BY PAUL F. BOULOS,
BRYAN W. KARNEY,
DON J. WOOD,
AND SRINIVASA LINGIREDDY

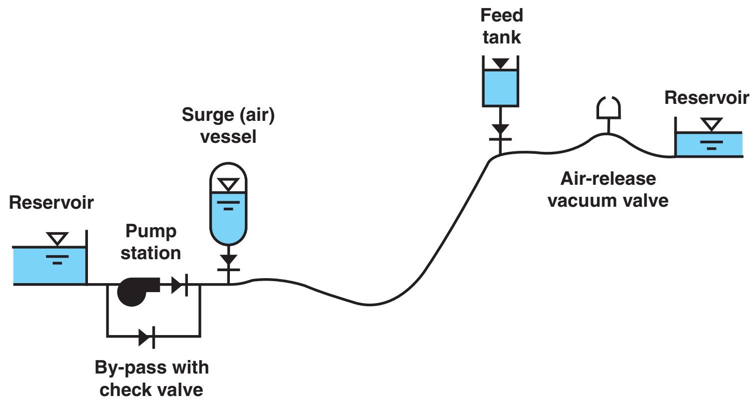
Transients can introduce large pressure forces and rapid fluid accelerations into a water distribution system. These disturbances may result in pump and device failures, system fatigue or pipe ruptures, and even the backflow/intrusion of dirty water. Many transient events can lead to water column separation, 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 ensuring safety and the safe operation of drinking water distribution systems. This article provides a basic understanding of the physical phenomena and context of transient conditions, presents practical guidelines for their suppression and control, and compares the formulation and computational performance of widely used hydraulic transient simulation schemes. Such capabilities greatly enhance the ability of water utilities to conceive and evaluate cost-effective and reliable water supply protection and management strategies and safeguard public health.

Hydraulic Transient Guidelines for Protecting Water Distribution Systems

Although transient flow is initially a challenging topic, most people have some first-hand experience with "water hammer" effects. A common example is the banging or hammering noise that is sometimes heard when a water faucet in a house is rapidly closed. Although great complexity sometimes arises, the mechanism in this simple example typifies all pipeline transients. The rapid closing of a valve converts the kinetic energy carried by the fluid into strain energy in the pipe walls, causing a "pulse wave" of abnormal pressure to travel from the disturbance into the pipe system. The hammering sound that is sometimes heard indicates that a portion of the fluid's original kinetic energy is converted not only into pressure but also into an acoustic form. This acoustic energy, as well as other energy losses (including fluid friction), causes the transient pressure waves to gradually decay until new steady pressures and velocities are again established.

Transient analysis of the performance of piping systems is often at least as important as the analysis of the steady-state operating conditions engineers usually use as the basis for system design. The total force acting within a pipe is obtained by summing the steady-state and transient pressures in the line. Tran-

FIGURE 1 Typical locations for various surge protection devices



sient pressures are most important when the rate of flow is changed rapidly, such as resulting from rapid valve closures or pump stoppages. Such disturbances, whether caused by design or accident, may create traveling pressure and velocity waves of large magnitude. These transient pressures are superimposed on the steady-state conditions present in the line at the time the transient pressure occurs. The severity of transient pressures must be determined so that the water mains can be properly designed to withstand these additional loads. In fact, pipes are often characterized by their "pressure ratings" that define their mechanical strength and have a significant influence on their cost.

CONSEQUENCES OF TRANSIENTS

Because transient waves are the mechanism for adjusting flow conditions, such events in water distribution systems are both inevitable and naturally occurring. However, transient events can be severe as well, possibly causing considerable damage, disruption, and expense. As a general rule, transient events are usually 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, 2003). Yet all systems will at some time be started up, switched off, or undergo flow changes, and so on, and will likely experience the effect of human errors, equipment breakdowns, earthquakes, or other risky disturbances. Although transient conditions can result in many situations, engineers are naturally most concerned with those that might endanger the safety of a plant and its personnel, have the potential to cause equipment or device damage, or result in operational difficulties.

TABLE 1 Primary attributes and design variables of key surge-protection approaches

