Transient water column separation can create serious consequences for pipeline systems if not properly recognized and addressed by analysis and operational and design modifications (mostly involving the placement of surge-protection devices). Therefore it is necessary to determine the likelihood of water column separation, evaluate its severity, and estimate its potential effect on the system. This article describes a rigorous Lagrangian method that implements the numerical discrete vapor cavity model for use in simulating transient water column separation in water distribution systems. As the numerical examples considered here demonstrate, results of the proposed method compared closely with the traditional Eulerian-based implementation approach. The method described is both robust and straightforward and will greatly improve the reliability and efficacy of Lagrangian-based network transient analysis models and the ability of engineers to more accurately predict system transients and properly select and design surge-protection devices for maximum system protection and safeguarding of public health.

A Lagrangian wave characteristic method for simulating transient water column separation

BY BONG SEOG JUNG,
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DON J. WOOD,
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Hydraulic transient simulation models are widely used by water utilities and engineering firms around the world in the planning, analysis, and design of water distribution piping systems (Boulos et al, 2006; Walski et al, 2003). These models are used to both evaluate potentially objectionable pressure transients (surges), which could lead to unacceptable operating conditions developing in the system and compromising its integrity, and to investigate "what if" scenarios associated with decisions regarding safe system operation. Examples of unacceptable conditions include pressures that are too high or too low and are created by unsteady or rapidly changing flow rates within the system. Such conditions can cause breaches in the hydraulic and physical integrity of the distribution system that increase the risk of negative public health outcomes. High-pressure transients (upsurges) can lead to system failure and excess leakage. Low-pressure transients (downsurges) can create vacuum conditions and pipeline collapse as well as opportunities for contaminated groundwater to intrude into the distribution system at a leaky joint or break, with possible consequences to public health. Depending on the size of the leaks, the volume of intrusion can range from a few gallons to hundreds of gallons (Boyd et al, 2004a; Boyd et al, 2004b; Funk et al, 1999). Recent studies by the National Research Council, the Water Research Foundation, and the US Environmental Protection Agency confirmed the potential for pathogen intrusion in drinking water distribution networks during low-pressure transients (Besner, 2007; Boulos et al, 2006; Fleming et al, 2006; NRC, 2006; Friedman et al, 2004; LeChevallier et al, 2003, 2002; Kirmeyer et al, 2001).

Low-pressure transients typically result from the uncontrolled trip-out of one or more pumps because of power failure. This in turn can result in unwanted water column separation when the pressure falls below atmospheric and reaches vapor pressure. At that time, a vapor cavity (cavitation) will form and fill the vacuum (one-phase flow becomes two-phase flow), and the rapid and severe pressure rise following the collapse of this cavity may lead to a severe and often destructive surge. Therefore a rigorous transient analysis is required to determine the severity of transient pressures under normal and emergency operations and to develop reliable control strategies—mostly involving the design and installation of one or more surge-protection devices—to avoid column separation. Such rigorous analysis is also needed to ensure that the system is sufficiently protected and objectionable transient pressures are contained within acceptable levels. However, the results of a transient analysis will be accurate and reliable only if the water column separation phenomenon is explicitly addressed and properly simulated.

Several approaches have been taken to numerically model pressure transients in water distribution systems (Boulos et al, 2006). The two most widely used and accepted methods are the Lagrangian wave characteristic method (WCM) and the Eulerian fixed-grid method of characteristics (MOC). The primary difference between the two numerical methods lies in the way pressure waves are tracked between the pipe boundaries (e.g., reservoirs, tanks, dead ends, partially opened valves, pumps, junctions, surge-control devices, and vapor cavities). The MOC tracks a disturbance in the time–space grid using a numerical method based on characteristics, whereas the WCM tracks the disturbance based on wave propagation mechanics. Both methods have been well documented in the literature (Ramalingam et al, 2009; Jung et al, 2007; Boulos et al, 2006, 2005; Wood et al, 2005a, 2005b; Wylie & Streeter, 1993; Streeter & Wylie, 1967; Wood et al, 1966) and have been implemented in various computer programs for pipe system transient analysis. However, some transient models do not simulate the nonlinear effects of water column separation but instead set the pressure at the cavity location at vapor pressure. This can lead to inaccurate results and prevent sound assessment of the consequences of column separation (Martin, 2000). Only when transient water column separation phenomenon is considered can accurate predictions be obtained. Protection of public health requires that water column separation be prevented and eliminated by the installation of properly designed surge-protection devices in order to maintain the highest level of water quality. This in turn dictates the necessity for adequate modeling of water column separation to predict the anticipated surge effects and improve the determination of preventive measures.

