It is a common practice to locate air valves at high elevations along water transmission mains. Improper sizing of an air valve could lead to the rapid expulsion of air, which might result in excessive pressure surges at the air valve. Although preventing cavitation at high points requires the rapid inflow of air into the pipeline and therefore a bigger inflow orifice, the use of the same orifice for outflow might result in the rapid expulsion of air. However, using dual-orifice sizes—a larger inflow orifice and a smaller outflow orifice—might prevent undue secondary pressure surges associated with the rapid expulsion of air. This article demonstrates, through two example applications, the positive impact of smaller outflow sizes on pressure surges following the expulsion of air. The study also gives a simplified equation to estimate the magnitude of pressure surges based on pipe characteristics, air-valve characteristics, and pressure inside the valve just before the final release of air.

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Pressure surges
in pipeline systems
resulting from
air releases

T he final release of air through air valves produces a pressure surge. This phenomenon, which results from the rapid deceleration of liquid at the instant the air is fully expelled, is called "air slam." It produces a pressure surge similar to the one produced by the rapid liquid deceleration that results from a valve closure. If the air is released too rapidly, an excessive pressure surge can occur. It is important to design air release valves to avoid excessive pressure surges.

ANALYSIS

The mass flow of air (nonchoking condition) through an orifice is given by (Wood & Funk, 1996; Wylie & Streeter, 1978)

$$m = C_D A_o \left\{ 2p\rho \left(\frac{\gamma}{\gamma-1}\right) \left[\left(\frac{p_a}{p}\right)^{2/\gamma} - \left(\frac{p_a}{p}\right)^{\frac{\gamma+1}{\gamma}} \right] \right\}^{1/2} \qquad (1)$$

in which m is mass flow rate (in slugs/s or kg/s), p is (absolute) pressure of air in the valve (lb/sq ft or N/m^2), p_a is atmospheric pressure, γ is a polytropic constant defining the expansion process, ρ is density of air in the valve (slugs/cu ft or kg/m^3), C_D is coefficient of discharge for the orifice, and A_o is flow area for the orifice (in sq ft or m^2). A polytropic constant of 1.0 implies an isothermal expansion process; 1.4 implies an isentropic process. It is common practice to assume

that $\gamma = 1.2$ when the nature of the expansion process is not known.

If the air pressure increases to 1.89 times atmospheric pressure, the flow becomes choked (i.e., it reaches sonic velocity), and the corresponding mass flow rate of air is given by

$$ m = C_D A_o \left[p\rho\gamma \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{\frac{1}{2}} \quad (2) $$

Equation 1 was used to produce the plots shown in Figure 1. These plots show the theoretical volumetric flow rates in cubic feet per second or cubic metres per second through a 1-ft (0.3-m) orifice using a value of 1.2 for the polytropic constant and a discharge coefficient, C_D = 1. The plots show actual volumetric flow rates based on the air density at the pressure in the pipe and the flow rate based on standard conditions (atmospheric pressure). These plots can be used to quickly determine the flow rate through any orifice by multiplying the value on the x-axis of Figure 1 by $C_D d^2$ in which d is the actual diameter of the orifice in feet or metres. The discharge coefficient, C_D, can vary from 0.45 to 0.75. A value of 0.62 is recommended if no data for this value are available.

