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How severe can transients be after a sudden depressurization?

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This article discusses how pipeline networks that experience sudden pressure differences, even in the absence of initial system flow, can create severe transient pressures. If a pipe is under static pressure and a valve is suddenly opened, a depressurization wave propagates through the system. As with any transient, reflection is based on the pipe material, and at a dead end the original and reflected waves superimpose. This superposition is almost invariably large enough for local pressures to drop below the gauge value and reach vacuum pressures, inducing cavitation. For the experiments reported in this article, negative pressures were measured for several seconds and a low-pressure event was followed by rapidly increasing pressures and associated impressive acoustic effects. This investigation highlights that depressurization events are potentially destructive and must be treated with appropriate caution because such shock loadings can cause structural failures.

KEYWORDS: *asset damage, cavitation, contamination intrusion, depressurization, shock loading, transients*

Water distribution system (WDS) engineers have become increasingly aware that significant pressure variations can accompany a variety of operational actions (e.g., pump starts and stops, valve movements). For instance, a large pressure rise can be created and propagate downstream from an upstream pump start or valve opening. These short-term events are known as transients—or surge or water hammer—and involve propagating waves of varying pressure. In essence, transients occur whenever flow conditions are altered: they are the physics of change, bringing news of any hydraulic adjustment throughout the network. Although transients are waves of both pressure and velocity, it is the effects of the pressure that are usually of greatest concern to designers and operators.

The usual ingredients for severe transient effects in pipeline networks arise when fluid velocities are rapidly adjusted and waves are created that convert the changes in kinetic energy into—at least until energy dissipation mechanisms can act—strain energy in the fluid and pipe wall. High-pressure events can be severe enough to exceed material limits and thus can be highly destructive or disruptive to networks causing pipe breaks and device failures. If low pressures are generated, there is a risk of pipe collapse or of the intrusion of external contaminants via leakage apertures or backsiphoning. In all cases the rate of change of the pressure (shock loading) effects is undesirable (Karney, 2003).

Transient phenomena have a remarkable ability to surprise both the novice and the experienced analyst. Transient events are by their nature rapid and sudden, occurring because of a system undergoing almost any changes in state; the initial wave train can, in turn, trigger a host of important but sometimes obscure consequences. These realities have the important implication that the process of acquiring intuition about the key design and control of transient variables is a long and arduous one. Yet intuition is clearly a worthwhile quest because it permits efficient and surehanded convergence of the most influential variables and actions. Intuition reduces numerical exploration by allowing analysts to see through endless and often extraneous details to those that are essential. Intuition also helps operators avoid mistakes by allowing them to take appropriate and safe actions. In fact, even attempts at automatic identification procedures (e.g., Jung & Karney, 2009, 2008; Jung et al, 2007a, 2007b) require a restricted search space to be computationally practical.

Perhaps one of the more reliable and tested rules of thumb for the transient analyst is to pay attention to the most severe changes in velocity. Velocity changes (whether slow or fast) invariably invoke pressure changes, but when the velocity changes are rapid they can map one-to-one with pressure changes. The constant of proportionality in such a relation is dictated by the well-known and often large water hammer wave speed (Boulos et al, 2006). This leads to one conventional set of transient considerations as well as to the resulting rules associated with velocity control during, for example, filling or routine pump and valve operations. In most guidelines (Jung et al, 2007a; AWWA, 2004, 2002; LeChevallier et al, 2002) and introductory texts (Massey, 1998), this is introduced via the Joukowski equation:

$$\Delta\left(\frac{p}{\gamma}\right) = \pm\,\frac{c}{g}\,\Delta U \tag{1}$$

in which Δ is the change of pressure head, p and γ are the pressure and fluid-specific weight, respectively, ΔU is an instantaneous change in velocity, *c* is the pipe's wave speed, and *g* is the gravitational acceleration. Using Eq 1, it is conceptually simple to describe the pressure rise resulting from the sudden start or stop of fluids flowing in a long uniform pipeline in which the difference between the initial and final velocities is known. However, this relationship is only applicable under highly restricted circumstances: single pipelines, elastic pipe material, and frictionless fluid (Massey, 1998).

The purpose of this article is to highlight the issues involved with the generation of transients from statically pressurized sections. Experiments show that significant and prolonged transients can be generated during depressurization events. Results are presented from two experimental facilities demonstrating the phenomenon.

DEPRESSURIZATION TRANSIENTS

One situation in which it is particularly hard to account for severe transients generated using the Joukowski equation occurs when the velocity of the fluid in a pipeline is equal before and after the operation, resulting in no net change. For example, if a section of pipeline between two valves is pressurized, there will be zero flow velocity between the valves but there must also be zero velocity in the pipelines outside of the valves. If only one of the isolating valves is opened, the pressure release will generate a large transient wave, even though there is no overall net flow in the pipeline. This situation may occur, for example, if valves around the repair of a pipe burst were not carefully opened or if there is a sudden release of pressure from a pipe burst. This can occur whenever an operation attempts to increase the flow rate in a pipe system but is prevented from doing so by any kind of flow restriction at its inlet.

The severity of the transients that depressurization situations generate can mean that lengths of the originally pressurized section and the adjacent pipeline experience negative pressures, frequently dropping to cavitation pressure. This poses two major problems in pipe networks: the generation of vapor bubbles or a column separation and the possibility of intruding contaminants. When the pressure in a pipeline drops to the vapor pressure, column separation occurs at specific locations (e.g., closed ends, high points). The liquid columns are separated by a vapor cavity that grows and diminishes according to the dynamics of the system. The collision of two liquid columns, or of one liquid column with a closed end, may cause a large and nearly instantaneous rise in pressure (Bergant et al, 2006).

