



White Paper

Surge Control in Pumping Systems

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Surge Control in Pumping Systems

INTRODUCTION

Water pipelines and distribution systems are subjected to surges almost daily, which over time can cause damage to equipment and possible contamination. Surges are caused by sudden changes in fluid velocity and can be as minor as a few psi to five times the static pressure. The causes and effects of these surges in pumping systems will be discussed along with equipment designed to prevent and dissipate surges. Only with the knowledge of all of the associated valves and surge equipment can a successful pumping system with acceptable surge levels be designed. Reference will be made to typical installations and examples so that an understanding of the applicable constraints can be gained.

Figure 1 illustrates a typical water pumping/distribution system where two parallel pumps draw water from a wet well then pump the water through check and butterfly valves into a pump header and distribution system. A surge tank and surge relief valve are shown as possible equipment on the pump header to prevent and relieve surges, respectively.

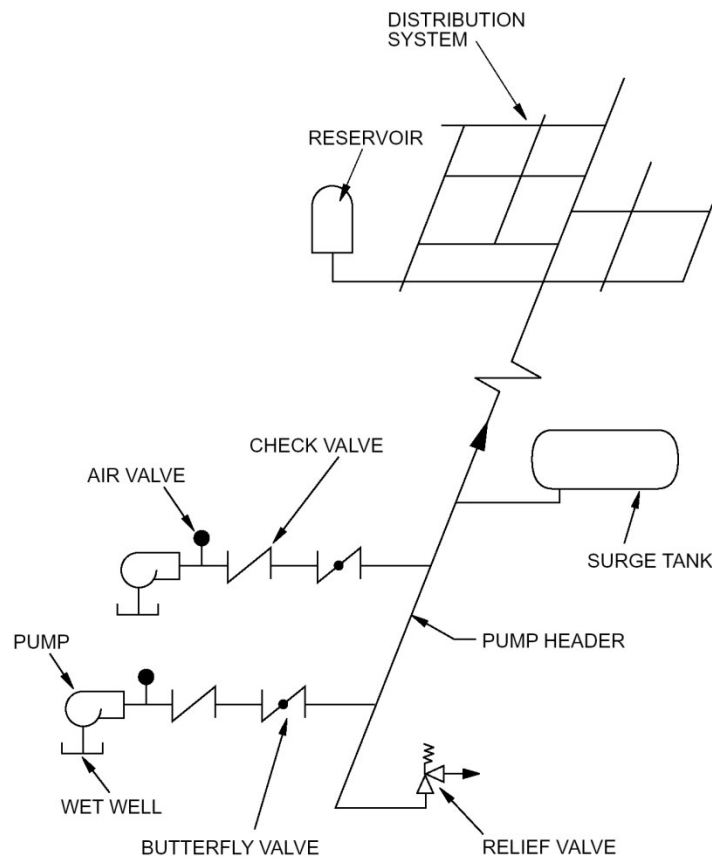


FIGURE 1. Typical Pumping/Distribution System

CAUSES AND EFFECTS

Surges are caused by sudden changes in flow velocity that result from common causes such as rapid valve closure, pump starts and stops, and improper filling practices. Pipelines often see their first surge during filling when the air being expelled from a pipeline rapidly escapes through a manual vent or a throttled valve followed by the water. Being many times denser than air, water follows the air to the

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outlet at a high velocity but is then rapidly restricted by the outlet causing a surge. It is imperative that the system fill flow rate be carefully controlled to less than 2 ft/sec fluid velocity and the air vented through properly sized automatic Air Valves. Similarly, line valves must be closed and opened slowly to prevent rapid changes in flow velocity. The operation of pumps and sudden stoppage of pumps due to power failures probably have the most frequent impact on the system and the greatest potential to cause significant and frequent surges.

If the pumping system is not controlled or protected, contamination and damage to equipment and the pipeline itself can be serious. The effects of surges can be as minor as loosening of pipe joints to as severe as damage to pumps, valves, and concrete structures. Damaged pipe joints and vacuum conditions can also cause contamination to the system from ground water and backflow situations. Uncontrolled surges can be catastrophic as well. Line breaks can cause flooding and line shifting can cause damage to supports and concrete piers and vaults. Losses can be in the millions of dollars so it is essential that surges be understood and controlled with the proper equipment.

SURGE BACKGROUND

Some of the basic equations of surge theory will be presented so that an understanding of surge control equipment can be gained. First, the surge pressure (H) resulting from an instantaneous flow stoppage is directly proportional to the change in velocity and can be calculated as follows:

$$H = a v / g$$

where:

H = surge pressure, ft water column

a = speed of pressure wave, ft/sec

v = change in flow velocity, ft/sec

g = gravity, 32.2 ft/sec²

The speed of the pressure wave (a) varies with the fluid, pipe size, and pipe material. For a medium sized steel line, it has a value of about 3500 ft/sec. For PVC pipes, the speed will be significantly less. For a 12 in. steel line with water flowing at 6 ft/sec, the magnitude of a surge from an instantaneous flow stoppage is:

$$H = (3500 \text{ ft/sec})(6 \text{ ft/sec}) / (32.2 \text{ ft/sec}^2)$$

$$H = 652 \text{ ft water column}$$

This surge pressure of 652 feet (283 psig) is additive to the static line pressure; therefore, the resultant pressure will likely exceed the pressure rating of the system. Further, the surge pressure will be maintained for several seconds as the wave reflects from one end of the piping system to the other end causing over pressurization of valves, pipe seals, and fittings. Then after a reflection, the pressure wave may cause a negative pressure and vacuum pockets for several seconds allowing contaminated ground water to be drawn into the system through seals or connections.