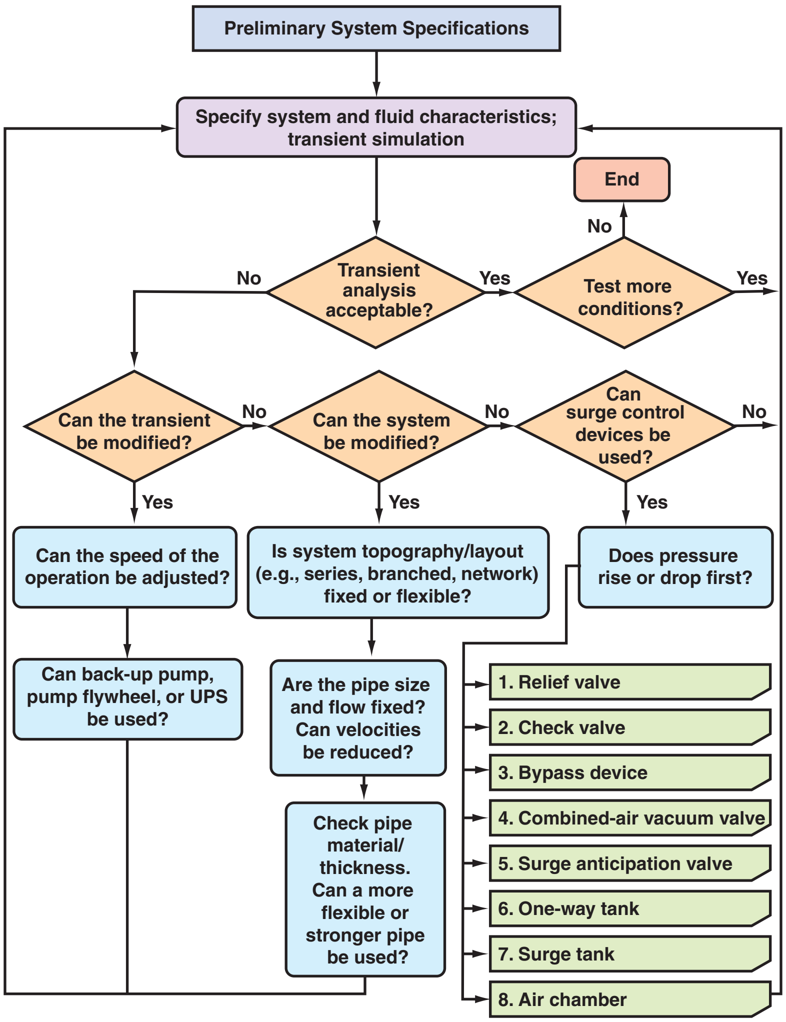
Protection Approach	Primary Attributes	Decision Variables
Check valve	Limits flow to one direction Permits selective connections Prevents/limits line draining	Size and location Specific valve configuration Antishock (dampening) characteristics
Pump bypass line	Permits direct connection and flow around a pump Can limit up-and-down surge	Size and location Exact points connected Check-valve properties
Open surge tank	Permits inflow/outflow to external storage May require water circulation Can limit up-and-down surge	Size and location Connection properties Tank configuration Overflow level
Closed surge tank (air chamber)	As pressure changes, water exchanged so volume of pressurized air expands or contracts Needs compressor	Location Volume (total/water/air) Configuration/geometry Orifice/connector losses
Feed tank (one-way tank)	Permits inflow into line from an external source Requires filling	Size and location Connection properties Tank configuration
Surge anticipation valve	Permits discharge to a drain Has both high- and low-pressure pilots to initiate action May accentuate downsurge	Size and location High- and low-pressure set points Opening/closing times
Combination air-release and vacuum-breaking valve	When pressure falls, large orifice admits air Controlled release of pressurized air through an orifice	Location Small and large orifice sizes Specific valve configuration
Pressure-relief valve	Opens to discharge fluids at a preset pressure value Generally opens quickly and closes slowly	Size and location High-pressure set point Opening/closing times

To identify and isolate conditions that deserve particular attention, engineers must first define the consequences of transient events that they fear most in a particular hydraulic system. These consequences could be any or all of the following (Pejovic et al, 1987):

- maximum pressure in the system;
- occurrence of local vacuum conditions at specific locations and/or cavitation, either within specific devices or within a pipe;
- hydraulic vibration of a pipe, its supports, or in specific devices and/or strong oscillations or rapid movement of the water masses; and
- risk or occurrence of contamination at cross-connections.

Maximum pressure in system. Maximum pressures during transient regimes may destroy pipelines, tunnels, valves, or other components, causing considerable damage and sometimes loss of human life. Less drastically, strong pressure surges may cause cracks in an internal lining, damage connections and flanges between pipe sections, or destroy or cause deformations to equipment (such as pipeline valves, air valves, or any water hammer protection device). Sometimes the damage is not noticed at the time but results in leakage and in intensified corrosion that over a period of time can significantly reduce the wall thickness and, when combined with repeated transients, may cause the pipeline to collapse.

FIGURE 2 Flowchart for surge control in water distribution systems



UPS—universal power supply

Vacuum conditions. If possible, vacuum conditions should be avoided, even at a high cost, because they can create high stresses and strains that are much greater than those occurring during typical operating regimes. Vacuum pressures may cause the collapse of thin-walled pipes or reinforced concrete sections, particularly if these sections are not designed to withstand such strains. These operational difficulties can occur in any pipeline system.

Cavitation. Cavitation occurs when the local pressure is lowered to the value of vapor pressure at the ambient temperature. At this pressure, gas within the water is gradually released and the water starts to vaporize. When the pressure recovers, water enters the cavity caused by the gases and collides with whatever confines the cavity (i.e., another mass of water 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 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.

Hydraulic vibrations. Strong hydraulic vibrations can damage pipelines, tunnels, tunnel internal linings, or measuring and control equipment, and even crumble concrete. Long-term moderate surges may gradually induce fatigue failures. Resonance is characteristic of any system forced near its natural frequency and is capable of destroying the entire system. Because it is virtually impossible, or at least expensive, to design a system

FIGURE 3 Schematic of pipe network for Example 1

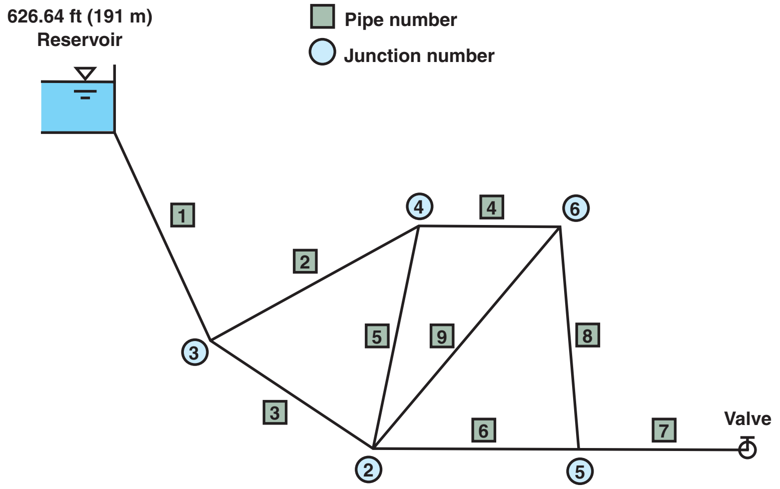
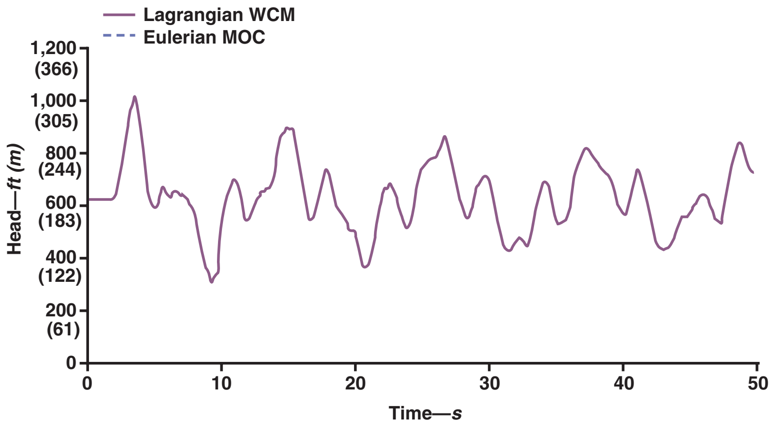