There is potential for damage to network assets because of this dynamic effect (Galante & Pointer, 2002; De Almeida, 1991). In addition, contaminants can intrude into pipes through leaks from reduced or negative pressure transients. The low-pressure transients generated by this mechanism will propagate around the network and introduce a considerable risk of drawing untreated and possibly hazardous water into a pipeline network (Meniconi et al, 2011; Collins et al, 2010; McInnis, 2004; Karney, 2003). Soil and water samples have been collected adjacent to drinking water pipelines and then tested for occurrence of total and fecal coliforms, *Clostridium perfringens*, *Bacillus subtilis*, coliphage, and enteric viruses (Besner et al, 2009; Karim et al, 2003). The study by Karim et al (2003) found that indicator microorganisms and enteric viruses were detected in more than 50% of the samples examined.

EXPERIMENTAL STUDY

Results from two sets of experimental studies are presented, providing a high level of confidence in the depressurization phenomenon explored. Results are presented from a recently constructed facility at the University of Sheffield, United Kingdom, a facility developed to explore low and negative transient pressures as part of a study of contaminant intrusion into water distribution systems (Collins et al, 2011, 2010). These tests include the effect of a leak aperture. This is followed by confirmatory results from experiments conducted on an existing facility at the University of Perugia, Italy, designed to explore transient behavior (Meniconi et al, 2010; Brunone et al, 2008) and adding the functionality of sound measurement.

Sheffield test system. A schematic of the Sheffield test setup is shown in Figure 1. The test facility consisted of a 150-m- (492-ft-) long medium-density polyethylene pipe loop (50-mm [2-in.] internal diameter, 6-mm [0.25-in.] wall thickness) to simulate a water distribution pipeline. Wave speed in the pipe loop is approximately 350 m/s (1,150 fps). The system was driven by a 4-kW, variable-speed pump[1] capable of generating up to 45 m (150 ft) static head or 4 L/s (63 gpm) corresponding to a velocity of 2.04 m/s (6.7 fps) at 20 m (65.6 ft) head. Steady-state flows and pressures were set by adjusting the pump speed and the system outlet control valve (Figure 1, object J). The system contained four quarter-turn butterfly valves (Figure 1, objects B, E, G, H). These manually operated valves were used to generate the transients; by closing different combinations, different section lengths could be pressurized. Flow-rate measurements were made with a magnetic flow meter installed at the pump and an ultrasonic meter installed at the system outflow. Pressure recordings were taken at three locations in the system (Figure 1, objects D, F, I), using a pressure transducer (measurement range vacuum ≠ 24 bar)[2] connected to an analog-to-digital converter. Pressure readings were recorded from the system at 400 Hz. Local tap water was used to supply the test rig that was cycled around the system. Figure 2 shows a schematic of the valve and pressure sensor numbering that was used in the tests. Depending on the test conditions required, the identity tags in Figure 2 may relate to different valves or monitors that are shown in Figure 1; however, their relative location is always as shown in Figure 2.

Generating transients with flow change. Initial results were obtained to demonstrate the size of the transients generated from a valve opening when there is a significant resultant flow. The system was initially configured for the tests by first closing the downstream valve—V2—and altering the pump speed to provide the required static pressure. Then with the downstream valve fully open, the upstream valve—V1—was throttled to give the required resultant flow rate in the system, with a constant pump speed. Closing V2 again statically pressurized the system. Data were then collected for the pressure released by a quick opening of V2, with the valve operation taking less than 1 s. Experiments were carried out for resultant flow rates of 1.3 L/s (17.2 gpm) and 2.3 L/s (30.4 gpm) with a static pressure head p_s/γ of 40 m (131 ft).

Generating transients with zero net flow. To generate the statically pressurized system, V2 was first closed and the pump speed was adjusted to give the required static head at the measurement point. V1 was closed after a static system had been achieved. The measured pressure transients were again generated by rapidly opening the downstream butterfly valve manually in less than 1 s. The resultant pressure oscillations were allowed to completely dampen out (30–60 s) before repeating the procedure.

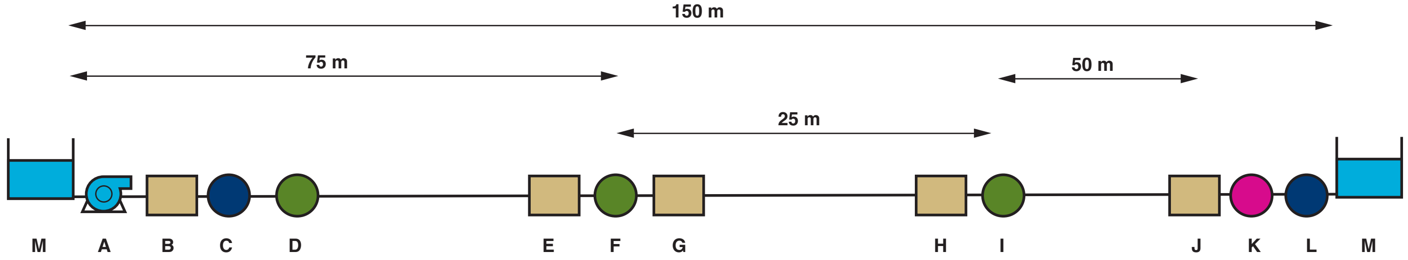
Tests were run with initial static pressure heads, p_s/γ, of 10, 20, 30, and 40 m (33, 66, 98, 131 ft), for three pressurized sections of 20, 75, and 95 m (66, 246, and 312 ft).