For example, the flow rate out of a 2-in. (50-mm) orifice under 10 ft (3 m) water of pressure is determined as follows. From Figure 1, the values on the x-axis corresponding to 10 ft (3 m) of pressure are 530 fps (161 m/s; standard) and 430 fps (131 m/s; actual). Using C_D = 0.62 and d = 0.167 ft, the flow rates can be computed as 9.13 cfs (0.26 m³/s; standard) and 7.75 cfs (0.22 m³/s; actual), by multiplying the x-axis values from Figure 1 by (0.62)(0.167)². An additional check may be made using the table for air discharge in AWWA M-51 (2002), which gives a discharge rate of 10.4 cfs (0.34 m³/s through a 2-in. (50-mm) orifice at 10 ft (3 m) pressure using a C_D = 0.7. Adjusting this to C_D = 0.62 gives a standard flow of
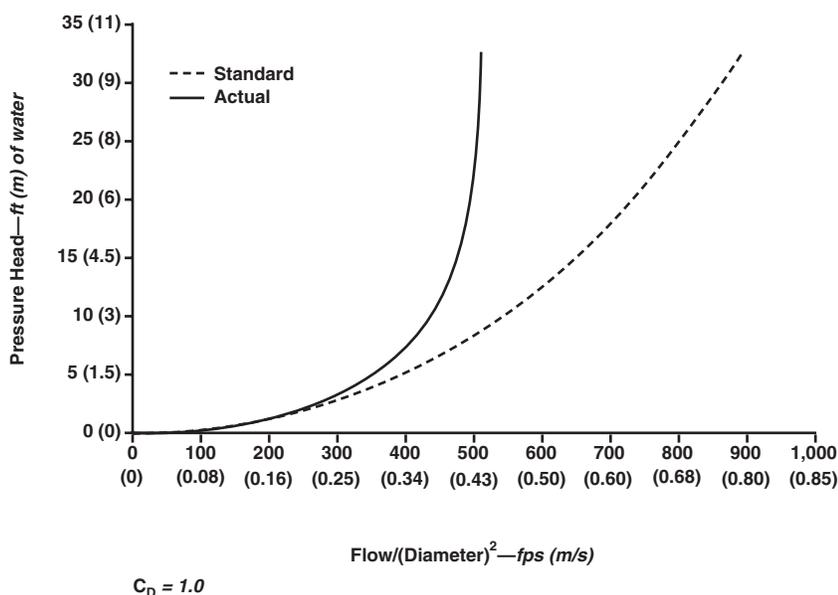
FIGURE 1   Flow of air through an orifice

$C_D = 1.0$

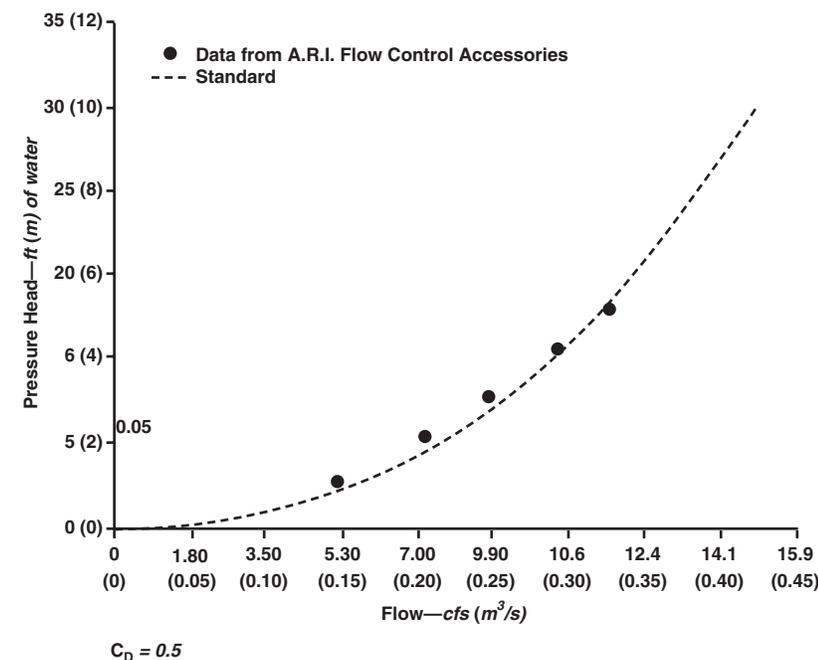**FIGURE 2   Comparison of air-valve performance data and theoretical predictions**

