6.165.9. Shock and Water Hammer Loading

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Summary

Transients can introduce large pressure forces and rapid fluid accelerations into a piping system. These disturbances may result in pump and device failures, system fatigue or pipe ruptures, and even the backflow/intrusion of contaminated water. Many transient events can lead to column separation, which can result in catastrophic pipeline failures. Thus, transient

events cause health risks and can lead to increased leakage or decreased reliability. Transient flow simulation has become an essential requirement for assuring safety and the safe operation of drinking water distribution systems. This chapter introduces the concept and fundamentals of hydraulic transients, including the causes of transients, governing equations, numerical methods for predicting their location, magnitude and duration, and practical guidelines for their suppression and control. Such capabilities greatly enhance the ability of water utilities to evaluate cost-effective and reliable water supply protection and management strategies and safeguard public health.

1. Introduction

Water hammer and shock loading refer to rapid and often large pressure and flow fluctuations resulting from transient flow conditions in pipes transporting fluids. Transient flow analysis of the piping system is often more important than the analysis of the steady state operating conditions that engineers normally use as the basis for system design. Transient pressures are most significant when the rate of flow is changed rapidly, such as resulting from rapid valve closures or pump stoppages. Such flow disturbances, whether caused by design or accident, may create traveling pressure and velocity waves of excessive magnitude. These transient pressures are superimposed on the steady state (static) conditions present in the line at the time the transient occurs. The total force acting within a pipe is obtained by summing the steady state and transient pressures in the line. The severity of transient pressures must thus be accurately determined so that the pipes can be properly designed to withstand these additional shock loads. In fact, pipes are often characterized by their "pressure ratings" (or pressure classes) that define their mechanical strength and have a significant influence on their cost.

Transient events have been responsible for equipment failure, pipe rupture, separation at bends, and the backflow of dirty liquid into the distribution system via intrusion. High-flow velocities can remove protective scale and tubercles and increase the contact of the pipe with oxygen, all of which will increase the rate of corrosion. Uncontrolled pump shutdown can lead to the undesirable occurrence of water-column separation, which can result in catastrophic pipeline failures due to severe pressure rises following the collapse of the vapor cavities. Vacuum conditions can create high stresses and strains that are much greater than those occurring during normal operating regimes. They can cause the collapse of thin-walled pipes or reinforced concrete sections, particularly if these sections were not designed (i.e., pipes with a low pressure rating) to withstand such strains.

Cavitation occurs when the local pressure is lowered to the value of vapor pressure at the ambient temperature. At this pressure, gas within the liquid is gradually released and the liquid starts to vaporize. When the pressure recovers, liquid enters the cavity caused by the gases and collides with whatever confines the cavity (i.e., another mass of liquid or a fixed boundary) resulting in a pressure surge. In this case, both vacuum and strong pressure surges are present, a combination that may result in substantial damage. The main difficulty here is that accurate estimates are difficult to achieve, particularly because the parameters describing the process are not yet determined during design. Moreover, the vapor cavity collapse cannot be effectively controlled. In less drastic cases, strong pressure surges may cause cracks in internal lining, damage connections between pipe sections, and destroy or cause deformation to equipment such as pipeline valves, air valves, or other surge protection devices. Sometimes the damage is not realized at the time, but results in

intensified corrosion that, combined with repeated transients, may cause the pipeline to collapse in the future.

Transient events can have significant water quality and health implications (Boulos et al 2006, 2005; National Research Council 2006). These events can generate high intensities of fluid shear and may cause resuspension of settled particles as well as biofilm detachment. Moreover, low pressure transients may promote the collapse of water mains, leakage into the pipes at loose joints, cracks and seals under sub-atmospheric conditions, and backsiphonage and potential intrusion of untreated, possibly contaminated groundwater in the distribution system. Pathogens or chemicals in close proximity to the pipe can become a potential contamination source, where continuing consumption or leakage can pull contaminated water into the depressurized main. Recent studies have confirmed that soil and water samples collected immediately adjacent to water mains can contain high fecal coliform concentrations and viruses (Kirmeyer et al 2001; Karim et al 2003). This is especially significant in systems with pipes below the water table. LeChevallier et al (2003) reported the existence of low and negative pressure transients in a number of distribution systems. Gullick et al (2004) studied intrusion occurrences in actual distribution systems and observed 15 surge events that resulted in a negative pressure. Friedman et al (2004) confirmed that negative pressure transients can occur in the distribution system and that the intruded water can travel downstream from the site of entry. Locations with the highest potential for intrusion were sites experiencing leaks and breaks, areas of high water table, and flooded air-vacuum valve vaults. In the event of a large intrusion of pathogens, the chlorine residual normally sustained in drinking water distribution systems may be insufficient to disinfect contaminated water, which can lead to damaging health effects. A recent case study in Kenya (Ndambuki 2006) showed that in the event of a 0.1% raw sewage contamination, the available residual chlorine within the distribution network will not render the water safe.

Transient events that can allow intrusion to occur are caused by sudden changes in liquid velocity due to loss of power, sudden valve or hydrant closure or opening, a main break, fire flow, or an uncontrolled change in on/off pump status (Boyd et al 2004). Transient-induced intrusions can be minimized by knowing the causes of pressure surges, defining the system's response to surges, and estimating the system's susceptibility to contamination when surges occur (Friedman et al 2004). Therefore, water utilities should never overlook the effect of pressure surges in their distribution systems. Even some common transient protection strategies, such as relief valves or air chambers, if not properly designed and maintained, may permit pathogens or other contaminants to find a "back door" route into the potable water distribution system. Any optimized design that fails to properly account for pressure surge effects is likely to be, at best, suboptimal, and at worst completely inadequate.

Pressure transients in liquid distribution systems are inevitable and will normally be most severe at pump stations and control valves, in high-elevation areas, in locations with low static pressures, and in remote locations that are distanced from overhead storage (Friedman et al 2004). All systems will, at some time, be started up, switched off, undergo unexpected flow changes, and will likely experience the effects of human errors, equipment breakdowns, earthquakes, or other risky disturbances. Although transient conditions can result in many abnormal situations and breaches in system integrity, the engineer is most concerned with those that might endanger the safety of a plant and its personnel, that have

the potential to cause equipment or device damage, or that result in operational difficulties or pose a risk to the public health.

Transient pressures are difficult to predict and are system dependent, including specific system layout, configuration, design and operation. Engineers must carefully consider all potential dangers for their pipe designs and estimate and eliminate the weak spots. They should then embark upon a detailed transient analysis to make informed decisions on how best to strengthen their systems and ensure safe, reliable operations (McInnis and Karney 1995; Karney and McInnis 1990).

2. Causes of Fluid Transients

Fluid transient events are disturbances in the liquid caused during a change in operation, typically from one steady state or equilibrium condition to another (Figure 6-1). The principal components of the disturbances are pressure and flow changes at a point that cause propagation of pressure waves throughout the distribution system. The pressure waves travel with the velocity of sound (acoustic or sonic speed), which depends on the elasticity of the liquid and that of the pipe walls. As these waves propagate, they create transient pressure and flow conditions. Over time, damping actions and friction reduces the waves until the system stabilizes at a new steady-state. Normally, only extremely slow flow regulation can result in smooth transitions from one steady-state to another without large fluctuations in pressure or flow.

Figure 6-1: Example steady state transition after a period of rapid transients.