Even higher velocities than the pumping velocity are attainable in long piping systems, especially when there are significant changes in grade. If the pumps are suddenly stopped due to a power failure, the kinetic energy of the water combined with the low inertia of the pump may cause a separation in the water column at the pump or at a highpoint in the pipeline. When the columns of water return via the static head of the line, the reverse velocity can exceed the normal velocity. The resultant surge pressure can be even higher than the 652 feet calculated above. Transient analysis computer programs are

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normally employed to predict column separation and the actual return velocities and surges. Transient programs can also model methods and equipment employed to control and prevent column separation such as the use of a Surge Tank, Vacuum Breaker, or Surge-Suppression Air Valve.

Thus far, the changes in velocity have been described as “sudden.” But how sudden must changes in velocity be to cause surges? If the velocity change is made within the time period it takes for the pressure wave to travel the length of the pipeline and return, then the change in velocity can be considered instantaneous and the equation for surge pressure (H) given earlier applies. This time period, often called the “critical period”, can be calculated by the equation:

$$t = 2L / a$$

where:

t = critical period, sec

L = length of the pipe, ft

a = speed of the pressure wave, ft/sec

For the earlier example, (12 in. line), the critical period would be as follows for a 4 mile long steel pipeline:

$$t = 2 (21,120 \text{ ft}) / (3500 \text{ ft/sec})$$

$$t = 12 \text{ sec}$$

Therefore, to cause surges, a pump does not need to stop quickly nor does the valve need to close instantaneously (or even suddenly). A normal flow stoppage of 5 or 10 seconds may cause the maximum surge (H) in long pumping systems. It follows that surge control strategies should be employed to slow down changes in velocity on all long pipelines.

PUMPS

Referring again to Figure 1, a key to controlling surges in pumping systems is to control the rate of increase and decrease of the flow velocity into the system. Pumps should be sized for the expected flow requirements. Oversized pumps can create havoc in certain pumping systems. Some pump station designs employ multiple pumps to match varying demand so that when one of the multiple pumps is started or stopped, it has a minor impact on the overall pipeline velocity. These systems control supply and can prevent surges during normal pump operation. Another option is to use specialized motor control equipment (i.e. variable frequency drives or soft start controls) to slow down the start and stop of a pump over 2 to 30 seconds. However, after a power failure the motor controls become inoperative and the pump will stop quickly and cause a sudden stoppage of flow. Almost all pumping systems need additional surge equipment to prevent surges after a power failure.

VERTICAL PUMPS AND WELL SERVICE AIR VALVES

Vertical pumps, as shown in Figure 2, lift water from a tank or wet well into a pipeline. When the pump is off, the suction water level is below the pump discharge pipe. The pump column refills with air after each pump stoppage. Air Valves play an important role in automatically venting the pump column air and controlling surges in pump columns. If the vertical turbine pump is started without an Air Valve, the air in the pump column would be pressurized and forced through the check valve into the pipeline causing air related problems. Air Valves for pump discharge service, called “Well Service Air Valves”, are similar to Air/Vacuum Valves but are equipped with either a throttling device or a regulated exhaust device and are designed to exhaust air on pump start-up and admit air upon pump shut down.

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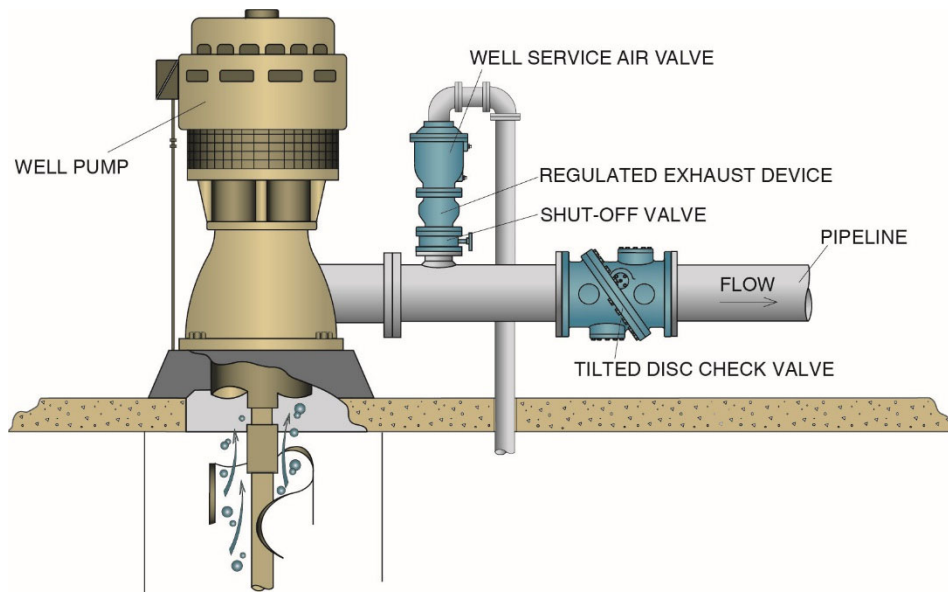


FIGURE 2. Vertical Turbine Pump

As shown in Figure 3, the Well Service Air Valve is a normally-open, float-operated valve which relieves the air in the pump column rapidly. When water enters the valve, the float automatically rises and closes to prevent discharge of the water.

Throttling devices are provided on the outlet of 3 in. and smaller valves to control the rate of air release, especially with slow opening pump control valves. The throttling device is adjusted with the external screw to slow the rise of the water in the pump column. However, after pump shutdown, a second port on the top of the throttling device provides full flow into the pump column to relieve the vacuum. The Dual Port Throttling Device is important because it provides full vacuum flow and prevents contaminated water from being drawn into the pipeline, which can happen if the device has a common exhaust and vacuum connection.