FIGURE 4 Head at node 3 for Example 1



MOC—method of characteristics
WCM—wave characteristic method

The Lagrangian WCM and the Eulerian MOC produced identical results indicated by the single line.

that withstands resonance, the only reasonable solution is to avoid it. Oscillations of the water masses between the reservoirs, basins, and water towers may cause noise, concussions, suction of air into the line, and other serious problems, including temporarily losing control of the system. If another incident happens to occur at the same time, the consequences could be disastrous. Accurate modeling is crucial, as neglecting some influences may lead to wrong conclusions and poor decisions.

Water quality and health implications. Transient events can also have significant water quality and health implications. These events can generate high intensities of fluid shear and may cause resuspension of settled particles as well as biofilm detachment. So-called "red water" events have often been associated with transient disturbances. Moreover, a low-pressure transient event, for example, arising from a power failure or pipe break, has the potential to cause the intrusion of contaminated groundwater into a pipe at a leaky joint or break. Depending on the size of the leaks, the volume of intrusion can range from a few gallons to hundreds of gallons (Funk et al, 1999; LeChevallier, 1999). Negative pressures induce backsiphonage of nonpotable water from domestic, industrial, and institutional piping into the distribution system. Dissolved air (gas) can also be released from the water whenever the local pressure drops considerably, and this may promote the corrosion of steel and iron sections with subsequent rust formation and pipe damage. 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. This further emphasizes the need to maintain an adequate level of disinfectant residual throughout the distribution system (LeChevallier, 1999; Trussell, 1999). Similarly, increasing overhead storage for surge protection (e.g., closed tank, open standpipe, feed tank, bladder tank) can result in long residence times, which in turn may contribute to water quality deterioration. These effects include chlorine residual loss and possible increases in the level of microorganisms (Clark et al, 1996). Proper operation and maintenance of these storage facilities are required to avoid poor quality water from entering the distribution system. Excellent reviews of the effects of pressure transients on distribution system water quality degradation are available in the literature (Wood et al, 2005; Gullick et al, 2004; Karim et al, 2003; LeChevallier et al, 2003; Kirmeyer et al, 2001; Funk et al, 1999; LeChevallier, 1999).

Engineers must carefully consider all potential dangers for their plants or designs and estimate and eliminate the weak spots. They should then embark on a detailed transient analysis to make informed decisions on how to best strengthen their systems and ensure safe, reliable operations (Karney & McInnis, 1990; McInnis & Karney, 1995). This article provides an introduction to the causes of transient events and explains how transient pressures can be controlled. Limited guidance is also provided for the analysis and computer simulation of such events.

CAUSES OF TRANSIENTS

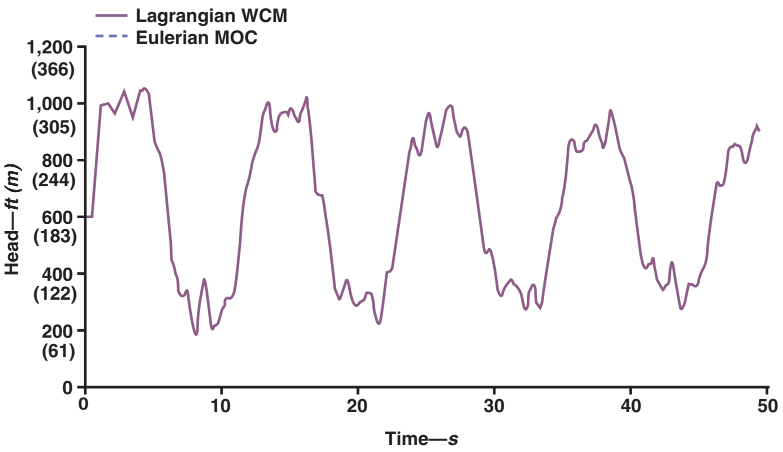
Hydraulic transient events are disturbances in the water caused during a change in state, typically effecting a transition from one steady or equilibrium condition to another. The principle components of the disturbances are pressure and flow changes at a point that cause propagation of pressure waves throughout the distribution system. The pressure waves travel with the velocity of sound (i.e., acoustic or sonic speed), which depends on the elasticity of the water and the elastic properties (e.g., material and wall thickness) of the pipe. As these waves propagate, they create a transient adjustment to the pressure and flow conditions throughout the system. Over time, damping actions and friction reduce the waves until the system stabilizes at a new steady state. Usually only extremely slow flow regulation can result in apparently smooth transitions from one steady state to another without obvious fluctuations in pressure or flow.

In general, any disturbance in the water caused during a change in mean flow conditions initiates a sequence of transient pressures (waves) in the water distribution system. Disturbances originate from changes or actions that affect hydraulic devices or boundary conditions. Typical events that require transient considerations include the following:

- pump startup or shutdown;
- valve opening or closing (variation in cross-sectional flow area);
- changes in boundary pressures (e.g., losing overhead storage tank, adjustments in the water level at reservoirs, pressure changes in tanks, and so on);
- rapid changes in demand conditions (e.g., hydrant flushing);
- changes in transmission conditions (e.g., main break or line freezing); and
- pipe filling or draining.