In general, any disturbance in the liquid generated during a change in mean flow conditions will initiate a sequence of transient pressures (waves) in the liquid distribution system. Disturbances will normally originate from changes or actions that affect fluid devices or boundary conditions. Typical events that require transient considerations include:

- pump shutdown or pump trip (loss of power)
- pump start-up
- valve opening or closing (variation in cross-sectional flow area);
- changes in boundary pressures (e.g., losing overhead storage tank, adjustments in the liquid level at reservoirs, pressure changes in tanks, etc.);
- rapid changes in demand conditions (e.g., hydrant flushing);
- changes in transmission conditions (e.g., main break or line freezing);
- pipe filling or draining – air release from pipes; and
- check valve or regulator valve action

If special precautions are not taken, the magnitude of the resulting transient pressures can be sufficient to cause severe damage. Figures 6-2 to 6-5 describe four typical hydraulic transient problems. The problem of shutting down a pump is illustrated in Figure 6-2. When the pump is suddenly shut, the pressure at the discharge side of the pump rapidly decreases and a negative pressure wave (which reduces pressure) begins to propagate down the pipeline toward the downstream reservoir. When the negative pressure wave reaches the high point (which already has a relatively low pressure due to the higher elevation) in the pipe, the pressure can drop below atmospheric to reach vapor pressure. At this pressure, gas

within the liquid is gradually released and the liquid starts to vaporize (column separation). On subsequent cycles of the transient when the pressure recovers, cavity can collapse generating a large pressure surge spike. On the suction side of the pump, the solid straight line represents the initial hydraulic grade and the dashed sloping line depicts the final hydraulic grade, while start-up transients are not shown.

Figure 6-2: Transient caused by pump start-up.

The problem of pump shutdown transient is illustrated in Figure 6-3. When a pump is started, the pressure at the discharge side of the pump rises sending a positive pressure wave (which increases pressure) down the pipeline toward the downstream reservoir. The resulting peak pressure can cause the pipe to collapse if the pressure rating of the pipe is less than the maximum surge pressure. When the initial positive pressure wave reaches the downstream reservoir, it is converted into a negative pressure wave which propagates back to the pump and may induce cavitation. On the suction side of the pump, the solid sloping line represents the initial hydraulic grade and the straight dashed line depicts the final hydraulic grade, while shutdown transients are not shown.

Figure 6-3: Transient caused by pump shut down.

Opening and closing a valve too fast can also result in severe hydraulic transients and are illustrated in Figures 6-4 and 6-5, respectively. When the valve in Figure 6-4 is rapidly opened, a negative pressure wave is initiated at the downstream valve and propagates upstream toward the reservoir decreasing the pressure in the pipe. Similar to the pump shut down scenario, the initial negative surge can drop to vapor pressure causing cavitation in the pipe. In the final example (Figure 6-5), rapidly closing the downstream valve generates a positive pressure wave at the valve that propagates toward the upstream reservoir increasing the pressure in the pipe.

Figure 6-4: Transient caused by rapid valve opening.

Figure 6-5: Transient caused by rapid valve closure.

Liquid distribution systems must be designed to handle both normal and abnormal operating conditions. If an analysis indicates that severe transients may exist, the main solution techniques generally used to mitigate transient conditions are (Boulos et al 2006):

- installation of stronger (higher pressure class) pipes
- re-routing of pipes
- improvement in valve and pump control/operation procedures;
- limiting the pipeline velocity;
- reducing the wave speed;
- increasing pump inertia; and
- design and installation of surge protection devices

3. Basic Pressure Wave Relations

3.1. Wave Action in Pipes

The relationship between pressure change (ΔP) and flow change (ΔQ), which is associated with the passage of a pressure wave, defines the transient response of the pipe system and forms the basis for the development of the required mathematical expressions. Figure 6-6 shows flow and pressure conditions, which exist a short time Δt apart, as a pressure wave of magnitude ΔP propagates a distance Δx in a liquid filled line.

Figure 6-6: Pressure wave propagation in a pipe.

During the short time Δt, the pressure on the left end of the liquid column is $P + \Delta P$ while the right end of the liquid column is P. This unbalanced pressure causes the fluid to accelerate. The momentum principle gives:

$$(P + \Delta P - P)A = r\Delta x \, {}^{\Delta Q}\!/_{\Delta t} \qquad \text{(6-1)}$$

where A is the pipe cross sectional area; r is the liquid density; and g is the acceleration of gravity. Canceling and rearranging give:

$$\Delta P = r\Delta Q \, {}^{\Delta x}\!/_{A\Delta t} \qquad \text{(6-2)}$$

The term ${}^{\Delta x}\!/_{\Delta t}$ is the propagation speed of the pressure wave. The wave speed is equal to the sonic velocity (c) in the system if the mean velocity of the liquid in the line is neglected. Since the mean velocity of the liquid is usually several orders of magnitude smaller than the sonic velocity, this is acceptable. Thus:

$$\Delta P = {}^{rc\Delta Q}\!/_{A} \qquad \text{(6-3)}$$

or in terms of pressure head:

$$\Delta H = {}^{c\Delta Q}\!/_{gA} \qquad \text{(6-4)}$$

or in a more general form

$$\Delta H = \pm \frac{c}{g} \Delta V \qquad \text{(6-5)}$$

where g is the acceleration of gravity. The resulting head rise equation is called the *Joukowsky* relation, sometimes called the fundamental equation of water hammer. The equation is derived with the assumption that head losses due to friction are negligible and no interaction takes place between pressure waves and boundary conditions at the end points of the pipe. The negative sign in this equation is applicable for a disturbance propagating upstream and the positive sign for one moving downstream. Typical values of c/g in Eq. 6-5 are large, often 100 or more. Thus, this relation predicts large values of head rise that highlights the importance of transient analysis. For example, if an initial velocity of

1 m/s is suddenly arrested at the downstream end of pipeline and c/g equals 100 s, a head rise of 100 m will result.
The sonic speed c for a liquid flowing within a line is influenced by the elasticity of the line wall. For a pipe system with some degree of axial restraint a good approximation for the wave propagation speed is obtained using:

$$c = \sqrt{E_f \,/\, r(1 + K_r E_f D / E_c t_l)} \tag{6-6}$$

where E_f and E_c are the elastic modulus of the fluid and conduit, respectively; D is the pipe diameter; t_l is the pipe thickness; and K_r is the coefficient of restraint for longitudinal pipe movement. Typically, three types of pipeline support are considered for restraint. These are:

Case a: The pipeline is restrained at the upstream end only.

$$K_R = 1 - m_p / 2 \tag{6-7}$$

Case b: The pipeline is restrained throughout.

$$K_R = 1 - m_P^2 \tag{6-8}$$

Case c: The pipeline is unrestrained (has expansion joints throughout).

$$K_R = 1 \tag{6-9}$$

where m_P is the Poisson's ratio for the pipe material. Table 6-1 lists physical properties of common pipe materials.

Table 6-1: Physical properties of common pipe materials.

3.2. Wave Action at Pipe Junctions

In a piping system, junction nodes have a significant impact on the direction and movement of pressures waves in the system. The effects of a pipe junction on pressure waves can be evaluated using conservation of mass and energy at the junction. Energy losses at the junction usually cause only minor effects and are neglected.
A wave of magnitude ΔH impinging in one of the junction legs, ***jin***, is transmitted equally to each adjoining leg (Figure 6-7). The magnitude of the waves is $T_{jin}\,\Delta H$ where the transmission coefficient, T_{jin}, is given by:

$$T_{jin} = \frac{2\left(\dfrac{g_{jin} A_{jin}}{c_{jin}}\right)}{\sum \dfrac{g_j A_j}{c_j}} \tag{6-10}$$

where the summation j refers to all pipes connecting at the junctions (incoming and outgoing). A reflection back in pipe ***jin*** occurs and is of magnitude $R_{jin}\ \Delta H$ where:

$$R_{jin} = T_{jin} - 1 \qquad (6\text{-}11)$$

For the simultaneous impingement of waves arriving in more than one leg the effects are superimposed.