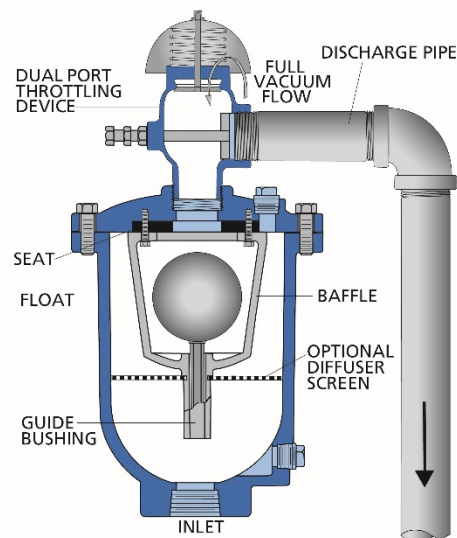


FIGURE 3. Well Service Air Valve

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CHECK VALVES

Another key element in pumping system design is the proper selection and operation of the pump discharge check valve. Every pump station designer has been faced with check valve slam, which is caused by the sudden stoppage of reverse flow through a closing check valve. To prevent slam, the check valve must either close very quickly or very slowly. Anything in the middle is no-man's land and a cause for concern. But just as important, the valve should protect the pumping system and piping from sudden changes in velocity if it is within its functional capabilities. The check valve should also be reliable and offer low head loss.

Two categories of check valves will be discussed in detail. The first, fast-closing check valves, represent the general category of check valves that operate automatically in less than a second and without the use of external power or signals from the pumping system. The other category is pump control valves, which operate very slowly (i.e. 60-300 seconds) to carefully control the changes in pipeline fluid velocity.

FAST-CLOSING CHECK VALVES

Fast-Closing Check Valves are simple, automatic, and cost effective but often are plagued with the problem of check valve slam and a resultant system pressure surge. Significant research has been done to understand the dynamic closing characteristics of various fast-closing check valves including ball check, swing check, tilted disc, resilient disc, dual disc, and silent check valves. If the deceleration of the forward flow can be estimated, such as with a transient analysis of the pumping system, the slamming potential of various check valves can be predicted. Then, several non-slam valve options will present themselves, and the performance features and costs can be used to select the best check valve for the application.

The most ubiquitous type of check valve is the traditional swing check valve. Swing check valves as shown in Figure 4 are defined in AWWA C508 for waterworks service and are designed to rapidly close to prevent backspinning of the pump during flow reversal. Traditional swing check valves have 90-degree seats with long strokes and are subject to slamming. These valves are therefore outfitted with a wide array of accessories, which are beyond the scope of the AWWA C508 Standard. Probably the most common accessory is a lever and weight. While it is normally assumed that the weight makes the valve close faster, it actually reduces slamming by limiting the stroke of the disc, but in return, causes a significant increase in headloss. The valve closure is also slowed by the inertia of the weight itself and the friction of the stem packing.

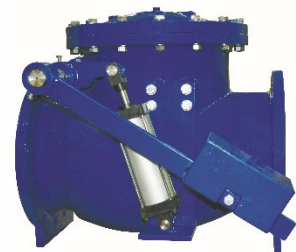


FIGURE 4. Swing Check

In more severe applications, an air cushion is sometimes used to slow down the impact of the valve closure. Everyone has seen how effective an air cushion works on a slamming storm door. But the conditions in a pipeline are significantly different. When a door slams, its momentum is smoothly absorbed by the air cylinder because as the door slows, the forces from the closing spring and outside wind become less and less. Conversely, when a check valve in a pipeline closes, the reverse flow is quickening at a tremendous rate so that every fraction of a second that the valve closure is delayed, the forces on the disc will increase by an order of magnitude. So while it may be true that an air cushion prevents the disc weight from slamming the disc into the seat of a valve in a product display booth, in actual practice, the air cushion merely holds the disc open long enough for the reverse flow to intensify and slam the disc even harder into the seat. Since air cushions are based on the use of air (which is

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compressible), they provide no positive restraint of the closing disc and cannot counteract the enormous forces being exerted by the reverse flow. The best use of an air cushion is to configure the device so that as the check valve opens, the air in the cylinder is compressed and is used to accelerate the closure of the check valve during closure.

A far more effective accessory for controlling swing check valve motion is an oil cushion, also referred to as an oil dashpot. Because oil is incompressible, the oil cushion will withstand the high forces exerted on the disc by the reverse flow and properly control the last 10% of valve closure. The pump must be capable of some significant backflow, though, because the oil dashpot will allow the check valve to pass flow back through the pump. Since the reverse flow forces on the valve disc are extremely high, the oil pressure often exceeds 2000 psig causing valves with these devices to be costly. The high-pressure oil cylinder is expensive and because it puts the valve stem under high loads, a special check valve with a large stem diameter is often needed. Because pumps can only withstand so much backflow, the closure time of dashpots are usually limited to 1 to 5 seconds. If the pipeline contains debris or sewage, a check valve with oil cushion can act as a screen during reverse flow conditions and quickly clog the line.

An even better solution is to select a check valve that closes before any significant reverse flow develops, thereby preventing a slam. One such valve is a spring-loaded, center-guided “Silent” Check Valve (SCV) as shown in Figure 5. A SCV is near slam-proof because of its short linear stroke, location of the disc in the flow stream, and strong compression spring. However, selecting a Silent Check Valve has several pitfalls such as high head loss, no position indication, and limitation to clean water applications.