These disturbances can create serious consequences for water utilities if not properly recognized and addressed by proper analysis and appropriate design and operational considerations. Hydraulic systems must be designed to accommodate both normal and abnormal operations and be safeguarded to handle adverse external events such as power failure, pipeline fracture, and so on. The main design techniques generally used to mitigate transient conditions include:

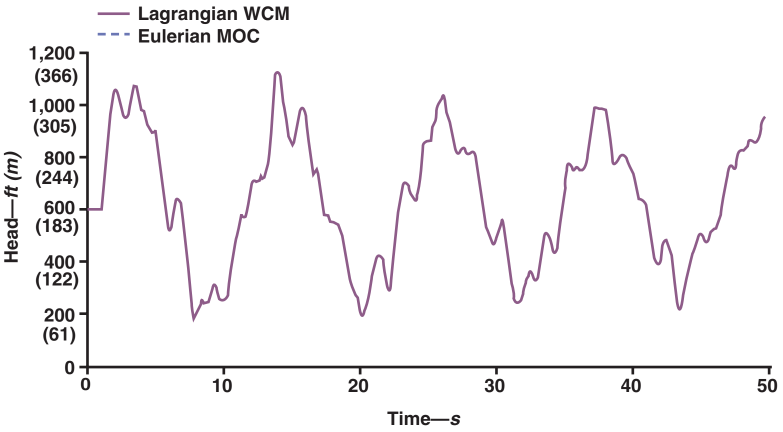
FIGURE 5 Head at node 5 for Example 1



MOC—method of characteristics
WCM—wave characteristic method

The Lagrangian WCM and the Eulerian MOC produced identical results indicated by the single line.

FIGURE 6 Head at node 6 for Example 1



MOC—method of characteristics
WCM—wave characteristic method

The Lagrangian WCM and the Eulerian MOC produced identical results indicated by the single line.

TABLE 2 Pipe characteristics for Example 1

Pipe Number	Length *ft (m)*	Diameter *in. (mm)*	Roughness	Minor Loss
1	2,000 (610)	36 (900)	92	0
2	3,000 (914)	30 (750)	107	0
3	2,000 (610)	24 (600)	98	0
4	1,500 (457)	18 (450)	105	0
5	1,800 (549)	18 (450)	100	0
6	2,200 (671)	30 (750)	93	0
7	2,000 (610)	36 (900)	105	0
8	1,500 (457)	24 (600)	105	0
9	1,600 (488)	18 (450)	140	0

- alteration of pipeline characteristics (e.g., pipe diameter),
- improvement in valve and pump control procedures, and
- design and installation of surge protection devices.

Hydraulic systems must be routinely started and stopped under normal operating conditions, but they can also sometimes suddenly trip out when unwanted events occur, such as a pump trip caused by a power failure, a pipeline fracture, an unintended valve closure, a sudden air release, or some similar event. Many systems and devices are designed specifically for preventing hydraulic water hammer effects. The proper selection and evaluation of these devices require a consistent transient analysis. The basic principles in the design of these systems include the following:

Transient events are usually 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.

- to estimate transients and to dimension system for the appropriate extreme stresses;
- to convert kinetic energy into potential (strain) energy in devices such as water towers, surge tanks, reservoirs, or air vessels;
- to add or remove a quantity of liquid at critical places of the system by using protective devices such as pressure regulators, relief valves, rupture disks, air chambers, surge tanks, water towers, one-way reservoirs, additional reservoirs, and so on;
- to admit air through suitable valves or aeration pipes, and later to vent the air through air valves;
- to change the natural frequency of the system or to change the frequency of excitation in order to prevent resonance; and
- to change (usually decrease) the wave speed in order to change (decrease) pressure oscillations during transients and to change the natural frequency of system.

The means of controlling pressure transients in water distribution systems will, in general, depend on whether the initiating event results in an upsurge (e.g., a high-pressure event caused by a closure of a downstream valve) or a downsurge (e.g., a low-pressure event caused by the failure of an upstream pump). Downsurge events can lead to the undesirable occurrence of water column separation, which itself can result in severe pressure surges following the collapse of a vapor cavity or the intrusion of contaminated water through a leak or other opening.

A number of surge protection devices are commonly used to help control transients in pipe systems. No two systems are completely identical and thus the ultimate choice of surge protection devices and choice of operating strategies usually differ. Of course, it is always best to avoid rapid flow changes whenever possible. A transient analysis should be carried out to predict the effect of each individually selected device. Because of the complex nature of transient behavior, a device intended to suppress or fix a transient condition could actually worsen the condition if the device is not properly selected or located in the system. Thus engineers must carefully evaluate the relative merits and shortcomings of all of the possible protection devices. A combination of devices may prove to be the most desirable and most economical.

A brief overview of various commonly used surge protection devices and their functions is provided in Figure 1, in Table 1, and in the following section. Additional details are available in Wood et al (2005), Boulos et al (2004), and Thorley (1991).

PRESSURE SURGE CONTROL DEVICES

Numerous protection devices have been invented to smooth the transition between states in a pipeline. The general principles of pressure surge control devices are to store water or otherwise delay the change in flow rate, or to discharge water from the line. Following is an overview of various common surge protection devices and their functions.

Simple surge tank (open). Open surge tanks or standpipes can be an excellent solution to both upsurge and downsurge problems. These tanks can be installed only at locations in which normal static pressure heads are small. They serve two main purposes:

- to prevent high pressures following shutdowns by receiving water or
- to prevent cavitation during start-up by providing water to a low-pressure region.

Surge vessel (air chamber, closed surge tank, bladder tank, hybrid tank). Surge vessels or air chambers have the advantage in 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 tanks are usually equipped with an air compressor to control the initial gas volume and to supply make-up air, which is absorbed by the water. Some closed surge tanks are equipped with a precharged 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.