Sheffield test results. Figure 3 shows the plot of two transient responses—for different final flow rates—to a fast-acting valve opening recorded at the three pressure sensors shown in Figure 2. Both examples shown correspond to the 95-m (312-ft) length of pressurized section with the upstream valve open to allow either a flow rate of 1.3 L/s (17.15 gpm) or 2.3 L/s (30.4 gpm) after the downstream valve is opened. As expected, a sharp downsurge was registered at the upstream pressure sensors (A and B) as the pressure was released because of V2 opening. At the downstream sensor, an initial upsurge was seen, followed again by a period of oscillation around the final head, which includes at least two short durations of negative pressure. Even in this simple single-pipeline scenario with overall flow changes, the Joukowski equation—and therefore the rule of thumb or intuition—does not accurately describe the dynamics of the system. The Joukowski equation estimates an increased transient magnitude with a greater velocity change. In this experiment, the system with the greater velocity change exhibits a decreased transient response, the pressure pulses are smaller, and the overall decay is quicker, with only two to three peaks before dying away (6–7 s).

Figure 4 shows the transient response when a 95-m (312-ft) length of pipe is pressurized to 40 m (131 ft) static head and then depressurized by quickly opening the downstream valve. Unlike the traces shown in Figure 3, the upstream valve is completely closed, resulting in zero net flow in the pipe. The pressure trace in Figure 4 is characterized by a sharp downsurge at sensors A and B, which drops the local head to the cavitation pressure. This manifests as the trace's flat section prominent at sensor A, but also at sensor B at 7 and 10 s. The first cavitated region at the upstream valve (sensor A) lasts for 1.9 s, after which it collapses, almost instantaneously increasing the head to at least 30 m (98 ft). The head at the upstream valve drops to the cavitation pressure three times, each of decreasing duration, after which the head oscillates around zero approximately 10–12 times before disappearing after about 25 s. Sensor C shows an upsurge and then repeated oscillations down to almost the cavitation pressure. The damping process produces waves, first of triangular form, and then to what appears to be nearly sinusoidal form, typical of visco-elastic effects of the medium-density polyethylene pipes used in the experimental rig (Soares et al, 2008; Covas et al, 2005a, 2005b).

The differences between the pressure traces recorded in Figures 3 and 4 are the result of different upstream boundary conditions. This can also be seen in Figure 5, which is an enlarged

FIGURE 1 Schematic of the Sheffield pipe loop

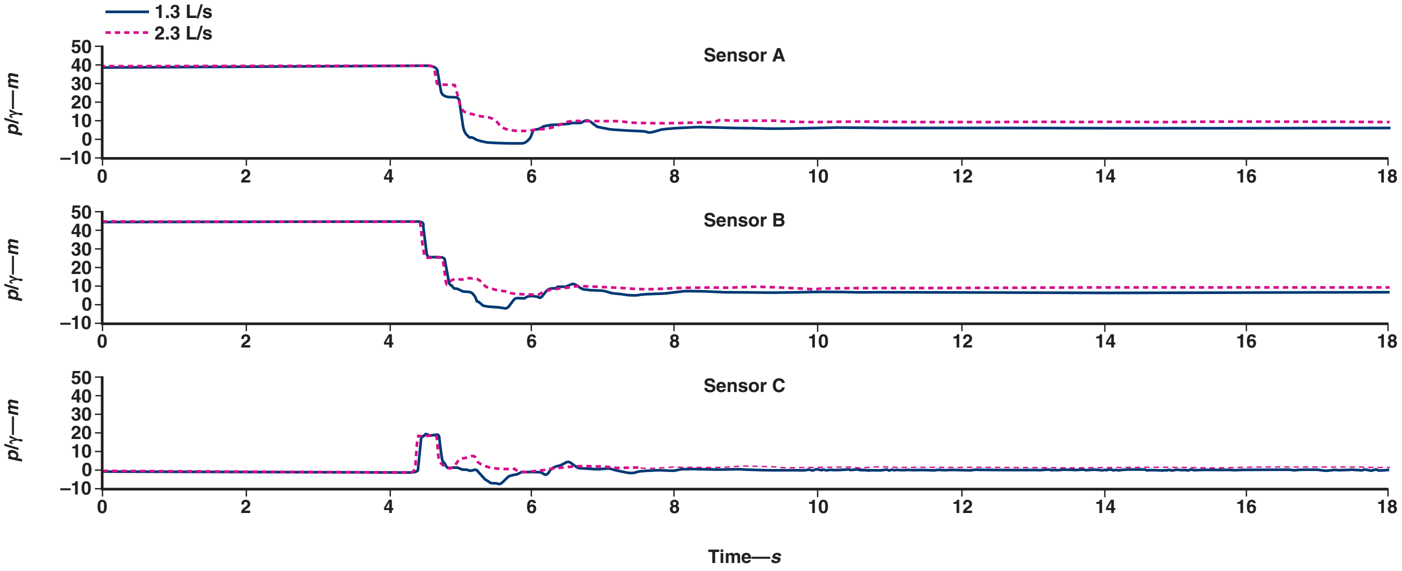


A—pump, B—pump valve, C—pump flowmeter, D—pump pressure sensor, E—test section upstream valve, F—test section pressure sensor, G—test section downstream valve, H—⅔ valve, I—⅔* pressure sensor, J—system control valve, K—dye fluorometer, L—output flowmeter, M—tank*