Figure 6-7: Effect of a pipe junction on a pressure wave.

Eq. 6-10 provides the basis for quickly evaluating the effect of wave action at two special junction cases: dead end junctions and open ends or connections to reservoirs. A dead end is represented as a two pipe junction with A_2 equal to zero. With A_2 equal to zero, T_{jin} equals 2 and R_{jin} is 1 which indicates that the wave is reflected positively from the dead end. This condition implies that the effects of pressure waves on dead-ends can be of significant importance in transient consideration. If the pressure wave reaching the dead-end is positive, then the wave is reflected with twice the pressure head of the incident wave. If the pressure wave reaching the dead-end is negative then the wave reflection will cause a further decrease in pressure that can lead to the formation and collapse of vapor cavity. For a reservoir connection A_2 is infinite so T_{jin} is zero and R_{jin} equals -1 that represents that a negative reflection occurs at a reservoir.

3.3. Wave Action at Control Elements

A general analysis of pressure wave action at a control element (e.g., pump, valve, orifice) in a pipe system is described below. This analysis provides relations to account for a variety of situations.

Figure 6-8: Condition at a control element before and after action.

Figure 6-8 shows a general situation at a control element where pressure waves ΔH_1 and ΔH_2 are impinging. At the same time the characteristics of the control element may be changing. It is assumed that the relationship between flow through the control element, Q, and the pressure head change across the control element, ΔH, always satisfies a characteristic head-flow equation for the control element having the general form:

$$\Delta H = A(t) + B(t)Q + C(t)\,Q\left|Q\right| \qquad (6\text{-}12)$$

The terms A, B, and C represent the coefficients for a general representation of the characteristic equation. These coefficients may be time dependent but will be known (or can be determined) at all times. The absolute value of Q is employed to make the resistance term dependent on the flow direction. This representation applies to both passive resistance elements such as valves, orifices, fittings and friction elements and active elements such as pumps. For passive resistance elements; however, only the coefficient C representing the effect of irreversible loss is not zero. This coefficient represents the ratio of the head loss to the square of the flow through the control element. For hydraulic considerations this type of square law relationship is appropriate. The sign of the pressure head change is dependent on

the direction of flow through the control element that necessitates the use of the absolute value of the flow rate as presented in Eq. 6-12.

In Figure 6-8, subscripts 1 and 2 denote conditions on the left and right side of the control element before the impinging waves arrive, while the subscripts 3 and 4 designate these conditions at the control element after the wave action. Here, Q_b and Q_a are the flows before and after the wave action, respectively.

The basic transient flow relationship for pressure-flow changes is applied to incoming and outgoing waves to yield the following for the outgoing waves:

$$\Delta H_3 = \Delta H_1 + b_1(Q_b - Q_a) \qquad (6\text{-}13)$$

$$\Delta H_4 = \Delta H_2 + b_2(Q_a - Q_b) \qquad (6\text{-}14)$$

where

$$b_1 = \frac{c_1}{gA_1} \quad \text{and} \quad b_2 = \frac{c_2}{gA_2} \qquad (6\text{-}15)$$

Pressure heads after the action are given by:

$$H_3 = H_1 + \Delta H_1 + \Delta H_3 \qquad (6\text{-}16)$$

and

$$H_4 = H_2 + \Delta H_2 + \Delta H_4 \qquad (6\text{-}17)$$

The characteristic equation relating the pressure head change across and the flow through the control element after the action is:

$$H_4 - H_3 = A(t) + B(t)Q_a + C(t)Q_a\left|Q_a\right| \qquad (6\text{-}18)$$

The coefficients of the characteristic equation, $A(t)$, $B(t)$ and $C(t)$, represent the values at the time of the wave action and may vary with time.

Substituting Eqs. 6-16 and 6-17 into Eq. 6-18 and rearranging results in a quadratic relationship for Q_a or:

$$\begin{aligned} &C(t)Q_a\left|Q_a\right| + (B(t) - b_1 - b_2)Q_a \\ &+ A(t) + H_1 + 2\Delta H_1 - H_2 - 2\Delta H_2 + (b_1 + b_2)Q_b = 0 \end{aligned} \qquad (6\text{-}19)$$

Eq. 6-19 can be solved directly for Q_a using the quadratic formula or iteratively using the Newton-Raphson method. Eqs. 6-13 and 6-14 are then solved to give the magnitude of the pressure waves produced by the action and Eqs. 6-16 and 6-17 yield the pressure head after the action takes place.

This general analysis represents a wide variety of control elements that can be subject to a range of conditions.

3.3.1 Control Element Characteristics

The coefficients of the control element characteristic equation (6-12) are determined using head/flow operating data for the control element. Some control elements such as pumps will utilize all three coefficients to represent the head/flow variation. In some cases, the characteristic equation will be based on data, which represents the head/flow relationship for a relatively small range of operation. For these applications, the coefficients used for the control element analysis will be based on data valid for the operation in the vicinity of the operating point and will be recalculated as the operating point changes. This is true for the analysis of variable speed pumps and for pumps using data representing a wide range of operating conditions, including abnormal situations such as flow reversal.

Many control elements, such as valves, can be modeled using only the C coefficient. These are referred to as resistive control elements where the head/flow relation is adequately described by a single resistive term. For this application, the coefficient $C(t)$ is defined as the control element resistance. The term resistance is defined as the head drop divided by the square of the flow $(\Delta H / Q^2)$. Here, the head drop is in meters (feet) and the flow is in $m^3 s^{-1}$ ($ft^3 s^{-1}$).

The control element resistance is directly related to other resistive parameters such as minor loss (K_M), valve flow coefficient (C_v), sprinkler constant (K_s) and others, which characterize the head/flow characteristic of a resistive control element.

3.3.2. Wave Propagation with Friction

Since all pipeline systems contain friction, the pressure wave is attenuated as its travels down a line. Line loss can be simulated by concentrating the losses in length L at an orifice as shown in the figure below. This orifice will then partially transmit and reflect pressure waves and account for the effect of wall shear. The friction orifice will therefore attenuate a pressure wave in a manner similar to the total attenuation that will occur as the wave travels the length L in the pipe.

Figure 6-9: Wave propagation in a pipe section considering friction.

In this representation, the loss at the orifice is:

$$\Delta H = H_2 - H_1 = \left[-\frac{f\,L}{2gDA^2} \right] Q^2 = CQ^2 \qquad (6\text{-}20)$$

where f is the friction factor, g is the acceleration of gravity; D is the pipe diameter; and A is the pipe area.

In this case, the coefficients of the characteristic equation (Eq. 6-12) for the line friction orifice are:

$$A(t) = B(t) = 0 \qquad (6\text{-}21)$$

and

$$C(t) = -\frac{fL}{2gDA^2} \qquad (6\text{-}22)$$

The friction factor can be determined using the flow rate through the orifice prior to the wave action. Although variations in the fiction factor occur due to flow changes, this coefficient can be treated as a constant in most simulations (Wood et al 2005a). Although it is true that some approximation errors will be introduced using this approach, these errors can be minimized or eliminated using a distributed friction profile.

4. Governing Equations

The fundamental equations describing hydraulic transients in liquid distribution systems are developed from the basic conservation relationships of physics or fluid mechanics. They can be fully described by Newton's second law (equation of motion) and conservation of mass (kinematic relation). These equations can incorporate typical hydraulic devices and their interactions with the wave conditions in the pipes.