Although a variety of numerical algorithms have been developed for modeling column separation in water distribution systems, the procedures reported were restricted to direct implementation within the framework of the Eulerian-based MOC transient method of analysis (Bergant et al, 2006; Martin, 2000; Bergant & Simpson, 1999; Wylie & Streeter, 1993). Among the various methods proposed, the discrete vapor cavity model (DVCM) is the most popular model used in currently available commercial programs for transient analysis. Its principal advantages lie in its inherent simplicity and ease of implementation as well as its ability to reproduce many features of the physical characteristics of water column separation in distribution systems (Bergant & Simpson, 1999).

Protection of public health requires that water column separation be prevented and eliminated by installation of properly designed surge-protection devices.

This article incorporates the DVCM water column separation model within the framework of the Lagrangian-based WCM transient analysis model. The implementation is based on the physical concept that a vapor cavity is formed when the pressure in the pipeline drops to the vapor pressure. The cavity expands and contracts at a constant cavity pressure equal to the vapor pressure and subsequently collapses at the instant the cavity volume is reduced to zero. The numerical examples considered here demonstrate that the results of the proposed method compare favorably with the traditional Eulerian-based implementation approach. The method is robust and straightforward and will greatly improve the reliability of Lagrangian-based network transient analysis models to estimate intrusion potential, identify problem areas and those susceptible regions in the distribution system that are of greatest concern for vulnerability to objectionable (low or negative) pressure surges, and evaluate how these may be avoided and/or controlled. As a result, the model should prove to be a valuable proactive tool for preserving distribution system hydraulic and water quality integrity and preventing potential problems.

WATER COLUMN SEPARATION IN PIPELINE SYSTEMS

Mechanics of water column separation. Water column separation refers to the rupture of water columns in pressurized pipelines. This phenomenon can be induced by low- or negative-pressure transients when the pressure falls to vapor pressure, causing the water to vaporize and effectively dividing the water column into distinct columns. This usually occurs in vertical pipes, dead-end pipes, pipes having steep slopes, or pipes having knees in their profile. The vapor cavity grows until a higher pressure develops. This can cause the cavity to collapse suddenly and produce a severe pressure surge when the water columns rejoin. This phenomenon may have a drastic effect on distribution system integrity and should always be considered in transient analysis.

Transient water column separation can create serious consequences for pipeline systems if not properly recognized and addressed by analysis as well as operational and design modifications.

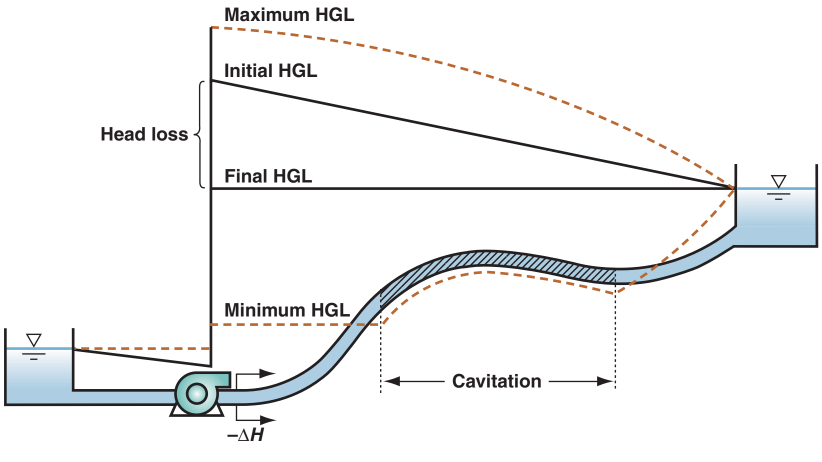
Water column separation must be avoided (or at least minimized) in pipeline systems because it reduces performance, generates annoying vibrations and noise, and causes damage to equipment. The pressure spikes resulting from the large number of bubbles collapsing near a solid surface over a long period of time may cause erosion, surface pitting, fatigue failure, and the eventual destruction of components or machinery (Cengel & Cimbala, 2006). This is one of the main reasons for placing air valves at pipeline summits because they can contribute to the control and suppression of negative transient pressures by admitting air freely and then retaining it for a sufficient time until the line pressure exceeds atmospheric pressure.

Transient pressure in a pipeline may be reduced to vapor pressure following power failure to a pump or by rapid valve operation. Figure 1 shows an example system in which pump trip is causing cavitation. The sudden loss of energy to the pump can be caused by an unexpected power failure or occur simply because the utility operator has switched off the power. In either case, the rotating pump impeller begins to decelerate with the pressure dropping on the discharge side of the pump and, in the case of an inline booster pump configuration, rising on the pump suction side. Upon power failure, a negative pressure wave generated at the pump begins to travel in the downstream direction. The initial drop in pressure, which occurs simultaneously with a reduction to zero at the pump discharge, is called potential surge or Joukowski pressure change, ΔH, and the change is directly proportional to the water velocity at cutoff and the velocity of the predicted surge wave, ΔV (Joukowski equation):

$$\Delta H = \frac{c\Delta V}{g} \tag{1}$$

in which c is the wave speed and g is the gravitational acceleration. When the negative-pressure wave reaches the high point of the pipeline (which already has a relatively low pressure), the pressure can drop to vapor pressure. At this pressure, gas within the water is gradually released, and the water starts to vaporize, resulting in water column separation. When the pressure increases because of a reflected positive-pressure wave, the water columns on each side of the cavity collide (i.e., cavity collapses), producing a pressure surge spike. In this case, both vacuum and strong pressure surges are present, a combination that may result in substantial system damage.