**Indicates the object is ⅔ of the way around the loop*

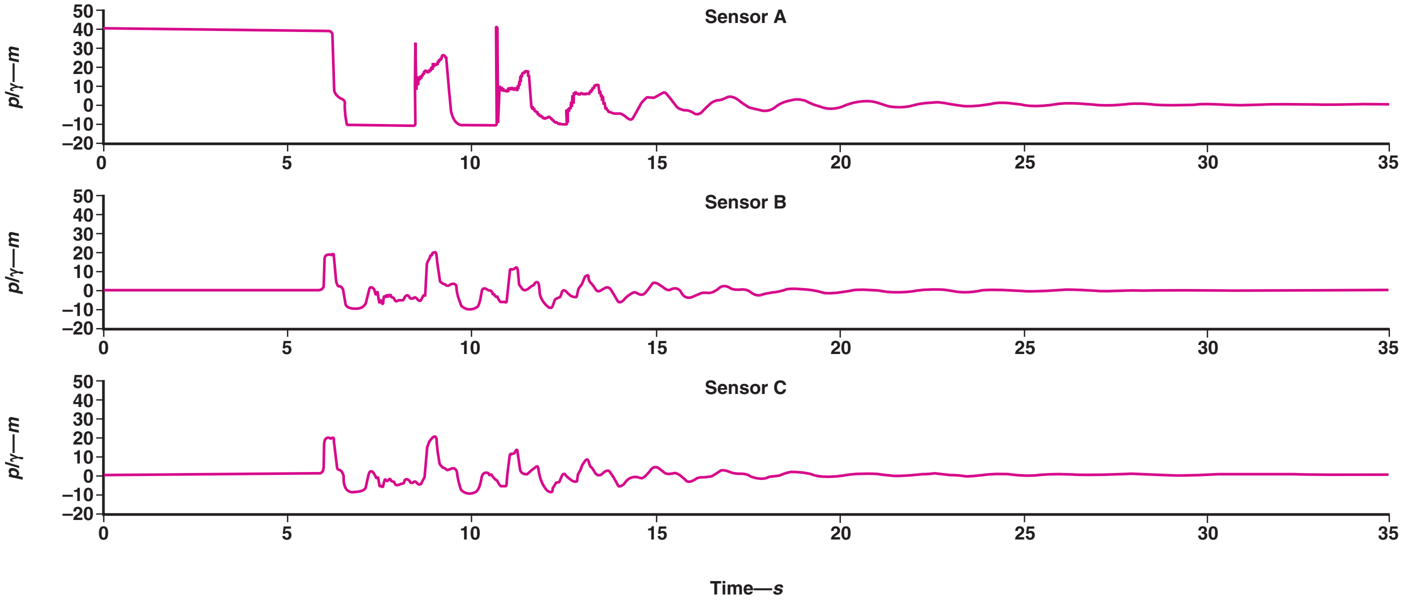
FIGURE 2 Schematic of the pressurized section between two valves (V1, V2) at Sheffield and the location of three pressure sensors (A, B, and C)

FIGURE 3 Transients generated from the fast opening of a valve, in which the upstream valve is not completely closed and a resultant flow occurs



γ—fluid-specific weight, p—pressure

FIGURE 4 Resultant transient from the fast decompression of a length of pipeline*



γ—fluid-specific weight, p—pressure, p_s—static pressure

*A significant amount of cavitation occurs at the upstream valve (sensor A).

view of the pressure traces generated from the downstream sensor C just after valve opening. The pressure rises for all cases are almost identical; it is only when the reflected wave returns that differences between cases with and without residual flow can be seen. This occurs because first some of the wave energy passes through the open valve; then friction from the resultant system flow damps the wave so the return wave is significantly diminished. In the case of no net flow, the pressure drops to about –10 m (–32 ft); with a 1.3-L/s (17.4-gpm) flow it only drops to about –8 m (–26 ft), and with a 2.3-L/s (30.4-gpm) flow in which the valve is open a greater extent, the head does not drop below zero.