Applying these basic laws to an elementary control volume, a set of nonlinear hyperbolic partial differential equations can be derived. If x is the distance along the pipe centerline, t is the time and partial derivatives are represented as subscripts, then the governing equations for transient flow can be written as:

Continuity

$$H_t + \frac{c^2}{gA} Q_x = 0 \qquad (6\text{-}23)$$

Momentum (Dynamic)

$$H_x + \frac{1}{gA} Q_t - f(Q) = 0 \qquad (6\text{-}24)$$

where H is the pressure head (pressure/density), Q is the volumetric flow rate, c is the sonic wave speed in the pipe, A is the cross sectional area, g is the gravitational acceleration, and $f(Q)$ is a pipe resistance (nonlinear) term that is a function of flow rate.

Unfortunately, no analytical solution exists for these equations except for simple applications that neglect or greatly simplify the boundary conditions and the pipe resistance term. When pipe junctions, pumps, surge tanks, air vessels and other hydraulic components are included, the basic equations are further complicated. As a result, numerical methods are used to integrate or solve the transient flow equations (Wylie and Streeter 1993; Tullis 1989; Chaudhry 1987).

5. Numerical Solutions of Transients

A transient flow solution can be obtained numerically by solving Eqs. 6-23 and 6-24 (along with the appropriate initial and boundary conditions) in which pressure and flow are variables dependent upon position and time. Five different numerical procedures are commonly used to approximate the solution of the governing equations. Three Eulerian methods update the hydraulic state of the system in fixed grid points as time is advanced in uniform increments. The two Lagrangian methods update the hydraulic state of the system at fixed or variable time intervals at times when a change actually occurs. Each method

assumes that a steady-state hydraulic solution is available that gives initial flow and pressure distributions throughout the system.

The Eulerian methods consist of the explicit method of characteristics, explicit and implicit finite difference techniques, and finite element methods. In closed conduit applications, by far the most popular of these techniques is the method of characteristics (MOC). The method of characteristics is the most accurate in its representation of the governing equations.

All characteristics methods convert the two partial differential equations of motion and continuity (Eqs. 6-23 and 6-24) into four total differential equations (that are then expressed in a finite difference form. When finite difference and finite element techniques are used, the derivatives in the governing equations are replaced with approximate difference quotients. By contrast, in the method of characteristics, only the nonlinear friction term needs to be approximated (which is typically done by a linear difference term). Explicit finite difference schemes have also significant restrictions on the maximum time step to achieve stable solutions. Although implicit methods usually overcome the stability limitations, they require a simultaneous solution for every unknown in the problem at each time step.

The second important distinction between the Eulerian methods is that only the method of characteristics explicitly links the time step to the space step, giving this fixed grid approach somewhat of a Lagrangian flavor. The main drawback of the method of characteristics is that the time step used in the solution must be common (fixed) to all pipes. In addition, the method of characteristics requires the distance step in each pipe to be a fixed multiple of the common time interval, further complicating the solution procedure.

In practice, pipes tend to have arbitrary lengths and it is seldom possible to satisfy exactly both the time interval and distance step criteria. This "discretization problem" requires the use of either interpolation procedures (that have undesirable numerical properties) or distortions of the physical problem (that introduces an error of unknown magnitude). Finally, in order to satisfy stability criteria and ensure convergence, the method of characteristics requires a small time step. The stability criterion is developed by neglecting the nonlinear friction term and is referred to as the *Courant* condition. The Courant condition relates the computational time increment (Δt) to the spatial grid size (Δx). A numerical scheme is stable if and only if $|\Delta x| \geq c\,|\Delta t|$. In other words, the Courant conditions require that the numerical distance a wave propagates $|\Delta x|$ must exceed the physical propagation distance $c|\Delta t|$.

The Lagrangian approach solves the transient flow problem in an event oriented system simulation environment. In this environment, the pressure wave propagation process is driven by the distribution system activities. The Wave Characteristic Method (WCM) is an example of such an approach (Wood et al 1966; Boulos et al 2006; Wood et al 2005a). The method tracks the movement of pressure waves as they propagate throughout the system and computes new conditions at either fixed time intervals or only at times when a change actually occurs.

The Lagrangian approach normally requires orders of magnitude fewer pressure and flow calculations, allowing very large liquid distribution systems to be solved in an expeditious manner, and has the additional advantage of using a simple physical model as the basis for its development. As such, practicing engineers can gain a better understanding of the mechanics of transient pipe flow. Finally, because the Lagrangian solution scheme is continuous in both time and space, the method is less sensitive to the structure of the

network and to the length of the simulation process itself and results in improved computational efficiency.
Both the Eulerian method of characteristics and the Lagrangian wave characteristic method will almost always produce the same results when using the same data and model to the same accuracy. The main difference is in the number of calculations, in which the wave characteristic method has an advantage. The MOC requires calculations at interior points to handle the wave propagation and the effects of line friction. The WCM handles these effects using pressure waves. Therefore, for the same modeling accuracy, the WCM will generally require fewer calculations and provide faster execution times. In addition, the number of calculations per time step does not increase for the WCM when greater accuracy is required. The WCM is therefore more suitable for analyzing large liquid distribution systems. An excellent comparison of the various methods can be found in Boulos et al (1990, 2006) and Wood et al (2005a-b).

6. Methods of Controlling Transients

The means of controlling pressure transients in liquid distribution systems will generally depend upon whether the initiating event results in an *upsurge* (e.g., a high pressure event caused by a shutdown of a downstream pump or valve) or a *downsurge* (e.g., a low pressure event caused by the failure of an upstream pump or valve closure). Downsurge events can lead to the undesirable occurrence of liquid-column separation (cavitation) that can result in severe pressure surges following the collapse of a vapor cavity or intrusion of contaminated liquid through a leak or other opening.
A number of surge protection devices are commonly used to help control starting and stopping transients in pipe systems. No two systems are completely identical; hence the ultimate choice of surge protection devices and operating strategies will usually differ. Of course, it is always best whenever possible to avoid rapid flow changes. A transient analysis should be carried out to predict the effect of each individually selected device. Due to the complex nature of transient behavior, a device intended to suppress or fix a transient condition could result in a worsening of the condition if the device is not properly selected or located in the system. Designers must evaluate the relative merits and shortcomings of all the protection devices that they may select. A combination of devices may prove to be the most desirable and economical. A brief overview of various surge protection devices and their functions is provided in Figure 6-10 and in the following discussions.

Figure 6-10: Common surge protection devices.

6.1. Devices and Systems

6.1.1. Simple Surge Tank (Open)

Open surge tanks or stand-pipes can be an excellent solution to both upsurge and downsurge problems. These tanks can be installed only at locations where normal static pressure heads are small. They serve two main purposes: a) to prevent high pressures following shutdowns by accepting liquid; or b) to prevent cavitation during start-up by providing liquid to a low-pressure region.

6.1.2. Surge Vessel (Air Chamber – Closed Surge Tank – Bladder Tank – Hybrib Tank)

Surge vessels or air chambers have the advantage that they can be installed anywhere along a line regardless of normal pressure head. They serve the same function as an open surge tank but respond faster and allow a wider range of pressure fluctuation. Their effect depends primarily on their location, vessel size, entrance resistance and initial gas volume and pressure. Closed surge vessels are normally equipped with an air compressor to control the initial gas volume and to supply make-up air, which is absorbed by the liquid. Some closed surge tanks are equipped with a pre-charged pressurized bladder (bladder surge tanks) that eliminates the need for an air compressor. Hybrid tanks are equipped with an air vent that admits air when the pressure goes below atmospheric pressure.
Surge vessels often provide effective protection against pressure surges in piping systems. These vessels are normally positioned at pump stations (downstream of the pump delivery valve) to provide protection against a loss of power to the pump. Several types of surge vessels are available.