$C_D = 0.5$

FIGURE 3   Conditions before and after an air slam

Q_A = air pressure
Q_A = volumetric air flow
d_o = diameter of orifice
d_p = diameter of pipe
$Q_1\,Q_2$ = initial volumetric flows in pipes 1 and 2
Q_3 = final volumetric flows
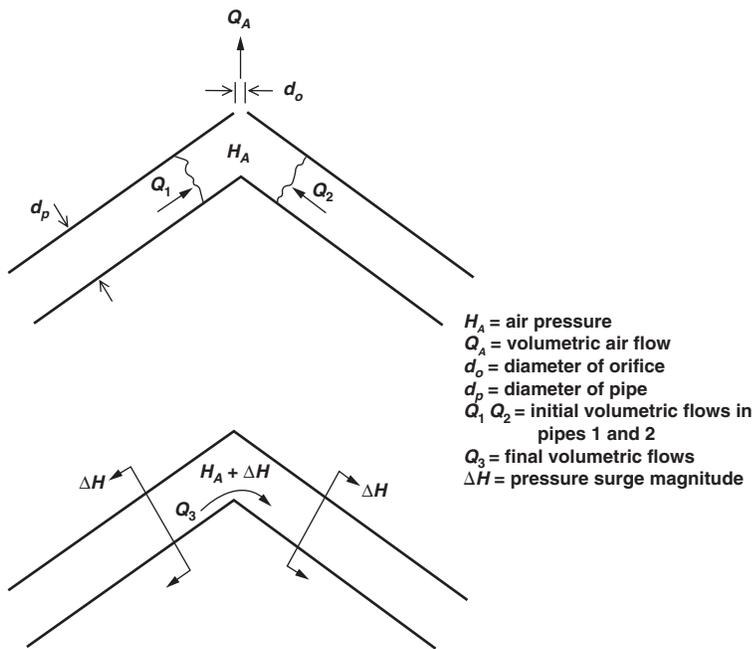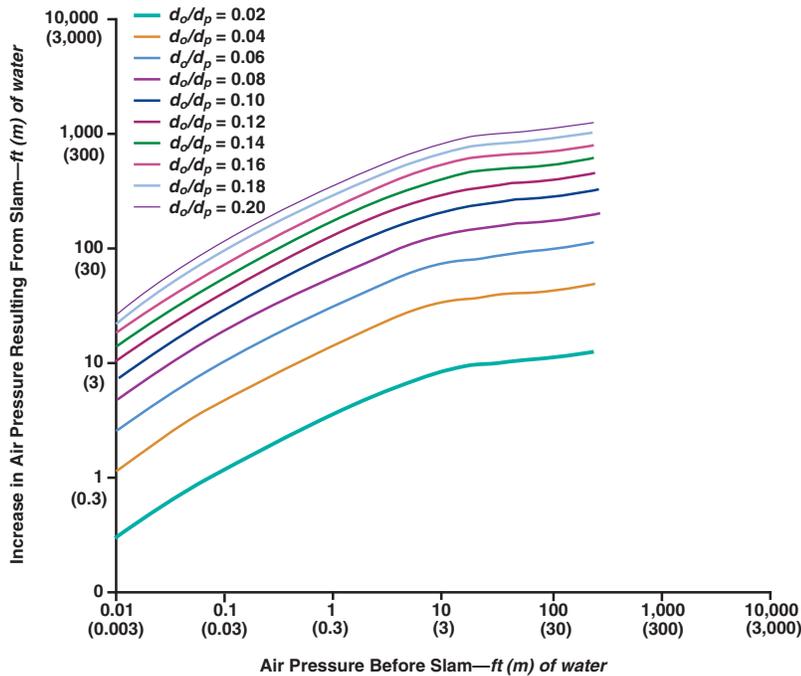ΔH = pressure surge magnitude

FIGURE 4   Air-slam pressures for different outlet orifice sizes

9.21 cfs (0.26 m³/s). The slight difference may be due to the use of a different value for the polytropic constant.