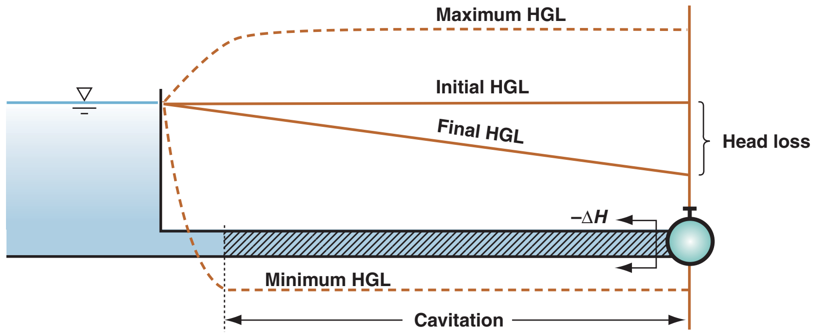
FIGURE 1 Pump trip causing cavitation



ΔH—change in head, HGL—hydraulic grade line

A rapid valve operation is another frequent cause of transient cavitation. Upon a sudden valve opening, the pressure head at the valve upstream attempts to drop by the Joukowski pressure change, and the downsurge is propagated into the upstream reservoir (Figure 2). Similarly, a rapid valve closure generates a negative pressure at the valve downstream, and the downsurge is propagated into the downstream pipe. If the pressure drop reaches the water vapor pressure, a vapor cavity forms.

FIGURE 2 Valve opening causing cavitation



ΔH—*change in head, HGL—hydraulic grade line*

Strategies for reducing transient water column separation. Transient water column separation can create serious consequences for pipeline systems if not properly recognized and addressed by analysis and operational and design modifications mostly involving the placement of one or more surge-protection devices. Because transient water column separation can result in catastrophic pipeline failures, many remedial strategies are available and range from system modification and operational considerations to the addition of one or more dedicated surge-protection devices (Boulos et al, 2006, 2005; Thorley, 1991). Direct action strategies attempt to influence the root causes of flow changes, such as adjusting valve or pump operations. Too rapid a valve closure or pump shutdown may lead to water column separation or excessively high transient pressures. Other possible strategies include such system modifications as pipe reinforcement (i.e., increasing a pipe's pressure rating), rerouting conduits, using larger-diameter pipes, changing the pipe material, or making strategic changes in system topology. These adjustments alter both the system and its transient response and can prevent formation of a vapor cavity.

The most common protection strategies involve diversionary tactics that require the use of various surge-protection devices. These devices operate on the general principles of storing water or otherwise delaying the change in flow rate or discharging water from the pipe. For example, air release/ vacuum-breaking valves are installed at high points in a pipeline to prevent negative pressure and cavitation by emitting air into the pipe when the line pressure drops below atmospheric conditions. A feed tank (one-way surge tank) is another effective device to prevent low pressures and potential water column separation by admitting water into the pipe subsequent to a downsurge. Because no two systems are hydraulically identical, the ultimate choice and combination of surge-protection devices may differ. Final checking of the adequacy and efficacy of the proposed solution should be conducted and validated using detailed surge modeling. The following case studies illustrate applications of representative strategies for preventing transient cavitation and water column separation.

The Lagrangian approach to transient analysis is based on tracking movement and transformation of pressure waves as they propagate over time throughout the water distribution system.

NUMERICAL WATER COLUMN SEPARATION MODEL

Review of models. An analytical solution to the problem of water column separation does not currently exist (Tullis, 1989). A variety of numerical models of column separation have been proposed, ranging from single-component to two-component two-phase transient flows. Excellent reviews of the methods can be found in the literature (Bergant et al, 2006; Bergant & Simpson, 1999). However, these procedures were restricted to direct implementation within the framework of the Eulerian-based MOC transient method of analysis (Bergant et al, 2006; Martin, 2000; Bergant & Simpson, 1999; Wylie & Streeter, 1993).

Among the various alternative methods proposed, the DVCM is the most popular model used in currently available commercial programs for transient analysis. The model is based on the physical concept that a vapor cavity is formed when the vapor pressure in the pipeline is reached, and the vapor cavity grows (maintaining a constant cavity pressure equal to the vapor pressure) and then subsequently collapses, producing a pressure spike at the instant the cavity volume is reduced to zero. The model's principal advantages lie in its inherent simplicity and ease of implementation as well as its ability to reproduce many features of the physical characteristics of water column separation in distribution systems. Assumptions and limitations of the method have been discussed in detail by other researchers (Bergant et al, 2006). Their research also provided a comprehensive survey of laboratory tests and field measurements. This approach can be extended for direct implementation within a Lagrangian transient analysis framework.