- **Compressor (Air) Vessel:** This vessel is equipped with a compressor to maintain the desired initial liquid level (and air volume) under normal operating conditions.
- **Bladder Tank:** This vessel has a bladder that is pre-charged to a predetermined pressure to maintain the desired air volume under normal operating conditions.
- **Hybrid Tank with Air Compressor:** This vessel behaves the same as the compressor vessel until the air pressure drops to atmospheric pressure. At that time, air is admitted through a vent at the top of the tank. The compressor is required to maintain the desired air volume under normal operating conditions.
- **Hybrid Tank with Dipping Tube:** This vessel provides the same functionality as one equipped with the air compressor without requiring the compressor. The dipping tube is a vertical pipe inside the surge tank which controls the closure of the air vent when the tank is filling and the length of the dipping tube is varied to maintain the desired air volume under normal operating conditions.

6.1.3. Feed Tank (One Way Surge Tank)

The purpose of feed tanks is to prevent initial low pressures and potential liquid-column separation by admitting liquid into the pipe subsequent to a downsurge. They can be either open or closed, can have a check valve to allow flow only into the pipe system, and can be installed anywhere on the line.

6.1.4. Pressure Relief Valve

A pressure relief valve ejects liquid out of a side orifice to prevent excessive high-pressure surges. The valve is activated when the line pressure at a specified location (not necessarily at the valve) reaches a preset value. Valve closure is initiated at a second prescribed head that is often around 20% lower than the activating head. The valve opens and closes at prescribed rates over which the designer often has some degree of control. The valves can eject liquid into the atmosphere or a pressurized region, or into an open or closed surge tank.

6.1.5. Surge Anticipation Valve

A surge anticipation valve is much like a pressure relief valve, but it can also be triggered to open on a downsurge in pressure (sensed at a specified location) in anticipation of an upsurge to follow. This valve, when activated, follows and completes a cycle of opening and closing based on valve opening and closing rates. For systems for which liquid-column separation will not occur, the surge anticipation valve can solve the problem of upsurge at the pump due to reverse flow or wave reflection. However, this valve must always be used with caution for it can make low pressure conditions in a line worse than they would be without the valve.

6.1.6. Air Release/Vacuum Valve

Air release/vacuum breaking valves are installed at high points in a pipeline to prevent low pressure (cavitation) by emitting air into the pipe when the line pressure drops below atmospheric conditions. The air is then expelled (ideally at a lower rate) when the line pressure exceeds atmospheric pressure. Two stage air valves release the air through a smaller orifice to prevent the "air slam" that occurs when all the air is released and the liquid column rejoins. A three stage air valve can be designed to release the air through a second (smaller) orifice to further reduce the "air slam."

6.1.7. Check Valve

A check valve allows flow only in one direction and closes when flow reversal is impending. For transient control, check valves are usually installed with other devices such as a pump bypass line as described below. Pumps are often equipped with a check valve to prevent flow reversal. Because check valves do not close instantaneously it is possible that a substantial backflow may occur before closure that can produce additional and sometimes large surges in the system. Check valve modeling includes a time delay between check valve activation and complete closure of the check valve. The check valve is often treated as a valve closing in a linear fashion that is activated by flow reversal and closes completely over the delay period. One of the great advantages of a check valve is that it can prevent pipes from draining, and keeping the pipe full of fluid tends to reduce start-up transients.

6.1.8. Pump Bypass Line

In low-head pumping systems that have a positive suction head, a bypass line around the pumps can be installed to allow liquid to be drawn into the discharge line following power failure and a downsurge. Bypass lines are generally short line segments equipped with a check valve (non- return valve) preventing back flow (from the pump discharge to the suction side) and installed parallel to the pump in the normal flow direction. They are activated when the pump suction head exceeds the discharge head. They prevent high-pressure buildup on the pump suction side and cavitation on the pump discharge side.

6.2. Choice of Surge Protection Strategy

A number of techniques can be used for controlling/suppressing transients in liquid distribution systems. Some involve system design and operation while others are related to the proper selection of surge protection devices. For example pressure relief valves, surge anticipation valves, surge vessels, surge tanks, pump bypass lines or any combination of them can be used to control maximum pressures. Minimum pressures can be controlled by increasing pump inertia or by adding surge vessels, surge tanks, air release/vacuum valves, pump bypass lines or any combination of that group. The overriding objective is to reduce the rate at which changes to the flow occur.

Surge protection devices will normally be installed at or near the point where the disturbance is initiated such as at the pump discharge or by the closing valve (with the exception of air relief/vacuum breaking valves and feed tanks). Figure 6-11 illustrates typical locations for the various surge protection devices in a liquid distribution system. When developing a protection strategy, it must be recognized that no two systems are hydraulically the same, hence, no general rules or universally applicable guidelines are available to eliminate pressure in liquid distribution systems. Surge protection devices and/or operating strategies must be chosen accordingly (Thorley 1991).

Figure 6-11: Typical locations for various surge protection devices.

The final choice will be based on the initial cause and location of the transient disturbance(s), the system itself, the consequences if remedial action is not taken and the cost of the protection measures themselves. A combination of devices may prove to be the most effective and most economical. Final checking of the adequacy and efficacy of the proposed solution should be conducted and validated using a detailed transient analysis.

7. Transient Modeling Considerations

Transient analysis of events occurring in piping systems requires many calculations and is an extremely demanding computational exercise. This is almost always carried out using transient modeling software. Having considered some of the detail of transient analysis and protection, it is perhaps helpful to conclude with some tips or guidelines that would assist in preparing a computer simulation files. In essence, the good news is that transient modeling uses much of the same data required for steady state modeling. A steady state analysis of the initial conditions for the transient analysis is required. There are, however a number of additional considerations for developing a transient analysis model.

- The precise location of hydraulic devices (pumps, control valves, check valves, regulating valves, etc.) is required for the model.
- Transient analysis can not accommodate exact pipe lengths so the analysis is carried out using a model with approximate pipe lengths. The length accuracy of the model (maximum difference between actual and model pipe lengths) must be sufficient to generate an accurate solution. However, increasing the accuracy will require a longer computational time.
- Cavitation must be modeled for transient analysis. If cavitation occurs at any location in the distribution system it can greatly affect the transient analysis results.
- Skeletonization guidelines are significantly different than those for steady state analysis. Dead end lines, for example, will have a very significant effect on a transient analysis while having no effect on the steady state analysis. Bong et al (2007) performed a

detailed study of the issues associated with liquid distribution model skeletonization for surge analysis. They concluded that skeletonization can introduce some significant error in estimating pressure extremes and can overlook liquid column separation and subsequent collapse at vulnerable locations in the distribution system.

- A transient model should carry out calculations at all local high and low points since the pressure extremes often occur at these locations.
- It is good practice to allow a transient model to operate at steady state for a short period before the transient is initiated. This provides additional assurance that the transient model is operating correctly.

8. Conclusions

Hydraulic transient, also called pressure surge or water hammer, is the means by which a change in steady state flow and pressure is achieved. When conditions in a liquid distribution network are changed, such as by closing a pump or a valve or starting a pump, a series of pressure waves are generated. These disturbances propagate with the velocity of sound within the medium until dissipated down to the level of the new steady state by the action of some form of damping or friction. In the case of flow in a liquid distribution network, these transients are the direct means of achieving all changes in velocity, gradual or sudden. When sudden changes occur, however, the results can be dramatic since pressure waves of considerable magnitude can occur and are quite capable of destroying equipments and pipelines. Only if flow regulation occurs very slowly is it possible to go smoothly from one steady state to another, without large fluctuations in pressure head or flow velocity.