COMPARISON OF THEORY WITH PERFORMANCE DATA

Manufacturers provide performance data for air valves. Figure 2 presents some data from A.R.I. Flow Control Accessories (2001) for a 2 in. (50 mm) orifice. Also shown is the theoretical curve using Eq 1 with a C_D = 0.60. It can be seen that the comparison of the theoretical and actual performance for this air valve is very good.

In many designs, the C_D required to account for the actual performance may be much lower than 0.62. This value applies to an ideal situation in which the orifice is circular and the approach to the orifice is unobstructed. Performance data on various air valves show that the C_D can be lowered considerably by the configuration of the air valve. For example, a rectangular orifice requires a C_D around 0.21 to account for the inefficiency of the rectangular shape.

PRESSURE SURGE RESULTING FROM AIR SLAM

Figure 3 shows conditions just before and after all the air is expelled through the orifice and defines the terms in Eqs 3 through 6. For simplification, it is assumed that the two connecting pipes have the same properties. When the air pocket collapses, a pressure surge of magnitude ΔH (feet or metres) is generated. The basic water hammer relationship, which relates change in flow rate to the resulting pressure surge, may be written as

$$\Delta H = \frac{C}{gA}\,(Q_1 - Q_3) \qquad (3)$$

$$\Delta H = \frac{C}{gA}\,(Q_2 + Q_3) \qquad (4)$$

in which g is the gravitational acceleration, C is the wave speed in the pipes, and A is the cross-sectional area of the pipes.

Equations 3 and 4 can be combined to give

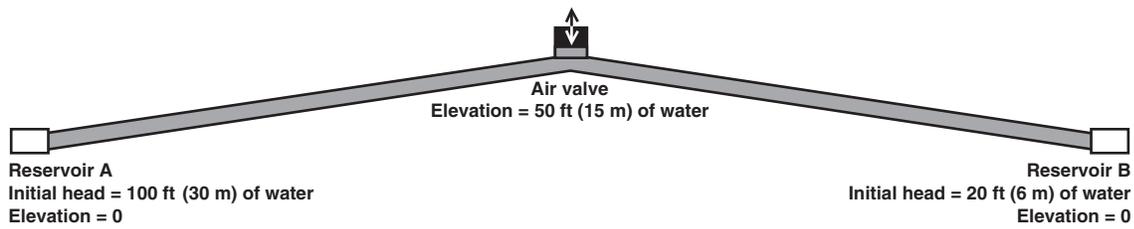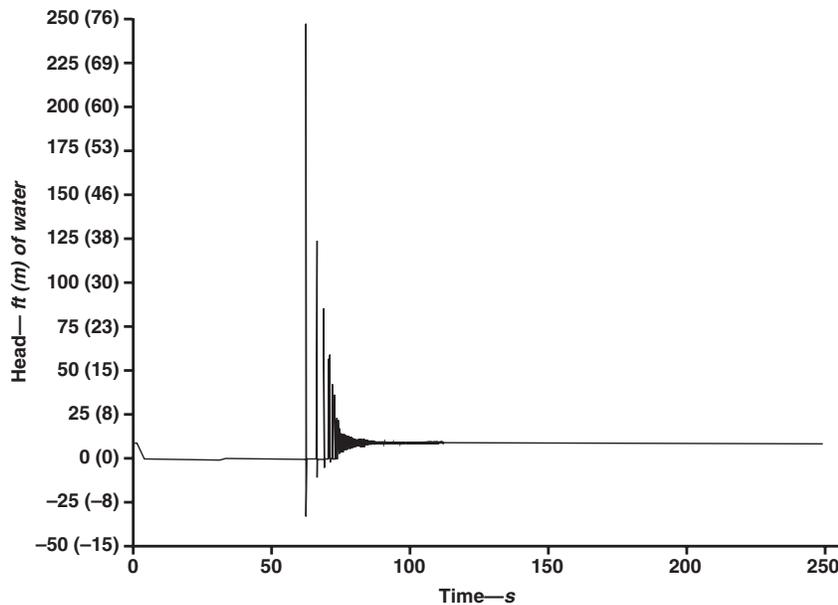**FIGURE 5** Transient flow model to calculate air slam