Lagrangian approach. The Lagrangian approach to transient analysis is based on tracking the movement and transformation of pressure waves as they propagate with time throughout the water distribution system in an event-oriented environment. In this environment, the transient analysis problem is driven by the distribution system pressure wave activities. The WCM is an example of such an approach (Boulos et al, 2006; Wood et al, 2005a, 2005b) and was first described in the literature as the wave plan method (Wood et al, 1966). With the Lagrangian approach, the water column separation analysis in a pipe system is described as in Figure 3 (Wood et al, 2005a). The basic transient flow relationship for pressure–flow changes is applied to incoming waves ΔH_1 and ΔH_2 to yield the following expressions for the outgoing waves ΔH_3 and ΔH_4:

$$\Delta H_3 = \Delta H_1 + F_1(Q_3 - Q_1) \tag{2}$$

$$\Delta H_4 = \Delta H_2 + F_2(Q_4 - Q_2) \tag{3}$$

in which $F_1 = c_1/gA_1$ and $F_2 = c_2/gA_2$ in which c is the wave speed, g is the gravitational acceleration, and Q is the volumetric flow rate. The subscripts 1 and 2 denote the conditions on the left and right side of the junction before the impinging wave arrives, whereas the subscripts 3 and 4 designate the conditions after the wave action. Pressures after the wave action are given by

$$H_3 = H_1 + \Delta H_1 + \Delta H_3 \tag{4}$$

$$H_4 = H_2 + \Delta H_2 + \Delta H_4 \tag{5}$$

If the pressures H_3 and H_4 drop below a specified value (normally the vapor pressure, H_v), a vapor pocket forms and grows at the junction, and the analysis is repeated by limiting both pressures H_3 and H_4 to H_v. By treating the junction as a reservoir at pressure H_v, Eqs 4 and 5 yield the following relations for the pressure wave magnitude:

$$\Delta H_3 = H_v - H_1 - \Delta H_1 \tag{6}$$

$$\Delta H_4 = H_v - H_2 - \Delta H_2 \tag{7}$$

Using Eqs 2, 3, 6, and 7, the flows on the left and right side of the junction are given as

$$Q_3 = Q_1 + (\Delta H_3 - \Delta H_1)/F_1 \tag{8}$$

$$Q_4 = Q_2 + (\Delta H_4 - \Delta H_2)/F_2 \tag{9}$$

The volume of the vapor cavity, V_c, depends on the transient time step, Δt, until the next action takes place and is given by

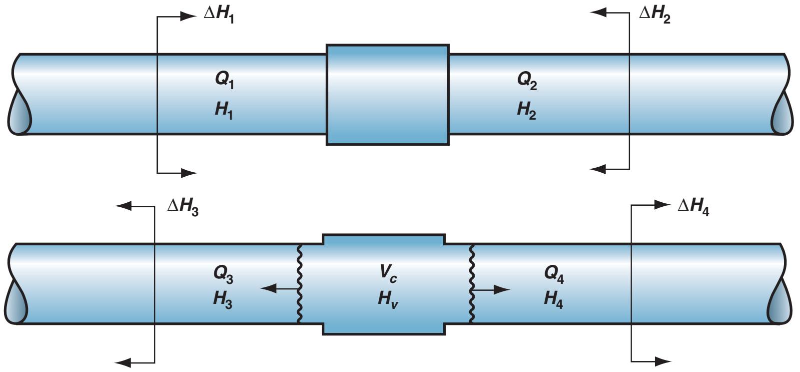
$$V_c = (Q_3 + Q_4)\Delta t \tag{10}$$

The vapor cavity continues to exist until the next action produces a volume change sufficient to collapse the vapor pocket.

COMPUTATIONAL RESULTS

Justification for the use of any transient analysis algorithm rests on its ability to solve problems by means of a computer implementation. This is best evaluated by comparing transient water column separation solutions obtained using the Lagrangian-based WCM and Eulerian-based MOC implementation approaches. The current research studied two example networks. Representative strategies for preventing transient water column separation are illustrated and applied with the case examples.

FIGURE 3 Formation of vapor cavity at a junction



ΔH—change in head, H—pressure, H_v—vapor pressure, Q—volumetric flow rate, V_c—vapor cavity volume

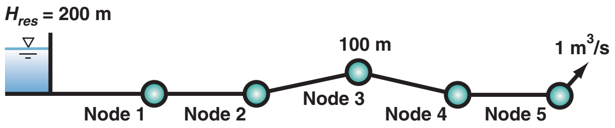
Subscripts 1 and 2 denote conditions on the left and right sides of the junction before the impinging wave arrives. Subscripts 3 and 4 designate these conditions at the junction after the wave action.