Clearly, flow control actions can be extremely important and these actions have implications not only for the design of the hydraulic system, but also for other aspects of system operation and protection. Problems such as selecting the pipe layout and profile, locating control elements within the system, formulating operating rules as well as the ongoing challenges of system management are all influenced by the details of the control system. A rational and economic operation requires accurate data, carefully calibrated models, ongoing predictions of future demands and the response of the system to transient loadings, and correct selection of both individual components and remedial strategies. These design decisions cannot be considered an after-thought to be appended to a nearly complete design. Transient analysis is a fundamental and challenging part of rational network design.

Surge analysis is essential to good design and operation of piping systems. Surge modeling provides the most effective and viable means of predicting potentially negative impacts of hydraulic transients under a number of worst-case scenarios, identifying weak spots, and evaluating how they may possibly be avoided and controlled. The basis of surge modeling is the numerical solution of conservation of mass and linear momentum equations. A number of widely used computer codes based on Eulerian and Lagrangian numerical solution schemes are currently available and have been successfully validated against field data and exact analytical solutions. The accuracies of the methods are generally comparable although the Lagrangian solution scheme has been shown to be more computationally efficient and is therefore more suitable when solving large liquid distribution systems. However, surge analysis computer models can only be effective and reliable when used in conjunction with properly constructed and well calibrated hydraulic network models. Poorly defined and calibrated hydraulic network models may result in poor prediction of

pressure surges and locations of vapor cavity formation and, thus, defeat the whole purpose of the surge modeling process.

Looped liquid distribution systems comprising short length of pipes may be less vulnerable to problems associated with hydraulic transient than a single long pipe system. This is because wave reflections (e.g., at tanks, reservoirs, junctions) will tend to limit further changes in pressure and counteract the initial transient effects. For networks with long pipelines and irrespective of whichever numerical basis is used, a good transient model will have nodes along those pipes defining the important high and low points to ensure accurate calculations are made at those critical locations. An important consideration is dead ends (which may be caused by closure of control or check valves) which lock pressure waves into the system in a cumulative fashion (wave reflections will double both positive and negative pressures). As a result, the effects of dead ends need to be carefully evaluated in transient analysis.

Proper selection of components for surge control and suppression in liquid distribution systems requires a detailed surge analysis to be effective and reliable. In addition, good maintenance, pressure management and routine monitoring (e.g., high-speed pressure data loggers) programs are an essential component of transient protection. With these capabilities, water utility engineers can greatly enhance their ability to better understand and estimate the effects of hydraulic transients and to conceive and evaluate efficient and reliable water supply management strategies, safeguard their systems and public health with maximum effectiveness, and forge closer ties to their customers. It is understanding complexity through simplicity.

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Biographical Sketches

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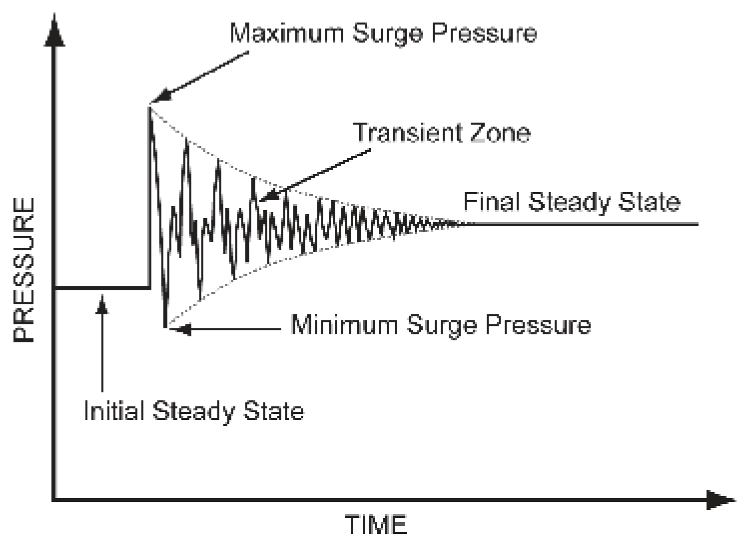

Figure 6-1: Example steady state transition after a period of rapid transients.

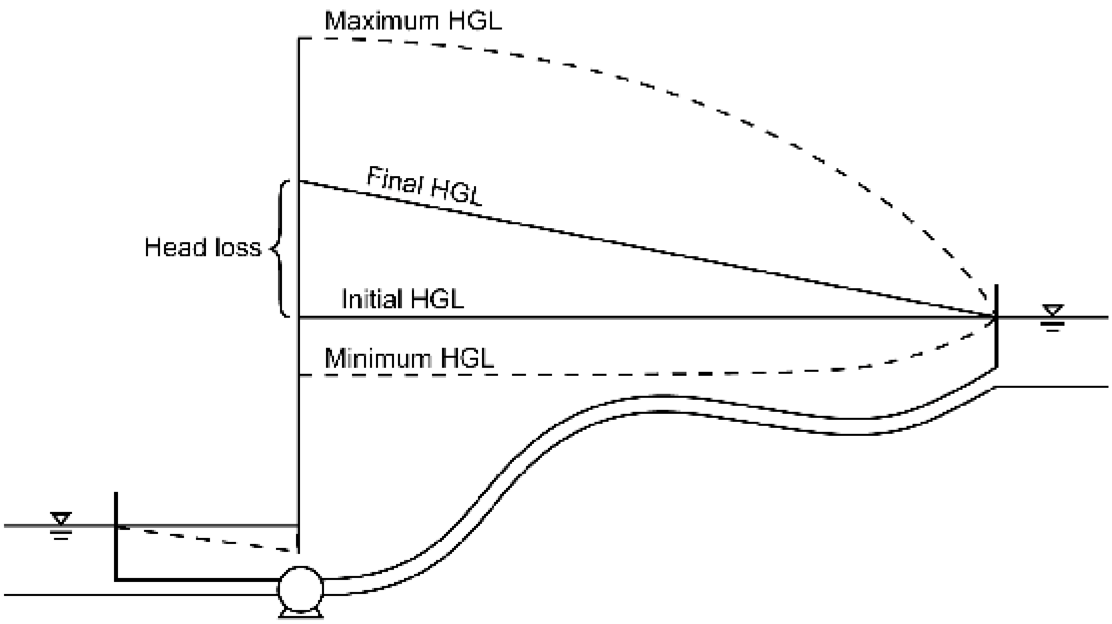

Figure 6-2: Transient caused by pump start-up.

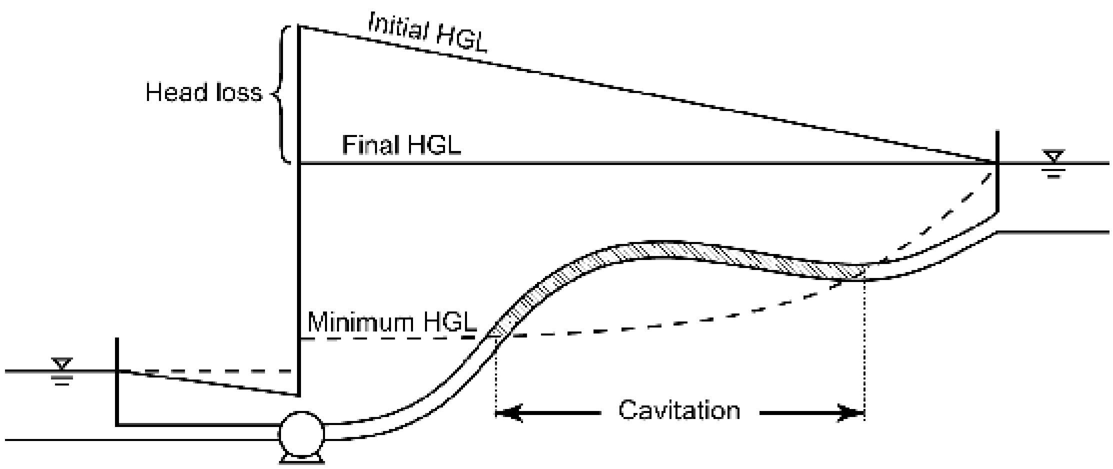

Figure 6-3: Transient caused by pump shut down.