On the other end of the spectrum is the Tilted Disc® Check Valve (TDCV). The TDCV as shown in Figure 6 has the lowest headloss because its port area is 140% of pipe size and its disc is similar to a butterfly valve disc where the flow is allowed to pass on both sides of the disc. The TDCV also has reliable metal seats and can be equipped with top or bottom mounted oil dashpots to provide effective means of valve control and surge minimization. The TDCV is fully automatic and requires no external power or electrical connection to the pump control.

The newest check valve listed in AWWA C508 and the valve having the greatest impact in the water/wastewater industry today is the resilient disc check valve, the Swing-Flex® Check Valve (SFCV), Figure 7. The SFCV is highly dependable with virtually no maintenance because the only moving part is the flexible disc. This valve has a 100% port slanted at a 45-degree angle, which provides a short 35-degree disc stroke, quick closure, and low head loss. The valve is also available with a mechanical position indicator and limit switches. A special model of this valve, the Surgebuster® (SB) has even faster closure due to the addition of a disc accelerator giving closure characteristics similar to that of a Silent Check Valve.



FIGURE 5. Silent Check



FIGURE 6. Tilted Disc®



FIGURE 7. Swing-Flex®

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Hence, with all of the check valve possibilities, one is available for every system with low head loss and slam-free operation. The closing characteristics of all types of check valves are shown for various system decelerations in Figure 8. The valves whose curves are furthest to the right have the best non-slam characteristics. The use and derivation of this data is explained in greater detail in the Val-Matic white paper "Dynamic Characteristics of Check Valves."

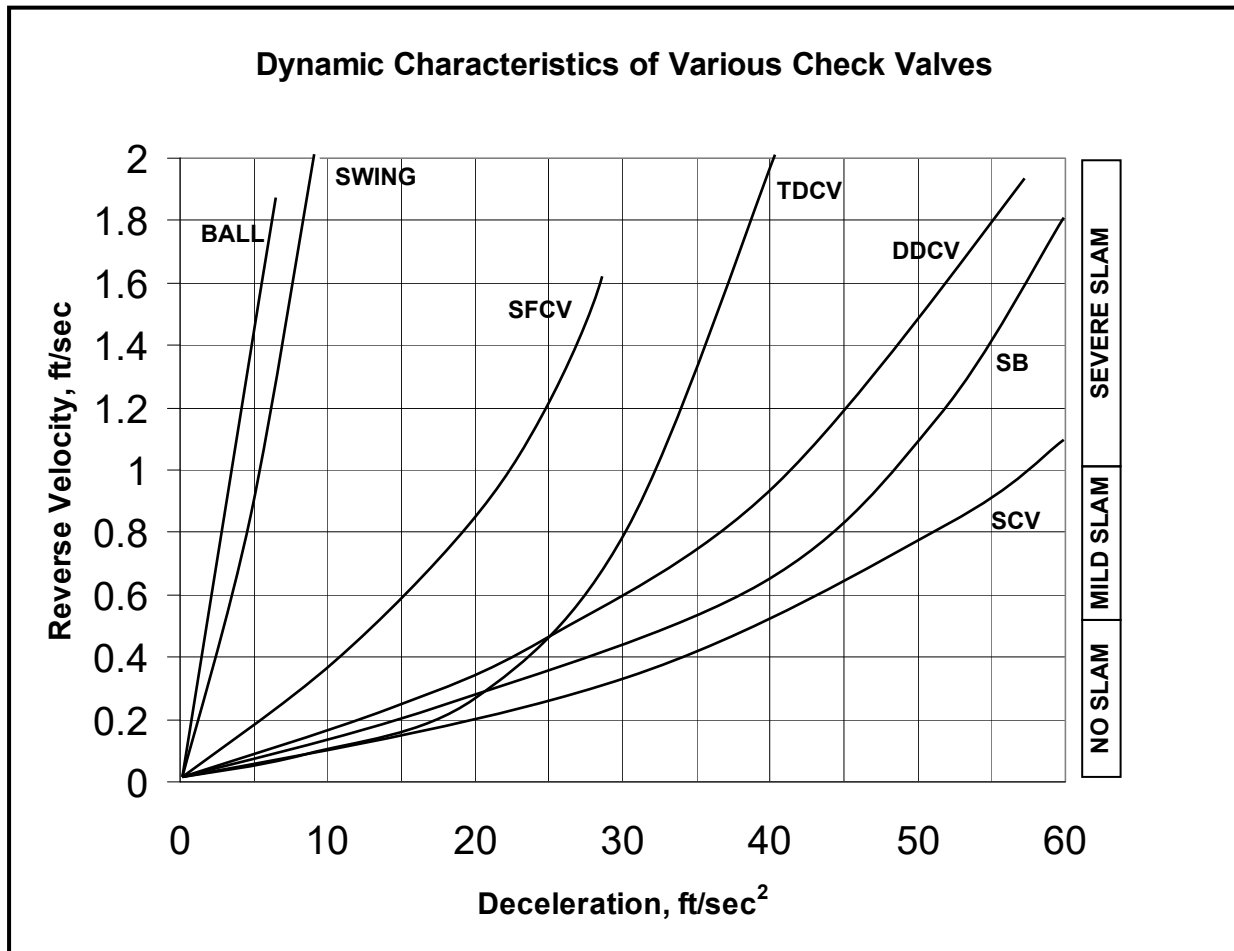


FIGURE 8. Dynamic Characteristics of Various Check Valves

PUMP CONTROL SYSTEMS

Even though a fast-closing check valve may prevent slam, it may not fully protect pumping systems with long critical periods from velocity changes during pump startup and shutdown. For pumping systems where the critical period is long, a pump control valve is often used. A pump control valve is wired to the pump circuit and provides adjustable opening and closing times in excess of the system critical time period. Pump control valves are hydraulically operated so the motion of the closure member of the valve (i.e. a butterfly valve disc) is unaffected by the flow or pressure in the line. Also, most pumps in service today have low rotating inertia and come to a stop in less than 5 seconds. The pump control valve can close rapidly during power outages or pump trips to protect the pump. However, when rapid closure is required, additional surge equipment may be needed.