Series pipe system. The first case study used the single water pipeline system shown in Figure 4. This system consisted of a 200-m (656.2-ft) head reservoir feeding a network of five pipe sections in series and five junctions. The diameter, length, Hazen-Williams roughness coefficient, and wave speed for each pipe were 1 m (3.3 ft), 1,000 m (3,280.8 ft), 100, and 1,000 m/s (3,280.8 fps), respectively. Node 5 had an external demand of 1 m^3/s (35.3 cu ft/s). A rapid demand decrease (to zero) over a 1-s time period at node 5 was initiated 5 s into steady-state equilibrium in order to introduce a transient condition. The water temperature in the pipeline was assumed at 25°C (77°F), so the water vaporized at a pressure of –10 m (–32.8 ft). The elevation of node 3 was 100 m (328.1 ft), and the elevation of the remaining nodes was 0 m, so node 3 experienced a water column separation with the given transient.

First, surge analyses using WCM and MOC were carried out without cavitation and water column separation effects. Figure 5 shows that the rapid demand decrease created the potential surge (Joukowski pressure change) of 129.5 m (424.9 ft), which is defined by Eq 1 in which c = 1,000 m/s (3,280 fps), V = 1.27 m/s (4.17 fps), and g = 9.81 m/s^2 (32.2 sq ft/s). After creating the initial surge, the positive surge wave was propagated to the upstream reservoir, converted into a negative surge, and propagated back to the downstream junction. This procedure was repeated until the surge wave was dissipated with friction loss along the pipeline.

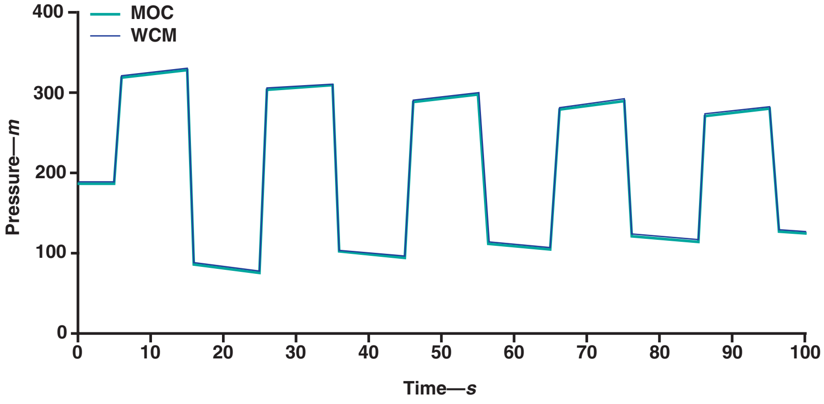
Next, WCM and MOC surge analyses incorporating water column separation were carried out, with the results shown in Figure 6. When the converted negative surge wave reached node 3, the transient pressure at node 3 dropped below the vapor pressure, –10 m (–32.8 ft), because the node had a low static pressure because of its high elevation. Therefore water started to vaporize at node 3. The vapor bubbles remained and grew at the node until a positive pressure developed. When the pressure recovered, the vapor bubbles collapsed suddenly and produced a pressure surge spike after 30 s. As shown in Figure 6, the maximum surge head (obtained by subtracting the maximum transient pressure from the initial steady pressure) with the cavitation effect was 245.7 m (806.1 ft), 76% higher than that without cavitation, 139.6 m (458 ft). This is because the surge pressure caused by vapor collapse was added to the initial surge pressure created by the rapid demand decrease. The maximum surge head with-