TABLE 3 Pipe system characteristics for Example 2

Pipe Number	Length *ft (m)*	Diameter *in. (mm)*	Roughness	Minor Loss	Node Number	Demand *gpm (L/min)*
1	2,844 (867)	6 (150)	130	0	10	9 (34)
2	2,059 (628)	10 (250)	120	0	11	75 (284)
3	204 (62)	12 (300)	120	6.4	12	0
4	2,337 (712)	8 (200)	140	1.9	13	0
5	3,296 (1,005)	8 (200)	140	0	14	45 (170)
6	1,983 (604)	6 (150)	130	0	15	21 (79)
7	686 (209)	8 (203)	140	0	16	0
8	2,633 (803)	8 (200)	140	0	17	18 (68)
9	3,138 (956)	6 (150)	130	0	18	30 (114)
10	1,648 (502)	8 (200)	140	0	19	15 (57)
11	2,801 (854)	6 (150)	130	0	20	45 (170)
12	1,464 (446)	8 (200)	140	0	21	0
13	2,399 (731)	8 (200)	140	3.4	22	60 (227)
14	2,550 (777)	8 (200)	140	0	23	0
15	1,753 (534)	10 (250)	120	0	24	0
16	1,532 (467)	8 (200)	140	0	25	0
17	2,938 (896)	8 (200)	140	0		
18	1,942 (592)	8 (200)	140	0		
19	3,447 (1,051)	8 (200)	140	0		
20	1,270 (387)	6 (150)	130	0		
21	260 (79)	12 (300)	120	7.5		

Surge vessels often provide effective protection against pressure surges in piping systems. These vessels are often best 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 water level (and air volume) under normal operating conditions.

Bladder tank. This vessel has a bladder that is precharged 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.

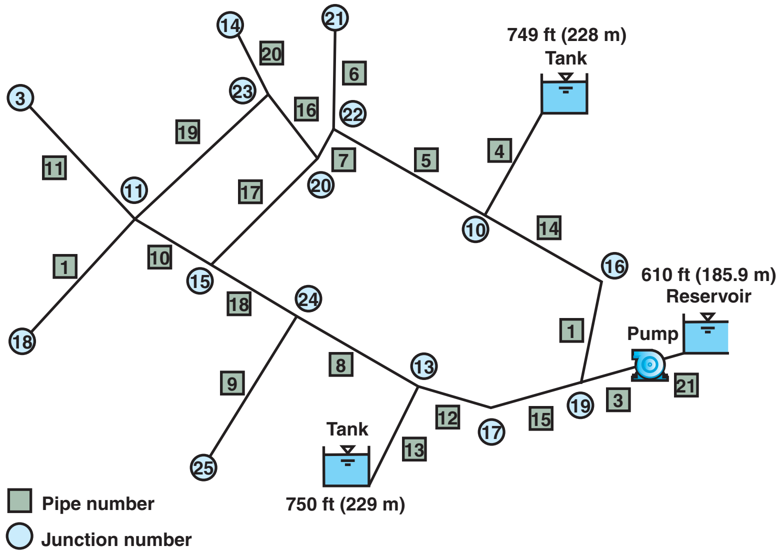
Hybrid tank with dipping tube. This vessel provides the same functionality as one equipped with the air compressor without requiring the compressor. The dipping tube controls the closure of the air vent when the tank is filling, and the length of the dipping tube is varied to maintain the desired air volume under normal operating conditions.

Feed tank (one-way surge tank). The purpose of a feed tank is to prevent initial low pressures and potential water column separation by admitting water into the pipe subsequent to a downsurge. Feed tanks 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.

Pressure-relief valve. A pressure-relief valve ejects water 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 about 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 water into the atmosphere, into a pressurized region, or into an open or closed surge tank.

Surge anticipation valve. A surge anticipation valve is much like a pressure-relief valve, but in addition it can be

FIGURE 7 Schematic of pipe network for Example 2



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 water column separation will not occur, the surge anticipation valve can solve the problem of upsurge at the pump caused by reverse flow or wave reflection. However, a surge anticipation 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.

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 of the air is released and the water column rejoins. A three-stage air valve is designed to release the air through a second (smaller) orifice to further reduce the air slam.

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 (described next). Pumps are also often equipped with a check valve to prevent flow reversal. Because check valves do not close instantaneously, it is possible that before closure a substantial backflow may occur that can produce additional and sometimes large surges in the system. Check-valve modeling includes a time delay between check-valve activation and its complete closure. 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. Not only does this save product, but also pipe filling is often problematic from a transient-control perspective. Thus, keeping the pipe full of water tends to reduce startup transients.

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 water to be drawn into the discharge line following a power failure and a downsurge. Bypass lines are usually short pipe segments equipped with a check valve preventing backflow (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 and are useful for two reasons: to prevent high-pressure buildup on the pump-suction side, and to prevent cavitation on the pump-discharge side.

CHOICE OF SURGE PROTECTION STRATEGY

As emphasized in the previous section, a number of techniques can be used for controlling transients in water distribution systems. Some strategies involve design and operational considerations alone, and some also use the addition of dedicated surge protection devices. Devices such as pressure-relief valves, surge anticipation valves, surge vessels, surge tanks, pump-bypass lines, or any combination thereof are commonly 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 flow changes occur.

Specific devices are usually installed at or near the point in which 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 1 illustrates typical locations for the various surge protection devices in a water distribution system. A comprehensive transient flow chart for considering the transient protection of the system as a whole is discussed in the next section.

However, in all of these choices, no two systems are hydraulically the same, and thus there are no general rules or universally applicable guidelines for eliminating objectionable pressures in water distribution systems. Any surge protection devices and/or operating strategies must be chosen accordingly. 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. 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 surge modeling.

The transient flow chart shown in Figure 2 is intended both to provide and to summarize a fairly comprehensive procedure or approach for providing transient protection (Boulos et al, 2004). The chart is more comprehensive and complete than many, for it envisions transient protection as having implications beyond the mere specification and selection of specialized surge protection devices.

The procedure begins at the top of the diagram with a preliminary specification of system attributes and configuration. This preliminary determination should never be discounted or given scant attention, because it can have a remarkably strong influence on all other steps. Once this system has been approximately specified, a preliminary computer simulation can be performed with these attributes to establish the baseline characteristics of the system response. Initially, the key transient loadings are likely to be sudden or emergency valve operations, pump startups or shutdowns, or emergency power failures, but other combinations of system interactions may eventually be investigated as well.