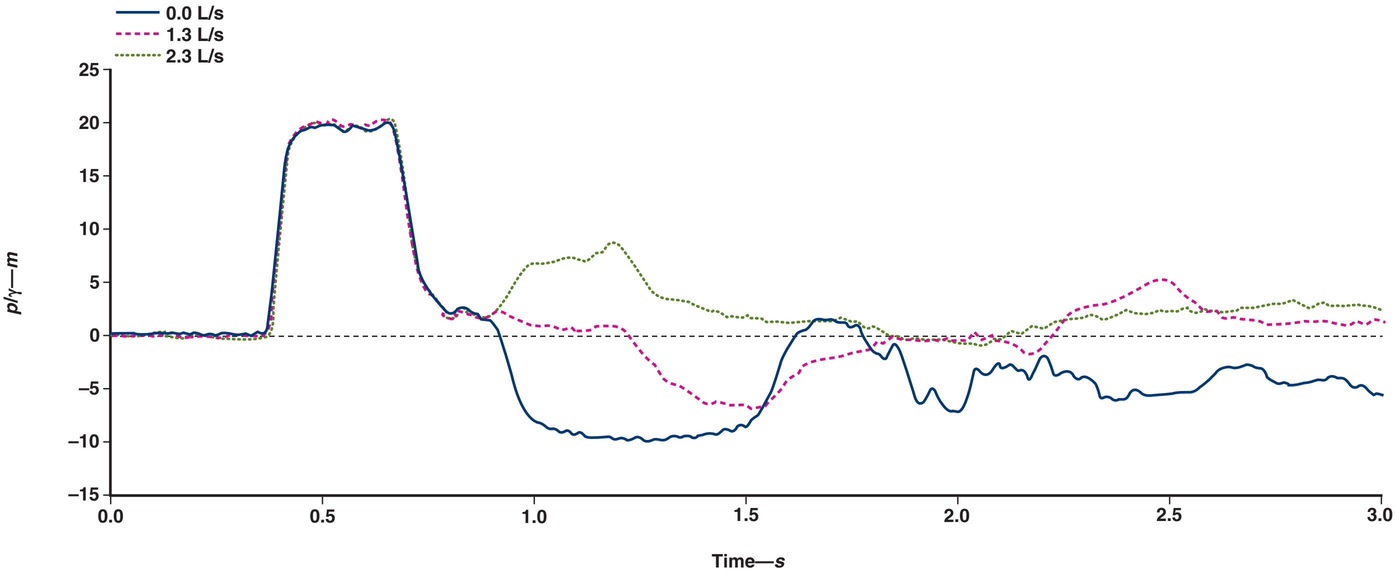
Duration of negative pressures. Intrusion of contaminants can only occur when the pipeline pressure drops below the groundwater's local pressure. Increasing the time that the pressure is below this value increases the risk of intrusion occurring and increases the volume of any intrusion should it occur. Figures 6 and 7 show the total time that the pipeline experiences negative pressure (with respect to the local atmosphere) for repeated section depressurizations at the pressure sensors in Figure 2, objects A and C, respectively. Increasing the initial static pressure in the system is an action that one might intuitively assume would increase the resistance of the system to negative pressures; however, the converse is true: increasing the static pressure initially increases the resultant duration of negative pressures. As the length of pipe that is initially pressurized increases, the duration of negative pressures also increases.

Perugia test system. Laboratory tests carried out at the Water Engineering Laboratory of the University of Perugia confirm that depressurization events often lead to surprisingly severe transient responses (Brunone et al, 2009). The Perugia rig is a 164-m- (538-ft-) long high-density polyethylene pipe (93.3-mm [3.67-in.] internal diameter and 8.1-mm [0.32-in.] wall thickness) with the instantaneous elastic modulus and pressure wave speed equal to 2,300 N/mm^2 (333,586 psi) and 385 m/s (1,263 fps), respectively.

During tests, simultaneous measurements of pressure and a new feature, sound pressure levels—δ—were made. Pressures were measured at 29.7 m (97.4 ft) and 70.6 m (231.6 ft) downstream of the inlet valve, p_N and p_M, respectively, in Figures 8 and 9, and at the outlet valve labeled p_{EV}. Several tests were executed with different values of the initial static pressure head: p_s/γ = 22.1 m (72.5 ft; Figure 8) and 38.6 m (126.6 ft; Figure 9).

Perugia test results. The Perugia system was statically charged to the initial pressure, and the downstream valve was opened with the inlet valve closed. In Figure 8, with p_s/γ = 22.1 m (72.5 ft), during the transient, significant pressure rises occurred along with cavitation at sections M and N. Figure 8 shows that the peaks in the sound level correspond closely to the collapse of vapor cavities during the transient and the sudden increase in the pressure (Figure 8, bottom panel). The sound signal was characterized by a sharp and rapidly propagating "crack" in both of the experimental systems. Such audible reminders of water hammer pressures, which also occurred but were not measured in the Sheffield tests, are often the first indication that column separation has occurred.

FIGURE 5 Overlay of the pressure traces of 0.0, 1.3, and 2.3 L/s (0, 17.2, and 30.4 gpm) resultant flow at sensor C*



γ—fluid-specific weight, p—pressure

****Traces are identical for the first upsurge but are then modified at the downsurge caused by the returning pressure pulse from the upstream valve (V1).***

Similar to the results from Sheffield, increasing the initial static pressure to p_s/γ = 38.6 m (126.6 ft; Figure 9) results in the pressure at points N and M remaining at the cavitation pressure for longer, and the magnitude of the recorded sound increases threefold when the cavitating fluid sections collapse. This increase in the noise is indicative of the increased shock loading that the system undergoes.