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The list of possible pump control valves is long because many valves can be equipped with the automatic controls necessary for pumping systems. Valves typically considered are butterfly, plug, ball, and globe-pattern control valves. Probably the most common criterion used to select a valve is initial cost, but for pumping systems, the selection process should be carefully undertaken with consideration given to:

- valve and installation costs
- pumping costs
- seat integrity
- reliability
- flow characteristics

The flow characteristics of pump control valves will determine how well they will prevent surges. The most desirable flow characteristic of a valve is one where the valve uniformly changes the flow rate when installed in the system. The flow data available from valve manufacturers are inherent flow characteristics usually expressed in terms of a flow coefficient (C_v) at various valve positions. By assuming a constant head loss across typical valves at all positions, the inherent characteristics of the valves can be compared as shown in Figure 9. On the left side is a quick-opening valve curve (such as a gate valve or swing check valve), which depicts a rapid change in the flow rate as the valve opens. On the other extreme is an equal percentage valve (such as a ball valve), which changes the flow rate uniformly with valve travel. However, these readily available curves only consider the valve headloss and ignore the system headloss. Inherent curves may be misleading when selecting a valve for a pumping system with long pipelines.

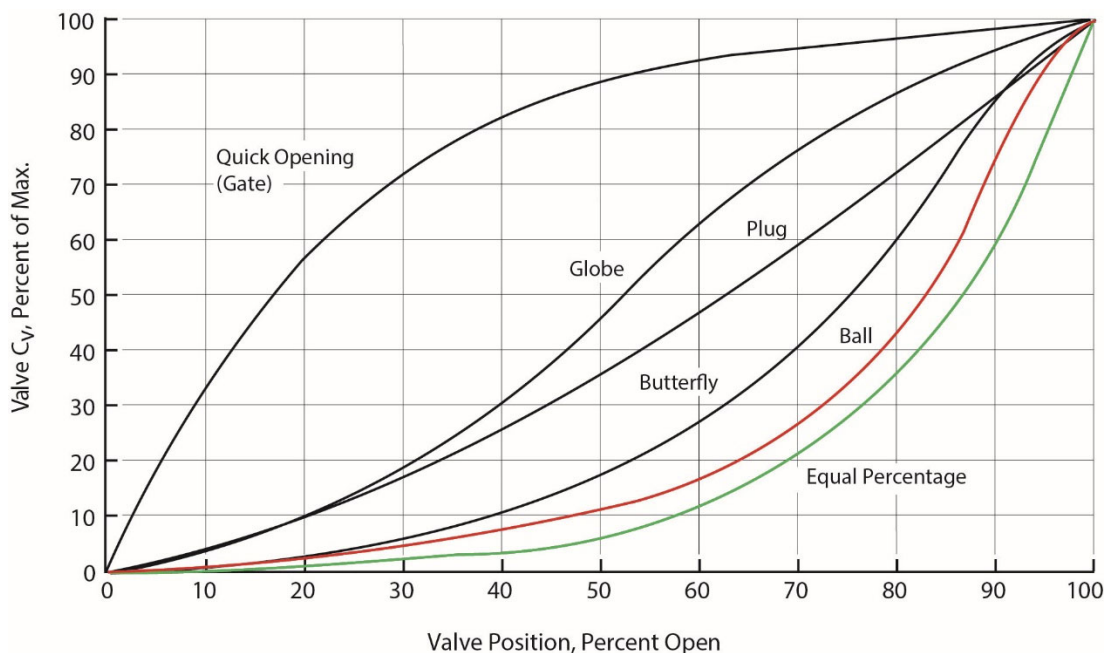


FIGURE 9. Inherent Flow Characteristics

The inherent characteristic curves must be transformed for a given pipeline application to consider the relative headloss of the piping system. When a valve such as a butterfly valve is installed in a pipeline, the location of the curve varies with the length of the pipeline as shown in Figure 10. The curve shown on the right is the inherent flow characteristic curve because the system is zero feet long. The other

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curves are installed flow characteristic curves because they vary with the system length. As the length of the pipeline increases, the characteristic curves for the same valve shifts to the left. Hence, the same valve can be very close to equal-percentage in one system and quick-opening in another. The longer the pipeline, the more the valve tends to be quick-opening. A quick-opening valve will change the flow suddenly and is more apt to cause surges because it effectively controls the flow for only one half of its travel. Ideally, the most desirable installed flow curve for a pumping system is linear such as the curve in the middle. Therefore, since inherent curves shift to the left when the system is included, the valve with an equal percentage inherent curve is the most desirable. Referring again to Figure 9, the most desirable valves for long systems would be butterfly and ball valves.