Once the preliminary transient response has been determined, it needs to be compared with some criterion of performance or, in other words, compared with what the transient response ideally should have been. What this means in practice is sometimes challenging and may require some experience and a number of iterations between water utility managers, operators, and designers. In practice, however, the minimum standard for transient design is usually set to ensure that the pipeline system will at no time experience pressures in excess of those it can routinely withstand and to ensure that it will also experience essentially no negative pressures.

There are times when this specification needs to be further expanded, possibly to consider transient velocities, forces, moments, or more complex cyclic pressure loadings. If the transient response is determined to be acceptable, it must then be determined if other likely loadings or transient initiation events need to be considered. Thus, following the top horizontal line in the flow chart, only once the transient response to all expected loadings has been determined to be acceptable has a suitable protection strategy been established.

If the transient response to any or all of a group of loadings is unacceptable, a modification of the system is necessary. In the flowchart shown in Figure 2, the modifications considered come in a variety of types. The first two considerations (i.e., adjusting the transient or the system attributes) are often neglected but do sometimes play a dramatic role in determining an effective design. The final set of options for transient devices is more routinely considered. More specifically, the strategies by which surge control is achieved may be classified as either direct action or diversionary tactics (Thorley, 1991). Direct action strategies attempt to influence the behavior of the primary causes of the flow changes, such as valve or pump operations. Diversionary tactics attempt to control the transient once it has been created.

Because transient events occur whenever conditions in the system are changed, the first issue in the "direct control" approach is to determine whether the rate at which the disturbance is created is locked in or whether it can be extended or made more gentle. This might be achieved through operator training or possibly by locking out a quick closure mechanism in the system. For example, in one system, taking steps to ensure that a set of quarter-turn ball valves could not be operated under normal operating conditions conveniently controlled the transient response and was the least-expensive control approach considered. Other similar actions include prolonging valve opening and closing times (two-stage valve closure or opening), coordinating valve closures (multiple valves), avoiding check-valve slams, ensuring proper fire hydrant operation (slow closing of fire hydrants), increasing pump inertia (addition of a flywheel in prolonged pump run-down), avoiding complete pump failures (putting one pump on a universal power supply), and minimizing resonance hazards. These are the kinds of alterations envisioned by the question, "Can the transient be modified?"

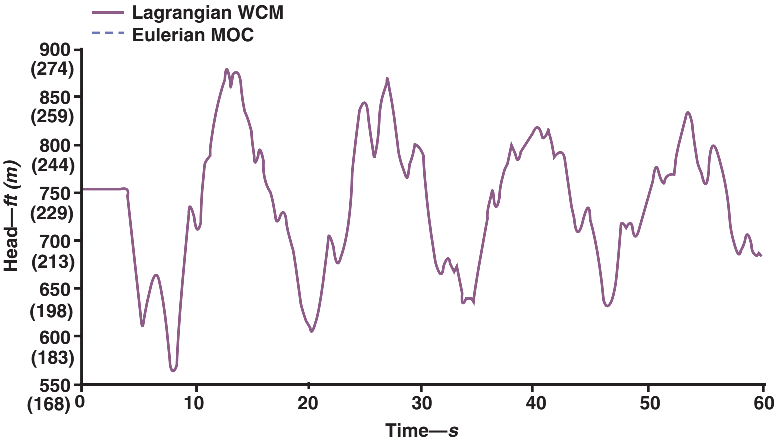
Other direct actions include strengthening (i.e., increasing pressure rating), rerouting pipelines, using larger-diameter pipes (or otherwise lowering the flow velocity), changing the pipe material, or applying strategic changes in system topology. These are the kinds of changes to be considered under the heading, "Can the system be modified?"

Because any of these changes will alter both the system and its transient response, after each change a new simulation should be performed. If done after everything

TABLE 4 Pump characteristic data

Head *ft (m)*	Flow *gpm (L/m)*	Efficiency *%*
220 (67.05)	0	68
200 (61)	600 (2,271)	77
160 (48.8)	1,200 (4,542)	70

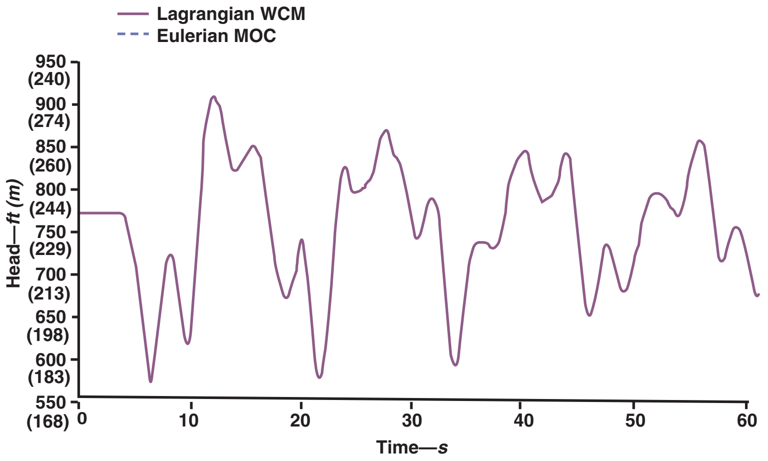
FIGURE 8 Head at node 14 for Example 2



MOC—method of characteristics
WCM—wave characteristic method

The Lagrangian WCM and the Eulerian MOC produced identical results indicated by the single line.

FIGURE 9 Head at node 18 for Example 2



MOC—method of characteristics
WCM—wave characteristic method

The Lagrangian WCM and the Eulerian MOC produced identical results indicated by the single line.

else has been settled, these changes are often expensive, but if made early in the design process, they may form part of an effective and inexpensive surge control approach.