DISCUSSION

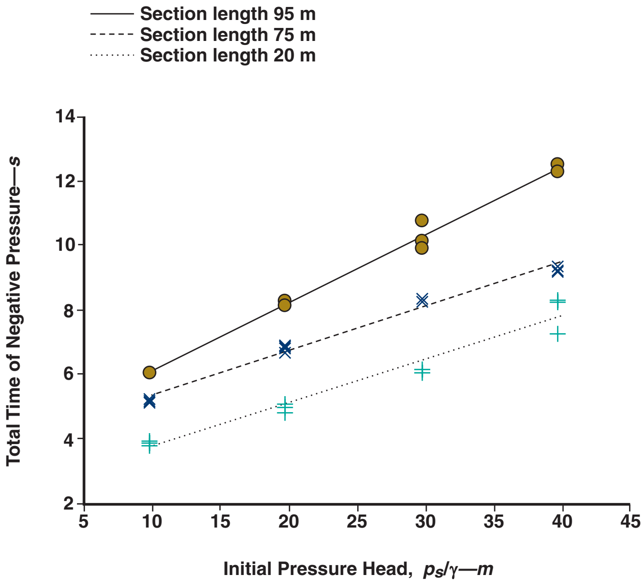
These results were obtained from a facility with polyethylene pipes because they provide slower wave speeds and therefore results can be obtained from shorter pipe lengths than would be possible with metallic pipes. Conceptually, though the results are applicable for all types of pipe, the dominant effect of different materials is to change the characteristic time (i.e., the time for a transient pressure wave to be reflected back to its source) of the system and attenuation of the signal. The magnitude of the initial pressure change will not be affected by pipe material because the lower limit of the pressure is given by the vapor pressure. How the signal propagates and reflections superimpose will be changed, however. Notably, the wave speed where column separation occurs will be largely unaffected by pipe material.

As a deeper reflection on the Joukowski relation would imply, the flow of transient information is a continuous interchange of pressure and velocity information, and it is often unimportant which change initiates the event. Thus whenever networks are under elevated pressure relative to the local environment, there is a nontrivial opportunity for a depressurization event to trigger a destructive transient sequence. This is particularly true for networks with high pressure that are otherwise confined (without an external flow source) because a check valve or dead end tends to lead to the constructive superposition of the pressure drop associated with the primary pressure wave and the reflection from the dead end (Jung et al, 2011). Prediction of the transient response is nontrivial for networks, which are a complex function of pipe-specific properties. A cavitation event will occur if the system is initially statically pressurized at greater than ~ 10 m (32.8 ft). The duration of the negative pressure is a linear function of the initial static pressure for a given system.

An important result of this depressurization is that negative pressures are produced. Durations up to 12 s were recorded in these tests, and for a considerable fraction of this time the pressure was at or near the vaporization point. This provides a significant driving force for the intrusion of contaminants into the distribution network through leaks, air valves, or other cross-connections. Another concern should be the effects of the shock loading on the network. When cavitation is first arrested, the pressure rises sharply from the vaporization pressure up to almost the initial static pressure in an extremely short time. This event is associated with the loud cracking noise and vibration. Although the resulting upsurge pressures are not extreme in magnitude, the strain rate on the pipe walls and other pipe fixtures is large and has the potential of exploiting weak points and causing pipe bursts and other damage.

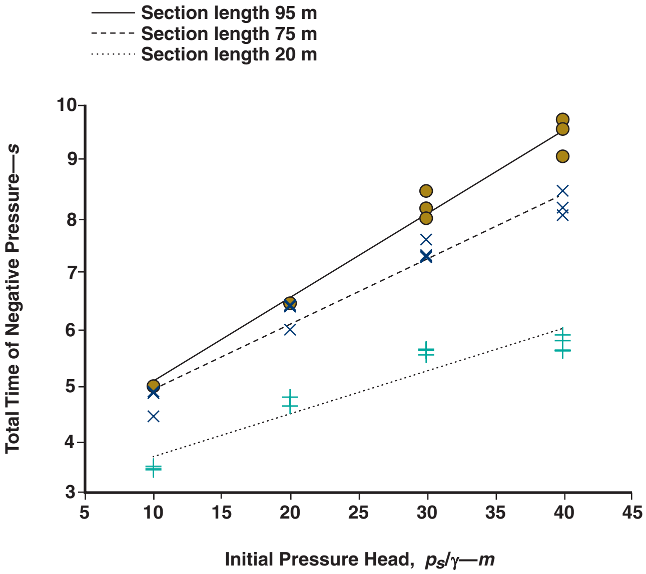
Whether as a result of extreme pressures induced by transients or as a contaminant pathway resulting from low/negative pres-

FIGURE 6 Total time the pipe experienced negative pressures at the pressure transducer downstream (sensor C) of the operated valve



γ—fluid-specific weight, p—pressure, p_S—static pressure

FIGURE 7 Total time the pipe experienced negative pressures at the pressure transducer at the upstream (sensor A) static valve