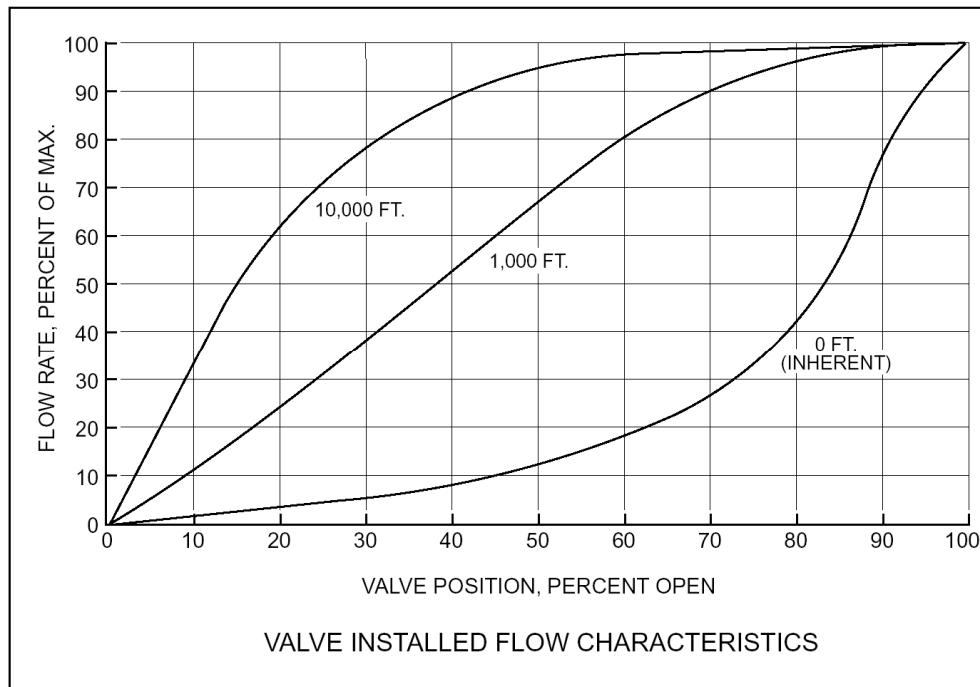


FIGURE 10. Installed Flow Characteristics

PUMP CONTROL VALVE OPERATION

Utilizing a ball valve, let us consider the operation of a typical pump control valve. A ball valve is operated by rotating its shaft 90 degrees and is normally equipped with a hydraulic cylinder actuator. The cylinder can be powered with pressurized water from the line or from an independent oil power system. We learned earlier that negative surge conditions can occur for several seconds, so a backup water or oil system is appropriate. Figure 11 illustrates a typical installation. Mounted on the valve are hydraulic controls electrically wired into the pump circuit. Four-way and two-way solenoid valves (SV) direct the operating medium to the cylinder ports to cycle the valve. The speed of opening and closing is controlled by independently adjustable flow control valves (FCV). Flow control valves are special needle valves with a built-in reverse check valve to allow free flow into the cylinder but controlled flow out of the cylinder.

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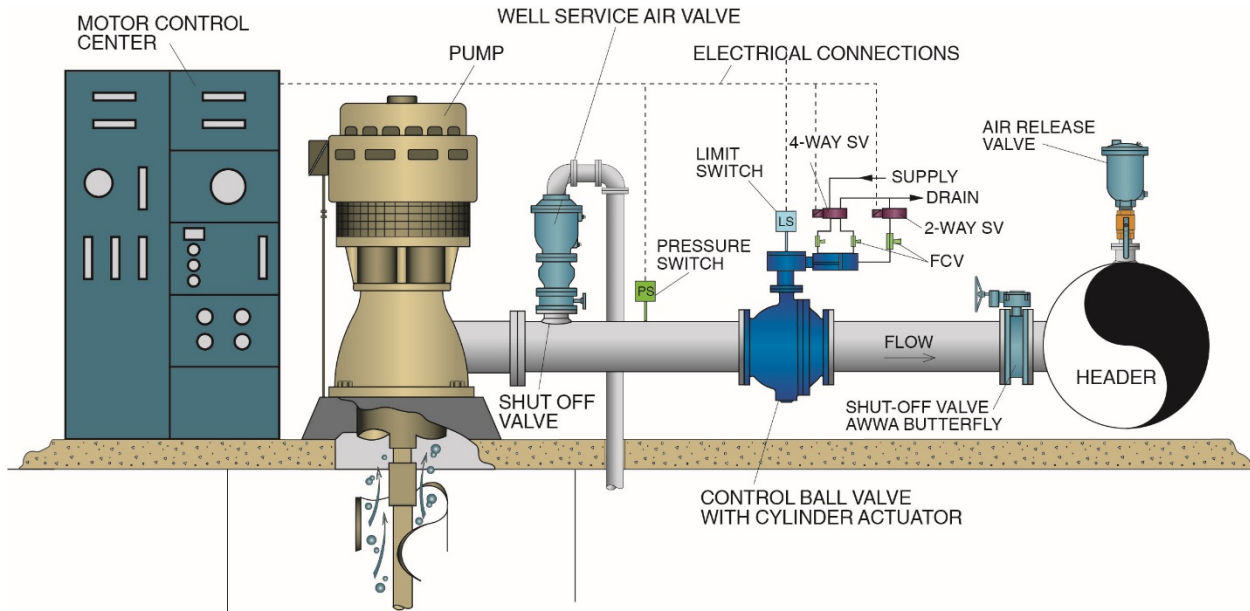


FIGURE 11. Pump Check Valve Installation

When the pump is started and pressure builds, a pressure switch (PS) located on the pump header signals the ball valve to open. During shutdown, the valve is signaled to close while the pump continues to run. When the valve nears the closed position, a limit switch (LS) located on the valve will stop the pump.

One additional function of the pump control valve must be considered; that is, to prevent the pump from backspinning after power failure or overload trip. Since pumps today no longer are equipped with flywheels, as with old diesel units, they have a low rotating inertia and come to rest in a just a few seconds. Therefore, after a power outage or pump trip, the pump control valve must close more rapidly to prevent backspinning. The valve hydraulic controls are equipped with a bypass line equipped with a 2-way solenoid valve (SV) to send the controlled cylinder flow around the normal flow control valve and through a large flow control valve (FCV), thereby closing the pump control valve automatically in 5-10 seconds after power failure. This is essential to prevent excess pump backspin and to prevent depletion of the hydro-pneumatic surge tank water back through the pump if one is utilized.