FIGURE 4 Single pipeline system



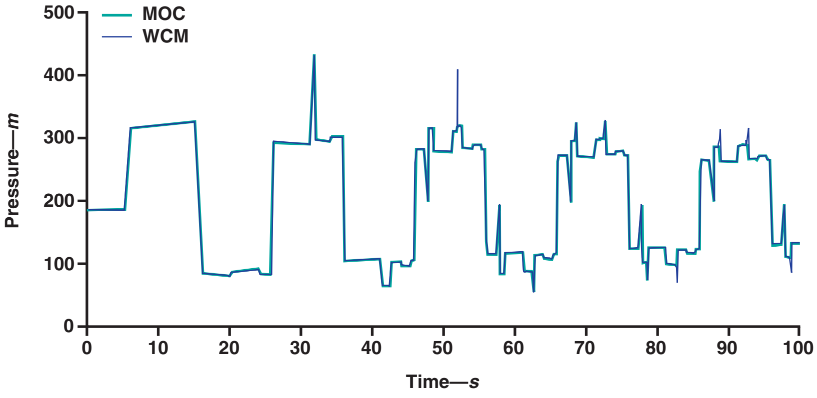
H_{res}—*head at reservoir*

FIGURE 5 Pressure head at node 5 without cavitation in the system



MOC—method of characteristics, WCM—wave characteristic method

FIGURE 6 Pressure head at node 5 with cavitation in the system



MOC—method of characteristics, WCM—wave characteristic method

TABLE 1 Cavitation-preventing strategies for the single pipeline system

Strategies	Maximum Pressure—*m (ft)*	Difference—*m (ft)*
None	245.7 (806.1)	NA
Modifications of transient		
Operational speed = 5 s	157.5 (516.8)	88.2 (289.4)
Operational speed = 10 s	136.6 (448.2)	109.1 (358)
Operational speed = 15 s	91.7 (300.9)	154 (505.3)
Modifications of system		
Pipe diameter = 2 m (6.6 ft)	32.9 (107.9)	212.8 (698.2)
Wave speed = 300 m/s (984.3 fps)	49.3 (161.8)	196.4 (644.4)
Use of surge-protection devices		
Air valve	220 (721.8)	25.7 (84.3)
Pressure-relief valve	132 (433.1)	113.7 (373)

NA—not applicable

out cavitation, 139.6 m (458 ft), was higher than the potential surge of 129.5 m (424.9 ft) because of the effect of line packing. As shown in Figures 5 and 6, the WCM and MOC produced virtually identical results.

Strategies to prevent cavitation. Because the cavitation phenomenon presented in the case study significantly deteriorated the system transient response, three strategies for preventing cavitation were considered; results are summarized in Table 1.

The first strategy considered modification of the transient by changing the operational speed directly. Here it was provisionally assumed that it might be possible to delay the operational speed from 1 to 5, 10, and 15 s. Figure 7 shows that the transient response was improved with the extended operational speed, and the maximum surge pressures for 1, 5, 10, and 15 s were 245.7 m (806.1 ft), 157.5 m (516.8 ft), 136.6 m (448.2 ft), and 91.7 m (300.9 ft), respectively. The maximum surge pressure for the 15-s case was even smaller than the potential surge of 129.5 m (424.9 ft) because the operational time was greater than the surge-wave traveling time of 10 s [= 2 × 5,000 m (16,404 ft)/1,000 m/s (3,280.8 fps)], resulting in a slow transient.

The second strategy considered modification of the transient response by adjusting system characteristics. Altering the pipe size changes the velocity for a given flow rate. If the diameter is increased, the resulting reduction in velocity decreases the magnitude of the initial pressure wave, alleviating the possibility of vapor cavity formation. Other researchers examined strategies for improving transient performance in this way (Jung & Karney, 2004). Figure 8 depicts the transient head profiles of the original pipe diameter [1 m (3.3 ft)] and the increased pipe diameter [2 m (6.6 ft)], resulting in the improvement of the maximum pressure by 212.8 m (698.2 ft). Alternatively, the transient response can be improved by a change in pipe material, i.e., using a flexible pipe such as high-density polyethylene rather than a rigid pipe material such as steel. Because the more flexible pipe material provides a smaller wave speed, it directly decreases the magnitude of the initial pressure change. As shown in Figure 8, if the wave speed is reduced to an assumed 300 m/s (984.3 fps) in the example system, the maximum pressure is decreased by 196.4 m (644.4 ft). Both pipe size and material modification strategies significantly improved the transient response, decreasing the initial upsurge as well as preventing vapor cavity formation and water column separation.

The third (and widely applied) strategy to prevent cavity formation and water column separation is the use of a surge-protection device such as an air valve. This device will open to admit air when the pressure at its location drops to atmospheric. Figure 9 shows the results when an air valve with an inflow diameter of 0.03 m (0.1 ft) and an outflow diameter of 0.01 m (0.03 ft) was installed at node 3 (the highest point in the system). As shown in the figure, the air valve reduced the maximum pressure by 26.7 m (87.6 ft), but the reduction was smaller than those obtained using the previous protection strategies. Because the transient was initiated by decreasing the downstream demand, a pressure-relief valve (PRV) was considered as an alternative to reduce the initial upsurge. The full opening diameter of the PRV was set at 0.1 m (0.3 ft). Its opening surge pressure, closing surge pressure, opening time, and closing time were assumed to be 50 m (164.1 ft), 30 m (98.4 ft), 1 s, and 10 s, respectively. The PRV was installed at node 4 (next to the upsurge source location). Figure 9 shows that the PRV decreased the maximum pressure by

> **Justification for the use of any transient analysis algorithm rests on its ability to solve problems by means of a computer implementation.**

113.7 m (373 ft) and controlled the cavitation problem more effectively than the air valve. This was because the PRV adequately dissipated the initial upsurge before it was converted into a downsurge from the upstream reservoir that caused the vapor cavity formation at node 3.