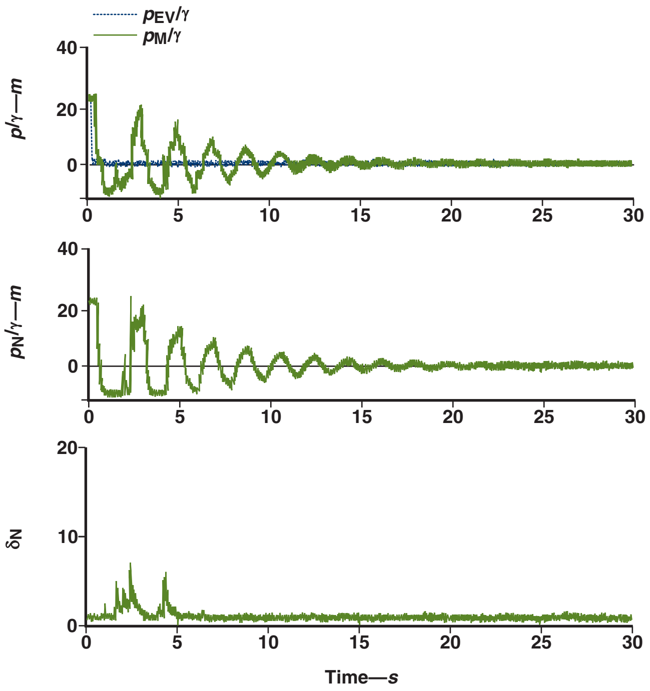
γ—fluid-specific weight, δ—sound pressure level, p—pressure, p_{EV}—pressure at outlet valve, p_M—pressure at inlet valve in section M, p_N—pressure at inlet valve in section N, p_S—static pressure sures, transients and leaks are intrinsically linked. Therefore to assess the effect that a leak to atmosphere has on the propagation of the depressurization wave, a 2-mm circular orifice was tapped into the Sheffield test facility downstream of valve 2 (Figure 2). A 75-m (246-ft) section was statically pressurized to 10 m (32.8 ft) and then released by the fast opening of the downstream valve. The resultant pressure trace is shown in Figure 10 superimposed on the trace generated without the leak. There is only a small difference between the traces at the first negative pressure; however, it becomes apparent after the first full oscillation that the leak provides a significant damping mechanism. As the high pressures are vented through the leak and negative pressures draw air into the pipe, the system is highly damped, and fluctuations disappear after only five oscillations. If water rather than air was being drawn into the system, the damping would still exist but would not be as severe. As a result, the exchange through the leakage aperture poses the risk of intrusion but decreases the severity of the wave, preventing further structural damage.

According to numerical model results, water column separation is more severe the closer the measurement is to the closed inlet, with the reflection point doubling the pressure drop (Jung et al, 2007b). This effect is seen in the experiential results: compare sensors A and B in Figure 4 and sensors M and N in Figures 8 and 9. As the pressure-monitoring point gets closer to the upstream closed valve, the length of time that the pressure is at the vaporization pressure naturally increases—but also the greater the pressure rise is on cavity collapse. During cavitation, the liquid undergoes a phase transformation to water vapor, either as a large cavity or as a series of bubbles (Bergant et al, 2006). The low pressures that drive the cavitation process also cause dissolved air to come out of solution, forming bubbles in the flow. The gaseous phase and cavities induce a decrease in the wave speed in the pipe that in turn increases the characteristic time of the pipe (i.e., the time for reflected waves to return to their generation position). The initial static pressures in the experimental systems drive the cavitation process, and a higher initial pressure causes a greater length of pipe to experience cavitation. These effects can be seen in the change in the wave frequency with time in Figures 4, 8, and 9 and the different initial wave frequency among these figures.

CONCLUSIONS

Water hammer pressures are not only potentially distracting and destructive to network operations, they also have the potential to compromise the water quality of a potable water network through transient intrusion or ingress events. Traditionally and

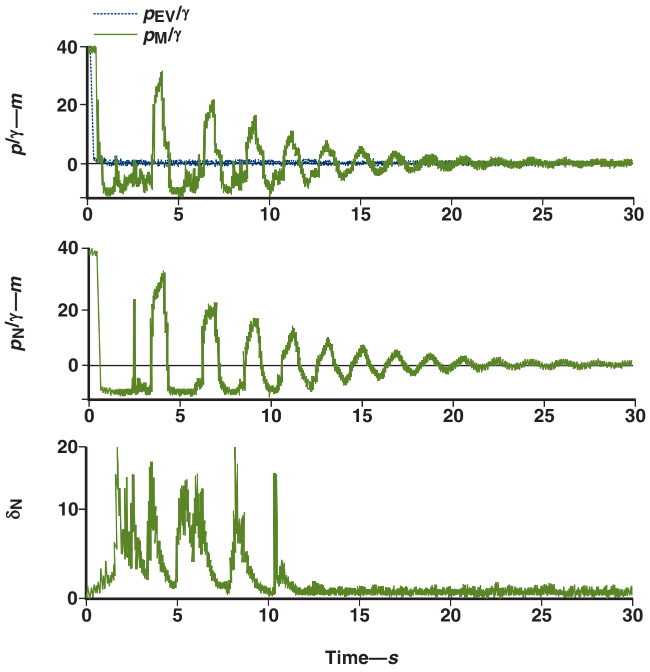
FIGURE 8 Pressure trace, $p_S/\gamma = 22.1$ m (72.5 ft), at sections EV, M, and N, and a time history of δ at section N from the Perugia experiments



Source: Brunone et al, 2009; IAHR, used with permission

γ—fluid-specific weight, δ—sound pressure level, p—pressure, p_{EV}—pressure at outlet valve, p_M—pressure at inlet valve in section M, p_N—pressure at inlet valve in section N, p_S—static pressure