SURGE RELIEF EQUIPMENT

Since it is impractical to use pipe materials, which can handle high surge pressures or slow the operating flow velocity to a crawl, surge relief equipment is needed to anticipate and dissipate surges from sudden velocity changes after power outages. Surge relief equipment will also provide protection against malfunctioning valves, improper filling, or other system problems.

STAND PIPES AND SURGE TANKS

Many types of surge relief equipment are used to safeguard pumping systems. For low-pressure systems, a standpipe open to atmosphere will relieve pressure almost instantly by exhausting water. For systems with higher pressure, the height of a standpipe would be impractical so a surge tank with pressurized air over water can be used to absorb shocks and prevent column separations as shown in Figure 12. For typical pumping systems, however, these tanks tend to be large and expensive and must be supplied with a compressed air system. When used, an additional fast-closing check valve is also needed to prevent surge tank water from escaping back through the pump. This is a common example

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of when you will see both a pump control valve and a fast-closing check valve installed. Further, the surge tank creates extremely high deceleration rates (i.e. 25 ft/sec^2), so the fast-closing check valves must be equipped with springs or bottom-mounted oil cushions or dashpots to prevent slamming.

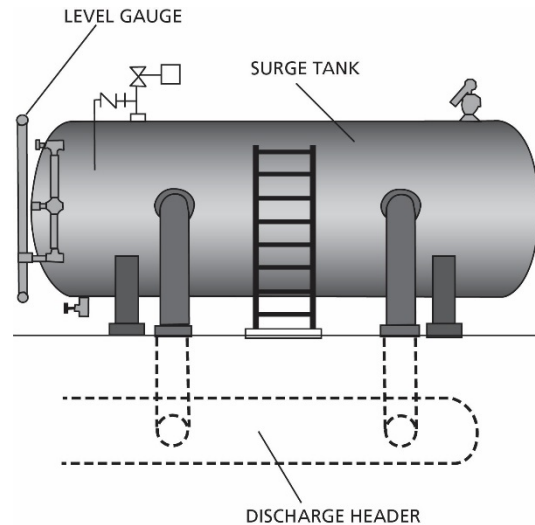


FIGURE 12. Hydro Pneumatic Surge Tank

SURGE RELIEF VALVES

Surge relief valves are often a more practical means of relieving pressure than a surge tank. In these valves, a pressure surge lifts a disc allowing the valve to rapidly relieve water to atmosphere or back to the wet well. Surge relief valves have the limitation that they may not open rapidly enough to dissipate surges in cases where column separation can occur. For these cases where the transient computer model predicts steep or rapid pressure surges, surge relief valves equipped with anticipator controls should be considered. A globe-pattern control valve equipped with surge relief and anticipator controls is shown in Figure 13. A surge anticipator valve will open rapidly upon the sensing of a high or low pressure event.

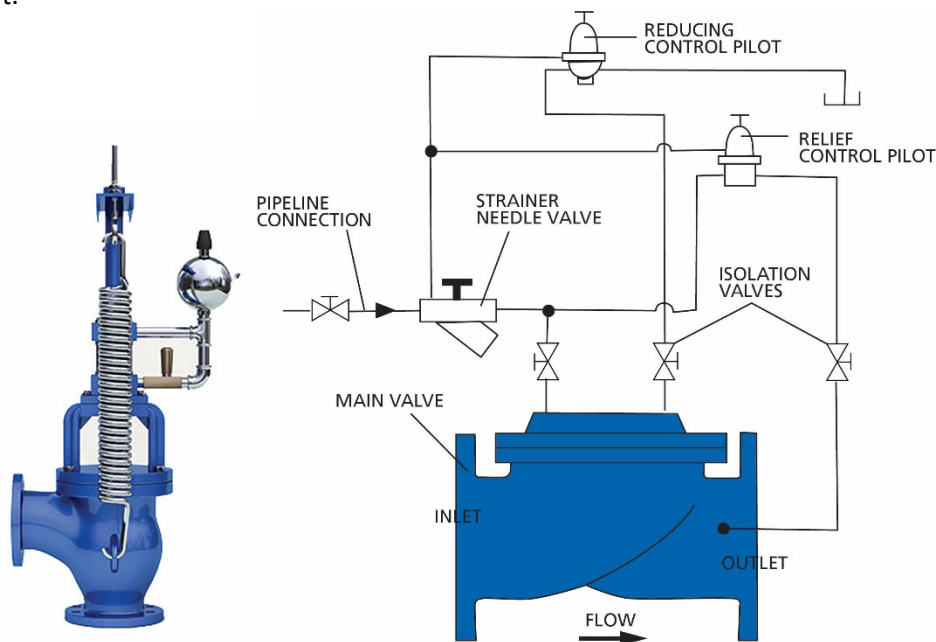


FIGURE 13. Surge Relief and Anticipator Valve

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When a pump suddenly stops, the pressure in the header will drop below the static pressure and trigger the surge anticipator valve to open. The valve will then be partially or fully open when the return pressure surge occurs. Anticipator valves typically open in less than five seconds, pass high flow rates, and reclose slowly at the pump control valve closure rate (60-300 seconds). The sizing of surge relief valves is critical and should be overseen by transient analysis experts.

SURGE-SUPPRESSION AIR VALVES

Air Valves help reduce surges in pipelines by preventing the formation of air pockets in pipelines during normal operation. Air pockets can travel along a pipeline and cause sudden changes in velocity and adversely affect equipment operation such as flow measuring devices. Air Valves are also designed to open and allow air to be admitted to the pipeline to prevent the formation of a vacuum pocket associated with column separation. Transient analysis computer programs are equipped to analyze the surge reduction from using various size Air Valves.