The final decision diamond in the flowchart illustrated in Figure 2 considers whether surge control devices should be directly employed. Such "diversionary tactics" make use of various surge protection devices by which fluid is drawn into or expelled from the piping system in order to reduce the rate of flow changes. This is the set of devices discussed earlier in this section. Overall, the process is iterative as each pass through the loop adjusts the system response, and the overall design gradually converges to an acceptable response.

GOVERNING EQUATIONS

Although a general understanding of transients is essential, detailed analysis requires a more quantitative description. The fundamental equations that describe hydraulic transients 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 time, and partial derivatives are represented as subscripts, the governing equations for transient flow can be written as:

Continuity

$$H_t + \frac{c^2}{gA} Q_x = 0 \tag{1}$$

Momentum (dynamic)

$$H_x + \frac{1}{gA} Q_t - f(Q) = 0 \tag{2}$$

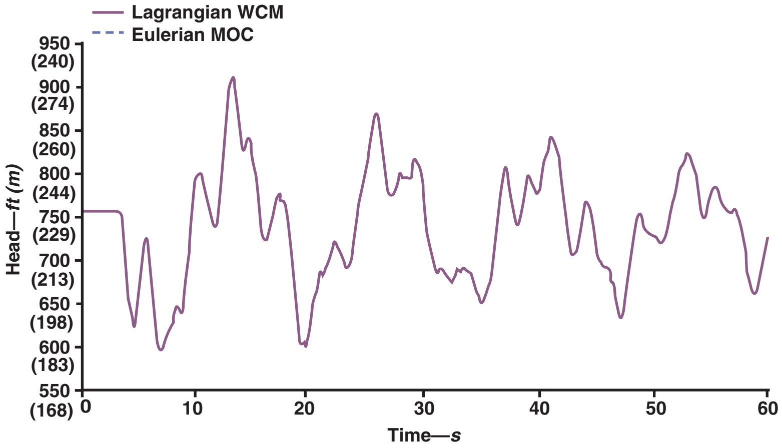
in which H is the pressure head (pressure/density), Q is the volumetric flow rate, c is the sonic wave speed in the pipe, A is the cross-sectional area, g is the gravitational acceleration, and $f(Q)$ is a pipe-resistance (nonlinear) term that is a function of flow rate.

These two governing relations, in conjunction with the boundary equation for specific devices, accurately describe the wave propagation phenomenon that occurs in a distribution system during a transient event. However, no analytical solution exists for these equations except for simple applications that neglect or greatly simplify the boundary conditions and the pipe-resistance term (Boulos et al, 1990). 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.

NUMERICAL SOLUTION METHODS

Although the intent of this article is not to provide a comprehensive numerical reference, an overview of the modeling approach provides important conceptual details. Such an understanding is essential if computer programs and simulation tools are to be used to maximum advantage.

FIGURE 10 Head at node 21 for Example 2



MOC—method of characteristics
WCM—wave characteristic method

The Lagrangian WCM and the Eulerian MOC produced identical results indicated by the single line.

A transient-flow solution can be obtained numerically by solving Eqs 1 and 2 (along with the appropriate initial and boundary conditions) in which pressure and flow are variables dependent on position and time. Both Eulerian and Lagrangian solution schemes are commonly used to approximate the solution of the governing equations. Eulerian methods update the hydraulic state of the system in fixed grid points as time is advanced in uniform increments. 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 equilibrium 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, the most well known of these techniques is the method of characteristics (MOC). The characteristics solution to hyperbolic partial differential equations was originally conceived by Riemann (1860). Several others have used the solution by characteristics for wave problems during the early to mid 1900s (Schnyder, 1929; Massau, 1889). In the mid 1900s, Lamoen (1947) used the characteristics method to solve the water hammer problems and Stoker (1948) applied the method of characteristics to solve the unsteady open-channel flow problems. The method of characteristics, introduced by Gray (1953), is considered to be the most accurate in its representation of the governing equations.

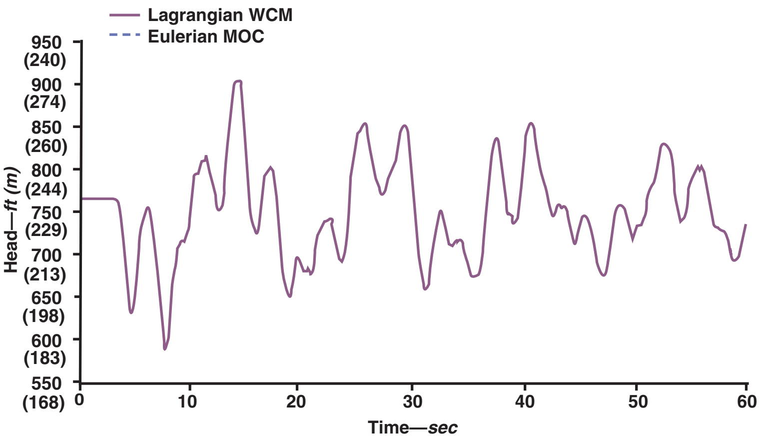
All characteristics methods convert the two partial differential equations of motion and continuity into four differential equations, which are then expressed in a finite difference form. When finite difference and finite element techniques are used, the derivatives in the governing equations are replaced with approximate difference quotients. By contrast, in the method of characteristics, only the nonlinear friction term must be approximated (which is typically done by a linear difference term). Explicit finite difference schemes also have 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, resulting in excessive computational and memory requirements even for present-day computers (Boulos et al, 2004).

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 exactly satisfy both the time-interval and distance-step criteria. This "discretization problem" requires the use of either interpolation procedures (which have undesirable numerical properties) or distortions of the physical problem (which 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 which c is the wave speed. In other words, the Courant condition requires 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 envi-

FIGURE 11 Head at node 25 for Example 2



MOC—method of characteristics
WCM—wave characteristic method

The Lagrangian WCM and the Eulerian MOC produced identical results indicated by the single line.

ronment (Wood et al, 2005; Boulos et al, 2004; Wood et al, 1966). In this environment, the pressure wave propagation process is driven by the distribution system activities. 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 (variable time intervals). The effect of line friction on a pressure wave is accounted for by modifying the pressure wave using a nonlinear characteristic relationship describing the corresponding pressure head change as a function of the line's flow rate. Although it is true that some approximation errors will be introduced using this approach, the errors introduced can be minimized using a distributed friction profile (piecewise linearized scheme). This approach, however, usually requires orders of magnitude fewer pressure and flow calculations, allowing very large 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. Because of this, 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. Another continuous transient simulation procedure with similar characteristics was presented by Basha and Kassab (1996).

