**

**Release of pressurised air.**
Because of design constraints most air valves have very small secondary orifice sizes to release pressurised air i.e. under one millimetre diameter in some instances. These small orifices block up very easily and on large pipelines simply do not release air fast enough. One manufacturer has solved this problem by replacing the round orifice with a slot which is closed off by a resilient strip driven by the valve’s float (rolling seal design - ARI). This allows for a much larger orifice which does not suffer from the traditional problems experienced by air valves (see fig 17).

![Fig 17 ARI Rolling Seal mechanism](image)

*It is the author’s opinion that the small orifice which releases pressurised air does not receive enough attention from pipeline designers and users, who often do not realise the importance of its correct operation. Most users of air valves only see the valve operational when the pipeline is being filled or drained and the large orifice does all the work. The small orifice is supposed to function when the pipe is operational and the valve is hidden in a manhole. A survey done on air valves which have been in service for over a year has indicated that a large percentage have small orifices that no longer work due to the fact that they have clogged up. In other instances air valves which leak have been prevented from leaking by maintenance staff by closing the isolating valve under it !!*

The importance of getting rid of air in pipelines cannot be overemphasised, and inspection and maintenance procedures should be implemented to rectify this often neglected item.
**Surge Tanks**

Surge tanks have become very popular as Surge protection devices and operate as follows:

They allow the injection of water into a pipeline at points where low pressures (vapour cavities) are formed due to:

- Pump trip (electrical failure)
- Low pressure points on the Hydraulic Gradeline
- Before and/or after points of rapid valve closure

Surge tanks are available in a few different formats with the main ones being

- Closed and pressurised with air. This requires an installed compressor and instrumentation with high maintenance to ensure continued correct operation.
- Open tanks at low pressure points. These are normally concrete or Steel structures with problems of maintenance and remote locations.
- Bladder tanks. These are by far the most suitable solution as they have a rubber bladder interface between the water and air and do not suffer from high maintenance costs. (See fig 18)

![Fig 18 Bladder Surge Tank](image)

In most installations, Air valves and Surge tanks compliment each other as they inherently perform the same function ie reduce the low pressure pockets formed after a pump trip and which reduces overall Waterhammer pressures. The only difference is that tanks inject water whereas Air valve inject air. Some engineers are under the impression that surge tanks are better as they do not inject “unwanted” air into pipelines.

*It is the author’s opinion that with the correct choice of high performance air valves available, the injection of air is beneficial as long as it is removed from the location of entry and under controlled rates as*
provided by some modern two stage closing air valves. With the correct selection and “mix” of air valves and Surge tanks, pipe optimization can be ensured at much cheaper costs than only Surge tanks.

**Conclusion**
All the equipments discussed for reducing Waterhammer serve the purpose of ensuring that water columns are accelerated or decelerated at acceptably slow rates and if high pressures are unavoidable, to relieve them out of the pipeline before they cause any damages. This is the key to the reduction of Waterhammer where logic can often be used to find solutions.
With the availability of new software, guesswork can be eliminated with Pressure envelopes calculated and Surge Suppression equipment modelled for optimum solutions.