Air valve
Elevation = 50 ft (15 m) of water

Reservoir A
Initial head = 100 ft (30 m) of water
Elevation = 0

Reservoir B
Initial head = 20 ft (6 m) of water
Elevation = 0

FIGURE 6 Surge analysis for a 4-in. (100-mm) orifice

$$\Delta H = \frac{C}{gA}\frac{(Q_1 + Q_2)}{2} \tag{5}$$

Just before the collapse of the air pocket, it can be assumed that $Q_A = Q_1 + Q_2$, and Eq 5 may be written as

$$\Delta H = \frac{C}{gA}\frac{Q_A}{2} \tag{6}$$

This assumption, which ignores compressibility effects on the continuity relation, is evaluated in the section ("Example Calculations") by comparing the results with those obtained considering compressibility effects. Making use of the information from Figure 1 and Eq 6, the magnitude of an air-slam pressure surge can be predicted given the air pressure before the slam:

The actual volumetric flow of air, Q_A, is

$$Q_A = Q_p\, d_o{}^2 C_D \tag{7}$$

in which Q_p is the value from the plots (Figure 1). Assuming $C_D = 0.62$, Eqs 6 and 7 can be combined to give:

$$\frac{\Delta H}{C/g} = 0.3944 Q_p \left(\frac{d_o}{d_p}\right)^2 \tag{8}$$

Fitting a power curve for the standard air-flow plot shown in Figure 1 yields (goodness-of-fit, $R^2 = 0.9952$):

$$Q_p = e^{-0.029(\ln H_A)^2\,+\,0.425\,(\ln H_A)\,+\,5.206} \tag{9}$$

Combining Eqs 8 and 9 results in

$$\frac{\Delta H}{C/g} = 0.3944 \left\{ e^{-0.029(\ln H_A)^2\,+\,0.425(ln\,H_A)\,+\,5.206} \right\} \left(\frac{d_o}{d_p}\right)^2 \tag{10}$$

Equation 10 may be used to calculate the magnitude of pressure surge following the expulsion of air for non-choking conditions. A similar equation may be obtained

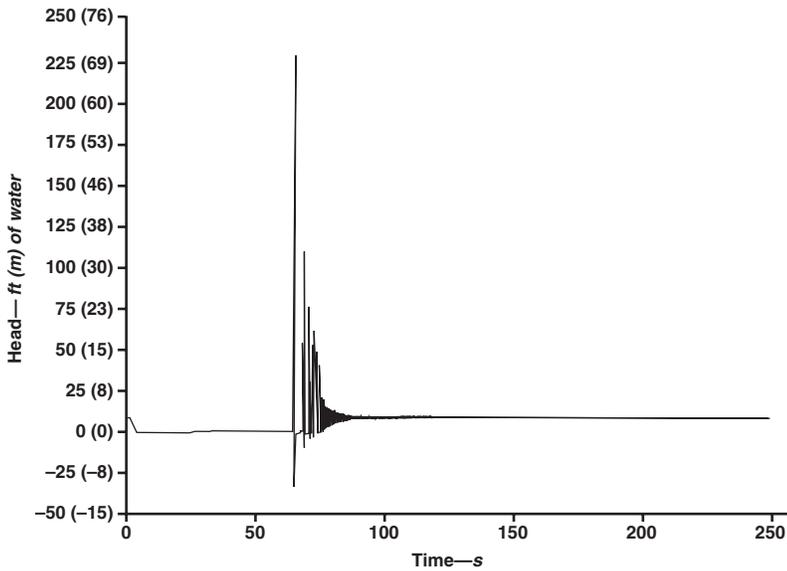## FIGURE 7 Surge analysis for a 2-in. (50-mm) orifice