Pipe network system. The case study used in the second example was studied by other researchers (Streeter & Wylie, 1967). As shown in Figure 10, the network comprised nine pipe sections, five junctions, one 300-m (984.3-ft) head reservoir, three closed loops, and one valve located at the downstream end of the system. Pipe lengths are shown in Figure 10; pipe diameter, Hazen-Williams roughness coefficient, and wave speed were 1 m (3.3 ft), 100, and 1,000 m/s (3,280.8 fps), respectively. Node 7 had an external demand of 2 m^3/s (70.6 cfs). The valve at node 7 was shut after 5 s into steady-state equilibrium to create a transient, and the nodal demand was subsequently reduced to zero over a 1-s time period. The elevation of node 5 was assumed to be 200 m (328.1 ft), and the elevations of the remaining nodes was set to 0 m.

In contrast to the previous example, the network system had uneven pipe lengths, causing different wave travel times. Surge analysis using MOC requires interpolation or adjustment between points in the space–time plane when the wave travel times in all computational units are uneven (Wylie & Streeter, 1993). In order to eliminate the interpolation error of the MOC, the pipes were internally divided by 100 m (328.1 ft), resulting in a computational time step of 0.1 s for all pipes.

First, the surge analyses were applied without cavitation effect. Figure 11 compares the transient results obtained using the MOC and WCM solution approaches at node 7. As shown in the figure, the results of both methods were virtually identical. Figure 12 shows

FIGURE 7 Pressure profile at node 5 using different operation times

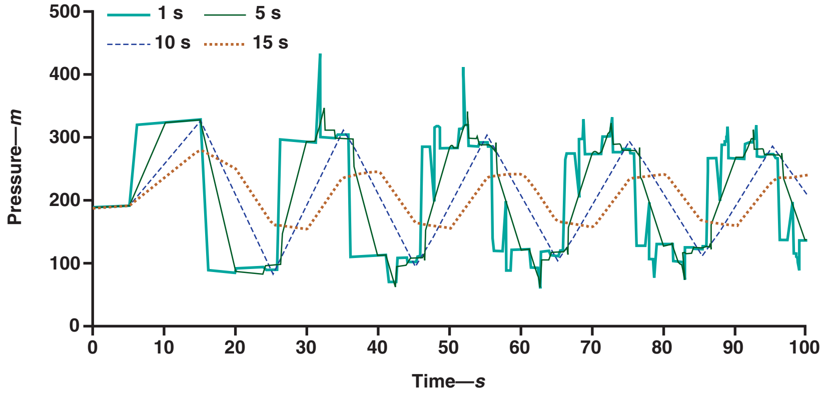
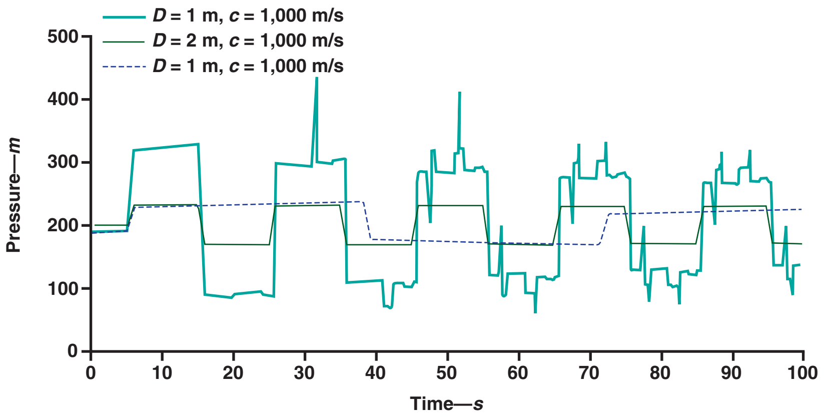
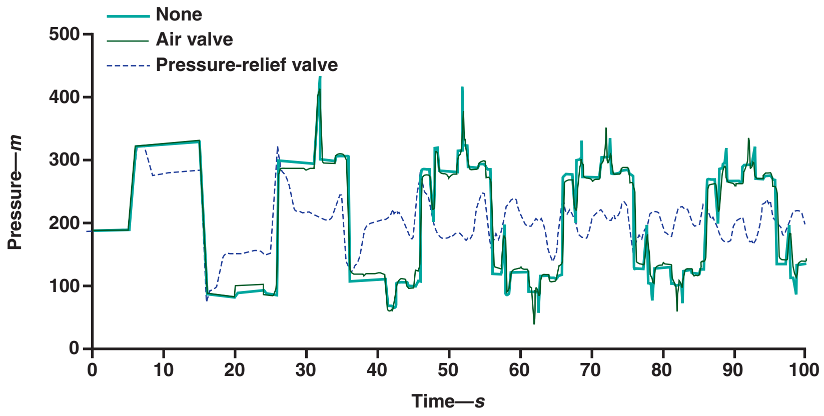