Both the Eulerian method of characteristics and the Lagrangian solution scheme 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 Lagrangian scheme has an advantage. A detailed comparison of the various methods can be found in Boulos et al (2004, 1990) and in Wood et al (2005). Two example water distribution network applications are discussed in the following section to demonstrate the comparable accuracy of both Eulerian and Lagrangian transient flow solution methods.

ILLUSTRATIVE NUMERICAL RESULTS

Justification for the use of any transient-flow algorithm rests on its efficiency and stability to solve problems by means of a computer implementation. Overall this is a comprehensive task, involving extensive analysis and investigation. More specifically, both the Eulerian and Lagrangian solution schemes were encoded within the same network-modeling package and tested under equivalent accuracy tolerances on a number of actual water distribution systems of various sizes. Results consistently showed that the accuracies of the methods are comparable. The efficacy of the methods are illustrated here by application to an actual water distribution system and to an example network taken from the literature. For the current purpose, two typical network examples from this set of tests are illustrated here.

Example 1. The first example network was studied earlier by Streeter and Wylie (1967) and is shown in Figure 3. The network comprises nine pipes, five junctions, one reservoir, three closed loops, and one valve located at the downstream end of the system. Table 2 summarizes the pertinent pipe system characteristics. The reservoir level is shown in Figure 3. Figures 4–6 compare the transient results obtained using the Eulerian MOC and the Lagrangian wave characteristic method (WCM) solution scheme (Boulos et al, 2004) following a sudden closure of the valve. A 20-ft (6.1-m) length tolerance was used in the analysis. As shown in the figures, both methods produced virtually identical results.

Example 2. To illustrate the comparable accuracy of both transient solution schemes on a larger, more complex system, the methods were applied to the network shown in Figure 7. The network in Figure 7 represents an actual water system and consists of 21 pipes, 16 junctions, 1 reservoir, 2 tanks, 2 closed loops, and 1 pump. Table 3 summarizes the pertinent pipe system characteristics. Table 4 lists the pump characteristic data. The reservoir and tank levels are given in the figure. Figures 8–11 compare the transient results obtained using the

Eulerian MOC and the Lagrangian WCM solution scheme following a 2-s pump shutdown. A 20-ft (6.1-m) length tolerance was used in the analysis. As can be seen from the figures, both methods yielded virtually identical results.

TRANSIENT MODELING CONSIDERATIONS

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, such as the following:

1. The precise location of hydraulic devices (pumps, control valves, check valves, regulating valves, and so on) is required for the model.
2. Transient analysis may require some minor adjustments in pipe lengths or wave speeds (or a combination of both). The accuracy of the model (maximum difference between actual and model pipe lengths or wave speeds) must be sufficient to generate an accurate solution. However, increasing the accuracy will require a longer computational time.
3. 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.
4. Skeletonization guidelines are significantly different from those for steady-state analysis. Dead-end lines, for example, will have a significant effect on a transient analysis and have no effect on the steady-state analysis.
5. A transient model should carry out calculations at all local high and low points because the pressure extremes often occur at these locations.
6. 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.

SUMMARY AND 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 water distribution network are changed, such as by closing a pump or a valve or starting a pump, a series of pressure waves is 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. Significantly, 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 because pressure waves of considerable magnitude can occur and are quite capable of causing unacceptable operation and even destroying equipments and pipelines. Only if flow regulation occurs very slowly is it possible to move smoothly from one steady state to another, without large fluctuations in pressure head or flow velocity.

Flow control actions are extremely important and 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 afterthought to be appended to a nearly complete design. Transient analysis is a fundamental and challenging part of rational network design.

Surge modeling provides the most effective and viable means of identifying weak spots, predicting potentially negative effects of hydraulic transients under a number of worst-case scenarios, 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 may be more computationally efficient when solving large water 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.

Water distribution systems comprising a short length of pipes (i.e., < 2,000 ft [600 m]) will usually be less vulnerable to problems associated with hydraulic transient. This is because wave reflections (e.g., at tanks, reservoirs, junctions) tend to limit further changes in pressure and counteract the initial transient effects. For networks with long pipelines and irrespective of which 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 check valves) that lock pressure waves into the system in a cumulative fashion. (Wave reflections will double both positive and negative pressures.) As a result, the effect of dead ends must be carefully evaluated in transient analysis.

A detailed transient flow chart was shown that offers a comprehensive guide to the selection of components for surge control and suppression in water distribution systems. Good maintenance, pressure management, and routine monitoring (e.g., high-speed pressure-data loggers) programs are an essential component of transient protection. Using a surge analysis computer model, water utility engineers will acquire sound capabilities that 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, and safeguard their systems and public health with maximum effectiveness.

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ABOUT THE AUTHORS

Paul F. Boulos *(to whom correspondence should be addressed) is president and COO of MWH Soft Inc., 370 Interlocken Blvd., Suite 300, Broomfield, CO, e-mail paul.boulos@mwhsoft.com. Boulos has a BS degree, an MS degree, and a PhD in civil engineering from the University of Kentucky in Lexington and an MBA from Harvard University in Cambridge, Mass. Boulos has more than 20 years of experience in water distribution engineering and has written more than 200 articles and engineering reports and three books on water distribution and sewer collection systems. Bryan W. Karney is a professor in the Department of Civil Engineering at the University of Toronto. Don J. Wood is a professor and Srinivasa Lingireddy is an associate professor, both in the Department of Civil Engineering at the University of Kentucky in Lexington.*

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