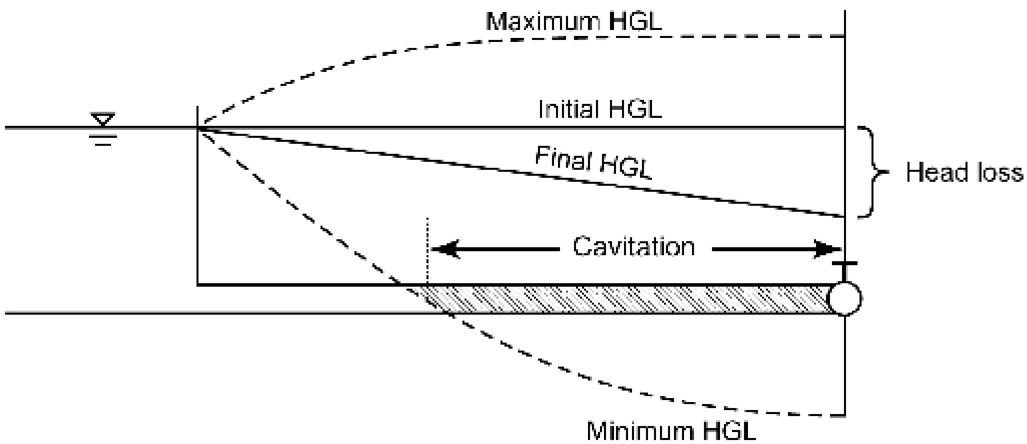

Figure 6-4: Transient caused by rapid valve opening.

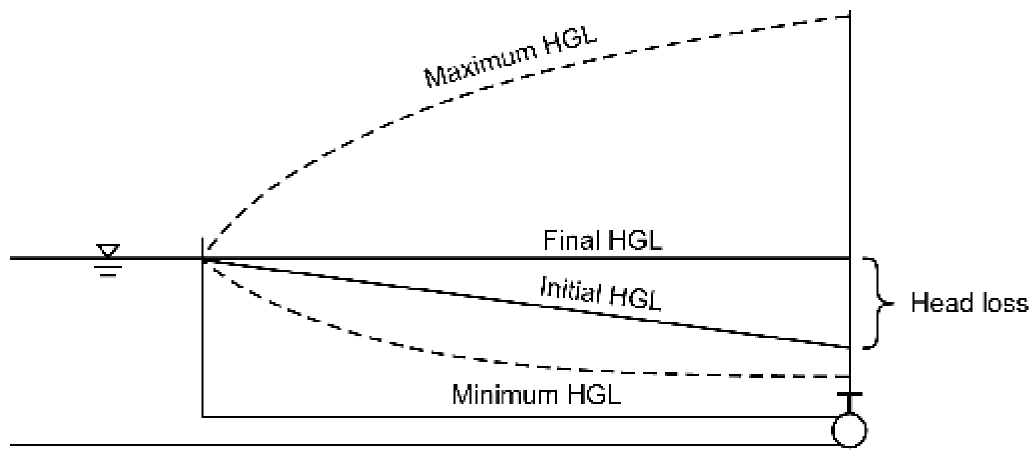

Figure 6-5: Transient caused by rapid valve closure.

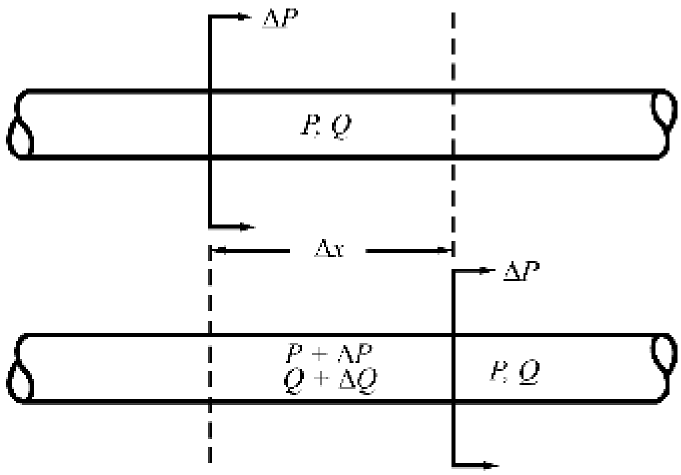

Figure 6-6: Pressure wave propagation in a pipe.

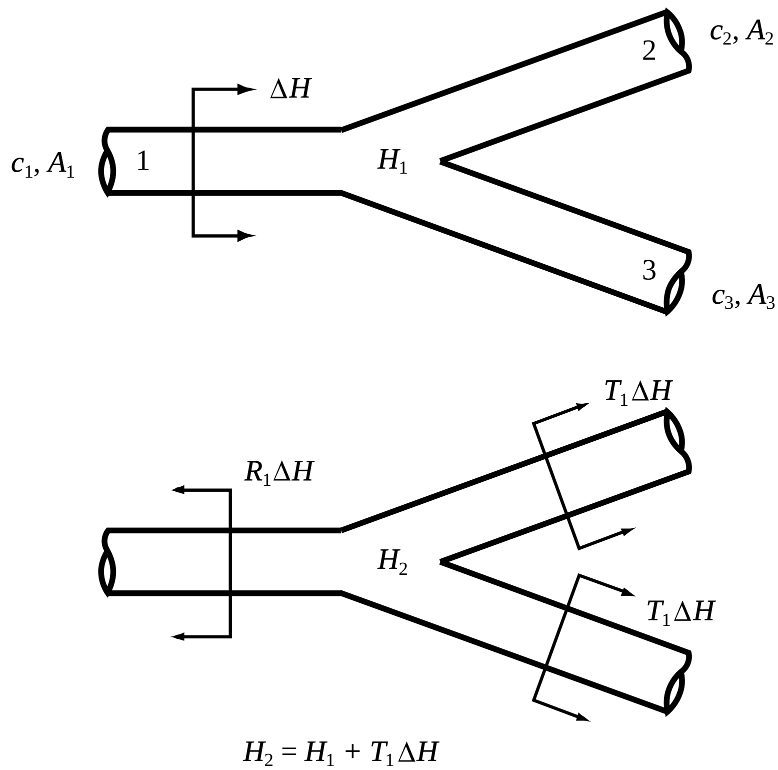

Figure 6-7: Effect of a pipe junction on a pressure wave.

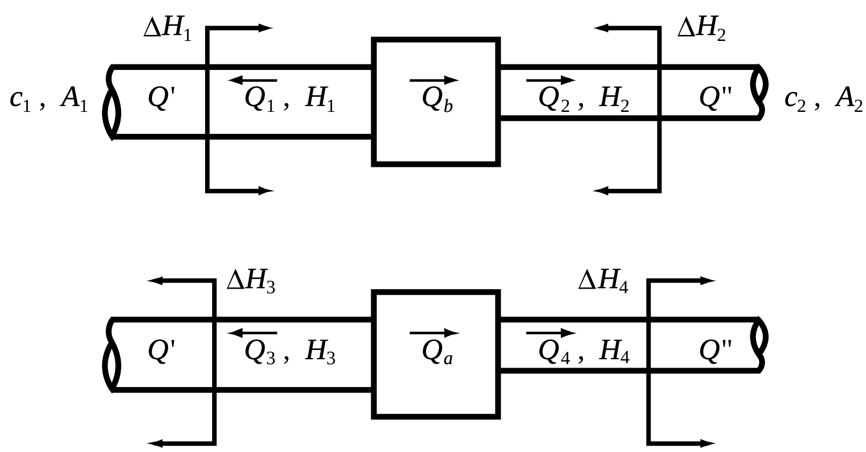

Figure 6-8: Condition at a control element before and after action.