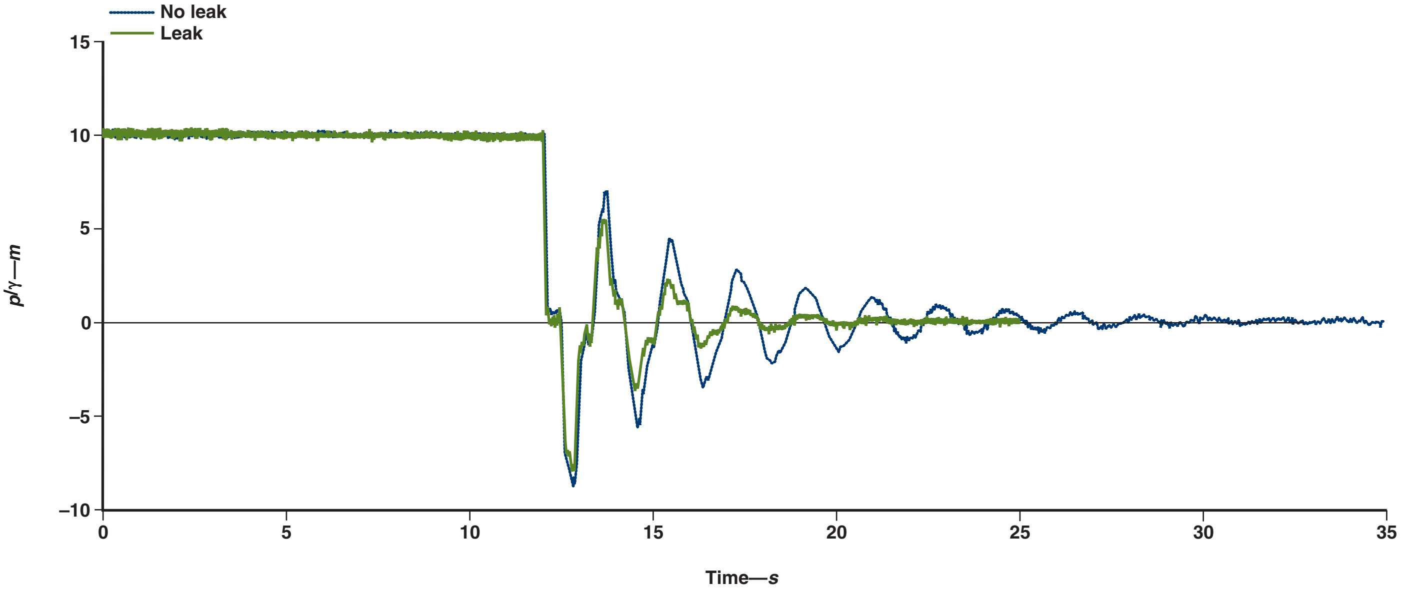
FIGURE 9 Pressure trace, $p_S/\gamma = 38.6$ m (126.6 ft), at sections EV, M, and N, and a time history of δ at section N from the Perugia experiments



Source: Brunone et al, 2009; IAHR, used with permission

γ—fluid-specific weight, δ—sound pressure level, p—pressure, p_{EV}—pressure at outlet valve, p_M—pressure at inlet valve in section M, p_N—pressure at inlet valve in section N, p_S—static pressure

FIGURE 10 Pressure trace showing the effect of a 2-mm (0.08-in.) circular leak on the depressurization wave; significantly higher damping is seen in the response with leak to the test without the leak



γ—fluid-specific weight, p*—pressure*

intuitively, transients have been associated with velocity changes, and the traditional reasoning is that the greater and more rapid the velocity changes, the more severe the resulting transient pressures and threats will be. But there is at least one important case in which a preoccupation with velocity is clearly misleading, the transient associated with rapid system depressurization, particularly in a closed system (i.e., one lacking a sustaining source of fluid). This article shows that through the experimental results collected at two independent laboratories, transients associated with system depressurization are potentially important for water distribution engineers to understand. Although peak transient pressures are unlikely to exceed the initial static pressure, the rapid changes and low pressures that occur may, for instance, adversely impinge on structural performance and increase the risk of contaminant intrusion respectively.

A depressurization might arise by design, as when a drain valve is opened, or by accident, as when a pipe suddenly ruptures or when a confining valve is accidentally and abruptly opened. If the original depressurization wave, which typically drops the local pressure from its initial value to atmospheric, is reflected from a dead end, the superimposition of the incident and reflected waves can be expected to locally create negative pressures and quite likely pressures low enough to initiate cavitation. In general and counter to intuition, the negative pressures resulting from a static depressurization are both more severe and longer lived in a given network with a higher initial pressure, which is ironic because a simplistic argument might assume that higher initial pressures makes a network more resistant to negative pressure. The good news is that the positive pressures that follow cavity collapse seldom reach the level of the initial state pressure in the network, though there is still a structural threat caused by negative pressures themselves and the dynamic effects associated with rapid changes in pressure and strain.

The presence of leaks in a network undergoing a depressurization event has both positive and negative implications for the transient analyst. On the positive side, leaks allow fluid to enter the pipe and can moderate and dissipate the transient pressure waves, making the event appear both milder and less prolonged. But they achieve these structural benefits only by permitting water from outside the pipe to enter the network, creating an obvious water quality risk in potable networks. Surge protection systems should be more consciously and carefully designed than to rely on leaks to offer a surge protection benefit. The real protection from surge pressure arises from understanding its causes and taking steps to treat the system more gently, which often includes taking sufficient time to both close and open valves, and recognizing that the presence of either pressure or velocity can indicate a transient threat to network integrity.

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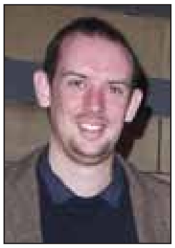
ABOUT THE AUTHORS



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PEER REVIEW

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FOOTNOTES

[1] COR-4 MVIE 1603-6/VR-EB pump, Wilo Multivert, Dortmund, Germany.

[2] 2200 series pressure transducer, Gems Sensors & Controls, Plainville, Conn.

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