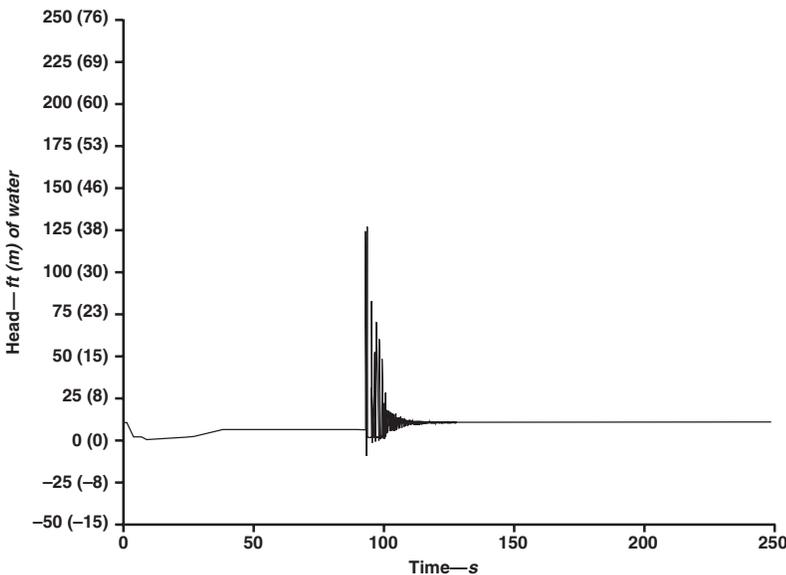## FIGURE 8 Surge analysis for a 1-in. (25-mm) orifice

TABLE 1 Summary of pressure increases through different-size orifices following expulsion of air

Orifice Size in. (mm)	Head in Air Valve (H_A) feet of water (psi)	ΔH, Eq 10 feet of water (psi)	ΔH Surge Analysis feet of water (psi)
4.0 (100)	0.059 (0.026)	236.4 (102.3)	237.8 (102.9)
2.0 (50)	0.825 (0.358)	228.4 (98.9)	218.1 (94.4)
1.0 (25)	4.690 (2.030)	111.6 (48.3)	120.6 (52.2)
0.5 (12.5)	7.810 (3.380)	33.4 (14.5)	42.3 (18.3)

for airflow under choking conditions as follows ($R^2 = 0.992$):

$$\frac{\Delta H}{C/g} = 0.3944 \, (0.465 \, H_A + 494) \left(\frac{d_o}{d_p}\right)^2 (11)$$

Figure 4 depicts the plot of Eqs 10 and 11 for a range of d_o/d_p ratios. Figure 5, in conjunction with a transient modeling program, would help engineers to arrive quickly at an appropriate outflow orifice size. For example, if the air pressure in a 5-in. (127-mm) outflow orifice on a 24-in. (600-mm) pipeline just before air slam is 10 ft (3 m) of water as determined from a transient analysis study, the corresponding increase in pressure after the air slam would be about 900 ft (274 m). If it is desirable to limit the air-slam pressure to less than 100 ft (30 m), the designer would choose an outflow orifice size of about 1.5 in. (38 mm) and evaluate its adequacy.

EXAMPLE CALCULATIONS

A transient flow model was set up to produce an air slam at an air valve and compare the result to that given by Eq 10. The transient flow model utilizes Eq 1 to calculate the flow out of the orifice and accounts for the compression of the entrapped air. Figure 5 shows the schematic for the pipeline system modeled. The head on the left of the valve is lowered from 100 ft (30 m) to 20 ft (6 m) in 10 s then raised back up to 100 ft (30 m) in the next 10 s. An air valve with a 4-in. (100-mm) inlet orifice and an outlet orifice varying from 4 in. (100 mm) down to 0.5 in. (12.5 mm) was analyzed. The air valve opens to admit air when the head is lowered below atmospheric pressure and then expels the air when the head increases. For each case, the head reaches a constant value for significant periods before the air slam occurs.