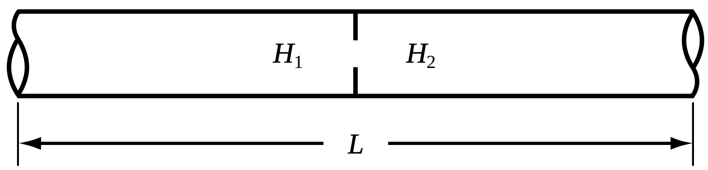

Figure 6-9: Wave propagation in a pipe section considering friction.

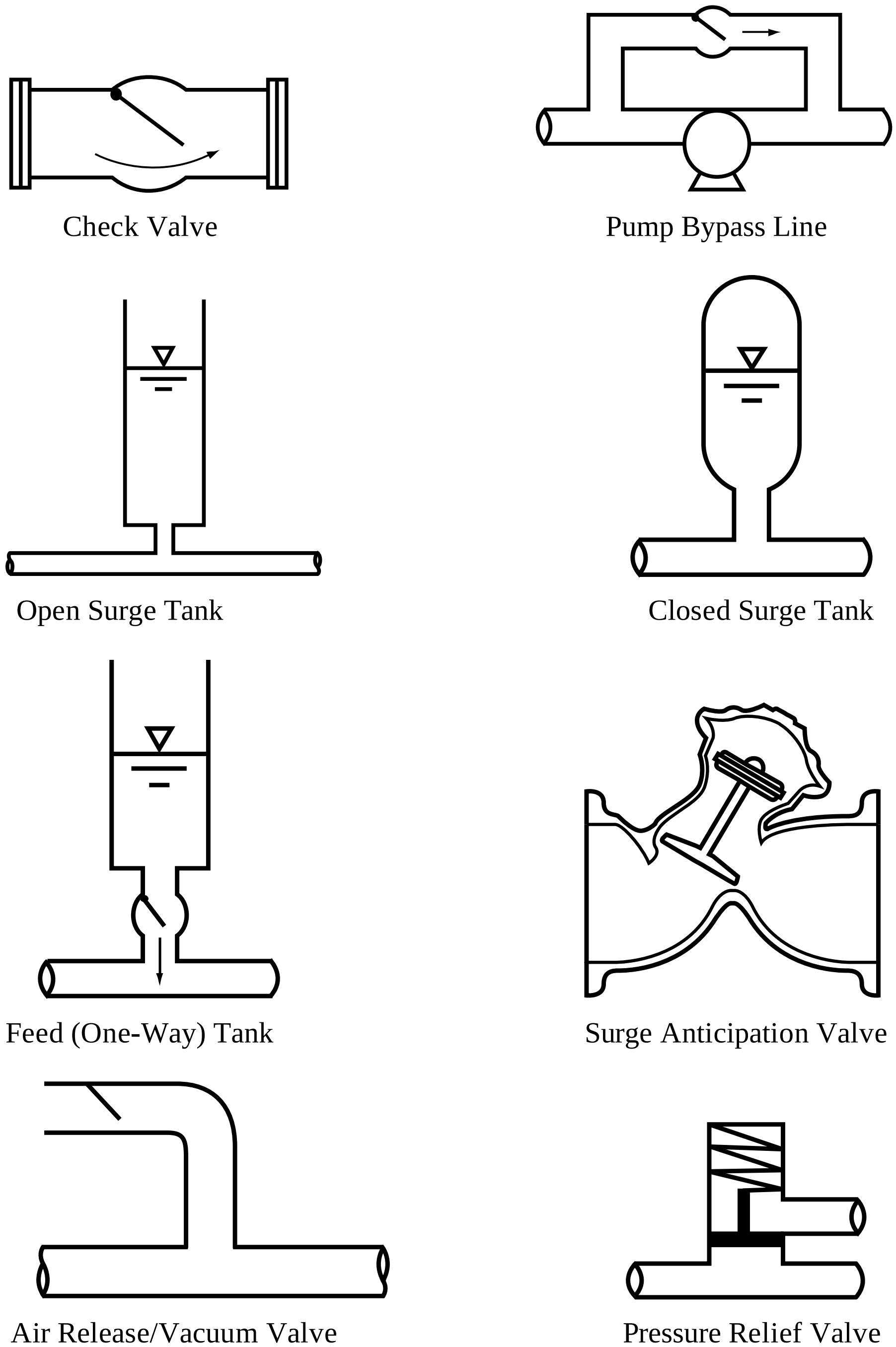

Figure 6-10: Common surge protection devices.

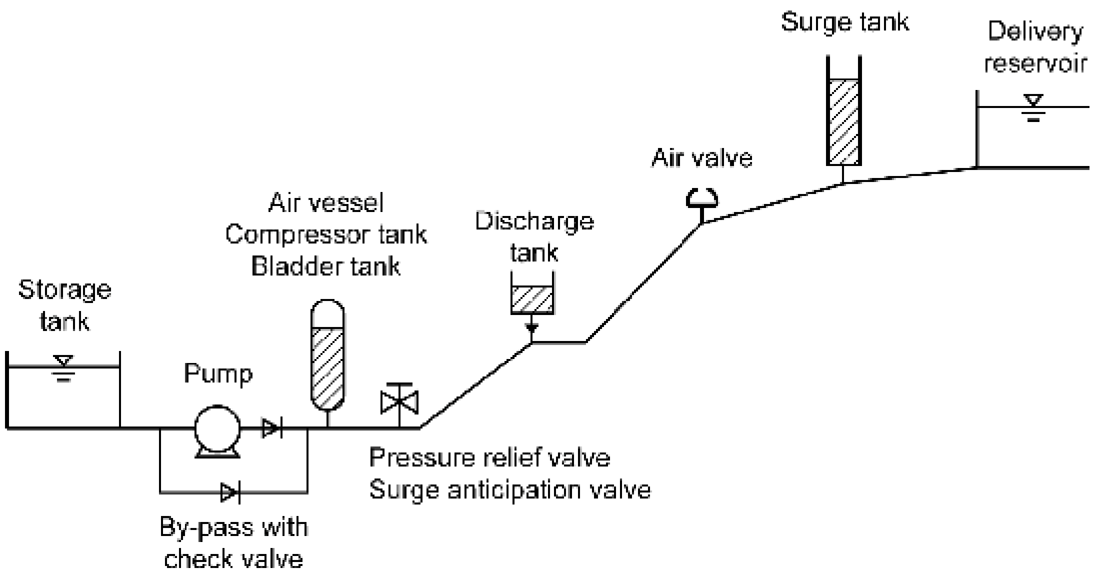

Figure 6-11: Typical locations for various surge protection devices.

Material	Young's Modulus E_c (GPa)	Poisson's Ratio μ_p
Asbestos Cement	23-24	-
Cast Iron	80-170	0.25-0.27
Concrete	14-30	0.1-0.15
Reinforced Concrete	30-60	-
Ductile Iron	172	0.3
PVC	2.4-3.5	0.46
Steel	200-207	0.30

Table 6-1: Physical properties of common pipe materials.