When column separation is expected at the Air Valve location, the Air Valve should be equipped with a Regulated Exhaust Device to cushion the rejoining water columns, see Figure 14. The Air/Vacuum Valve and Regulated Exhaust Device allow air to enter the pipeline unrestricted to prevent a vacuum in the pipeline. When the water columns rejoin, the air is exhausted and the restrictor disc closes, which provides for the slow release of the air at about 5% of the full rate thereby dampening the returning water columns. When the air is exhausted, the Air/Vacuum Valve float rises to prevent water discharge. Any remaining air or entrained air is automatically exhausted through the Air Release Valve.

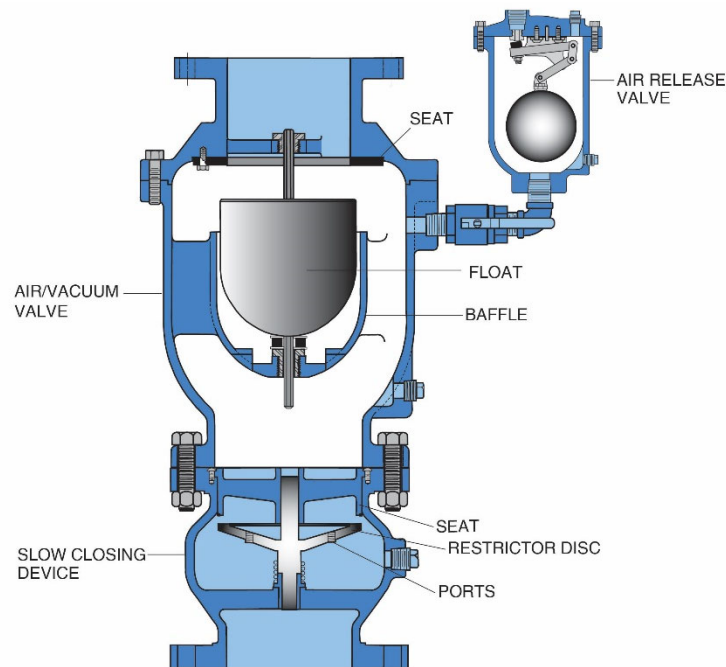


FIGURE 14. Float, Air Release Valve, Restrictor Disc and Regulated Exhaust Device

VACUUM BREAKER VALVES

Another type of Air Valve used at critical points in large pipelines or penstocks where column separation may occur is a Vacuum Breaker (VB) as shown in Figure 15. The VB has components very similar to the Regulated Exhaust Device, except the VB disc is held closed by a spring while the Regulated Exhaust disc

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is normally open. Hence, the Vacuum Breaker cannot expel air; only admit air to prevent the formation of a vacuum pocket. This keeps the pipeline at a positive pressure and reduces the surge associated with a column separation. In essence, a large cushion of air is admitted and trapped in the pipeline after a pump trip. The air is then slowly released over a few minutes through the adjoining air release valve, which has a small (i.e. 1/4 in) orifice. Again, transient analysis programs are designed to model this type of Air Valve solution as well.

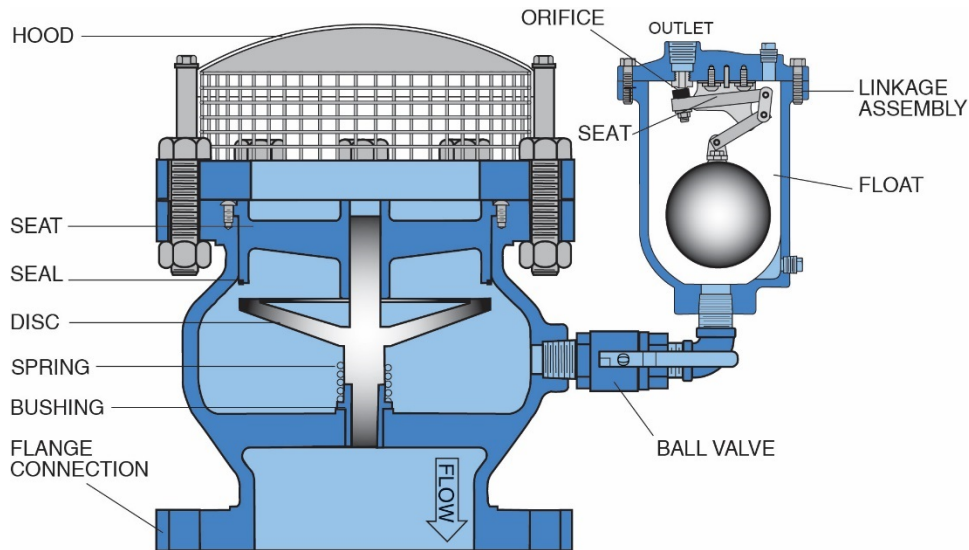


FIGURE 15. Vacuum Breaker and Air Release Valve

SUMMARY

Surges can cause contamination and damage to water systems and are prevalent in long pipelines. The importance of treating surge control as one integrated system cannot be emphasized enough. Consideration must be given to the Pump Control, Air Release, Check Valves, Air Valves, and Surge Relief equipment. Fast-closing check valves are an economical way of preventing pump back-spin without slamming, but may not be effective in preventing surges in long pipelines. Pump control valves such as hydraulically-operated ball valves provide more control of the velocity and are available in many types and several criteria should be evaluated to make the best selection.

Even with a control valve, though, a surge can be generated when the control valve closes rapidly after power failure to prevent pump backspin. Therefore, long pipelines may require additional surge control and surge relief equipment such as Surge Tanks, Surge Relief Valves, and Surge-Suppression Air Valves. Finally, it is important to use transient analysis software to model the system so that the system can be started up with confidence.

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