FIGURE 8 Pressure profile at node 5 using modified system characteristics



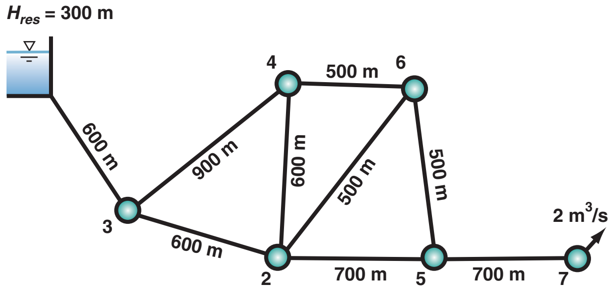
c—*wave speed,* D—*pipe diameter*

FIGURE 9 Pressure profile at node 5 using surge-protection devices



the results of MOC and WCM incorporating the DVCM transient water column separation model. The initial upsurge from node 7 was propagated to the upstream reservoir, and then the converted downsurge caused the transient pressure at node 5 to fall below the vapor pressure. The cavitation at the node deteriorated the transient response and increased the maximum pressure by 59.9 m (196.5 ft). As can be seen in Figure 12, the two numerical methods produced virtually identical results.

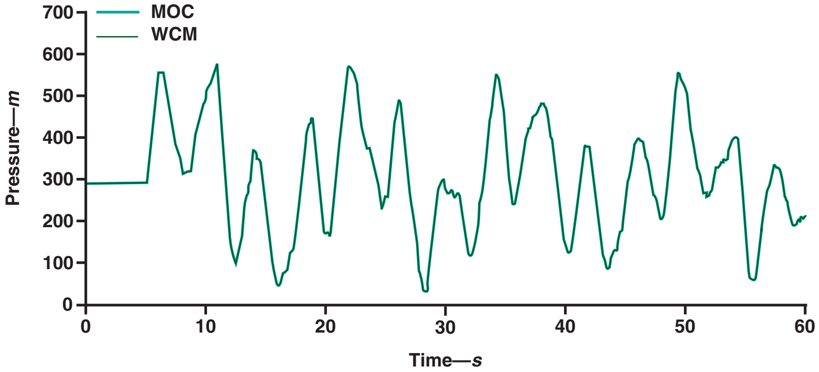
FIGURE 10 Pipe network



H

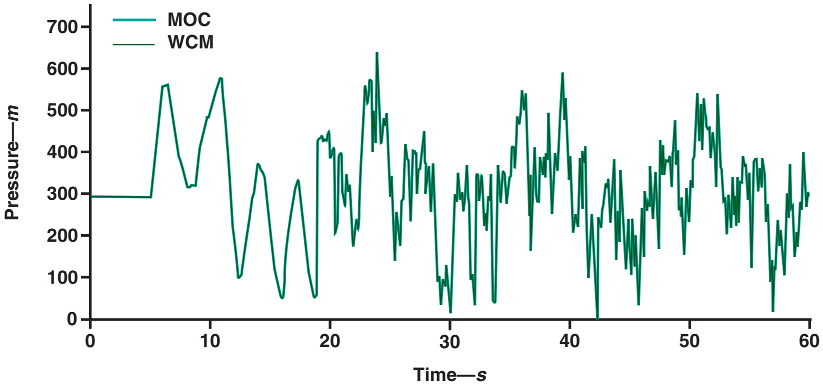
H_res—*head at reservoir*

FIGURE 11 Pressure at node 7 without cavitation in the system



MOC—method of characteristics, WCM—wave characteristic method

FIGURE 12 Pressure at node 7 with cavitation in the system



MOC—method of characteristics, WCM—wave characteristic method

CONCLUSIONS

Many factors can cause a water distribution system to lose its hydraulic integrity so that water quality becomes impaired. Paramount among these factors are low- or negative-pressure transients that can lead to the undesirable occurrence of water column separation, which itself can result in pipeline collapse or contamination of the distribution system via intrusion. The ability to model transient water column separation is therefore essential to ensure proper system protection and performance.

In this research, the Lagrangian WCM of transient analysis was extended to include modeling of water column separation in water distribution systems. The methodology for simulating water column separation was based on the physical concept that a vapor cavity is formed when the vapor pressure in the pipeline is reached, and the vapor cavity grows while the pressure is held at vapor pressure and subsequently collapses at the instant the cavity volume is reduced to zero. The resulting approach proved both robust and straightforward and was shown to produce results identical to those obtained from a Eulerian-based implementation approach.

The proposed method greatly improves the reliability of Lagrangian-based network transient models in analyzing unsteady flows in distribution systems and estimating the magnitude of potential problems. Such capabilities will greatly enhance the ability of design engineers to more accurately predict system transients and undesirable conditions and properly select and size surge-protection devices for maximum system protection and safeguarding of public health.

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Date of submission: 12/03/08
Date of acceptance: 01/30/09

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