Table 1 summarizes pressure changes when all air is expelled through different orifice sizes, and Figures 6 through 9 show the transient responses predicted from a surge analysis for each of the four cases. For the surge analysis, the compressibility of the air within the air valve is fully taken into account. The close comparison between the results shows that the continuity

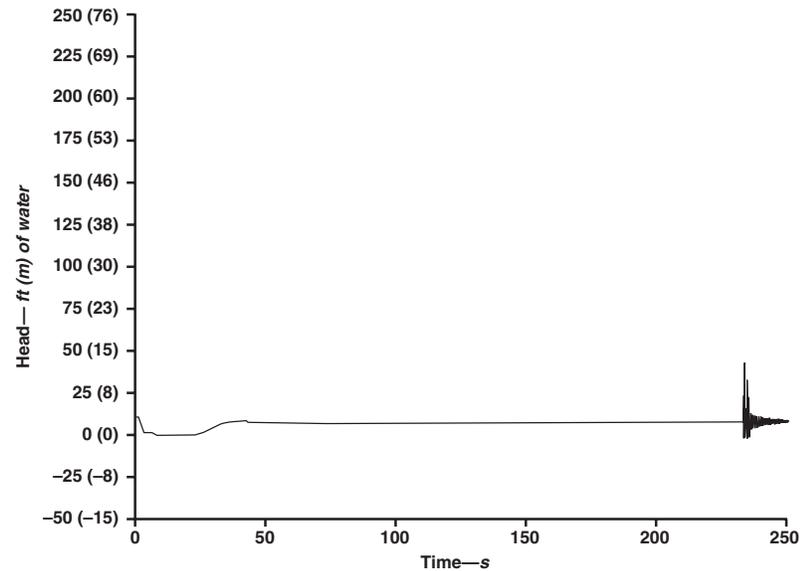assumption used to obtain Eq 10 is justified.

Similar results were documented on a more complex water transmission main. The schematic for this example pipeline is shown in Figure 10. This pipeline comprises more than 8,000 ft (2,438 m) of 12-in. (305-mm) line with a 165-hp (123-kW) pump pumping from a ground-level storage facility to an elevated storage tank. A 3-in. (75-mm) air valve is located at the highest elevation point (50 ft [15 m] higher than the ground-level storage facility) along the pipeline profile. Transient condition for this pipeline was generated by a 5-s controlled shutdown (linear variation in pump speed) of the pump at time $t = 5$ s followed by a 5-s pump startup. There is a 30-s lag between the pump shutdown and the subsequent pump startup.

Figures 11 through 13 show the transient response from surge analysis for three outflow orifice sizes: 3 in.

FIGURE 9   Surge analysis for a 0.5-in. (12.5-mm) orifice

(75 mm), 1 in. (25 mm), and 0.5 in. (12.5 mm). Clearly, using the 0.5-in. (12.5-mm) orifice results in an essentially negligible secondary transient (compared with the other two orifice sizes) because of air slam. However, the performance of a 1-in. (25-mm) orifice might be adequate as well, based on the capacity of the pipe material to withstand surge pressures. In this case, it might be prudent to use a 1-in. (25-mm) orifice because it expels the air more quickly than the 0.5-in. (12.5-mm) orifice.

SUMMARY AND CONCLUSIONS

Air valves are an integral part of long pipelines passing through undulating terrains. Although large inflow orifices are warranted to alleviate cavitation conditions during transient events, same-size outflow orifices could sometimes result in detrimental pressure surges following the final release of air. Through two example applications, this article shows the impact of outflow orifice size on the surge pressures resulting from the final release of air. Both examples show that an outflow orifice smaller than the inflow orifice is desirable to alleviate undue secondary pressure surges caused by the final release of air. In one of the applications, a 0.5-in. (12.5-mm) outflow orifice resulted in an air-slam pressure of less than 100 ft of water (30 m) compared with nearly 550 ft (168 m) of air-slam pressure resulting from a 3-in. (75-mm) outflow orifice. The article also presents a simplified equation for estimating pressure surges based on the pressure head before the final release of air and on other known pipe and valve characteristics. This equation ignores the compression of entrapped air within the air valve, but the predictions from the simplified equation compare well with

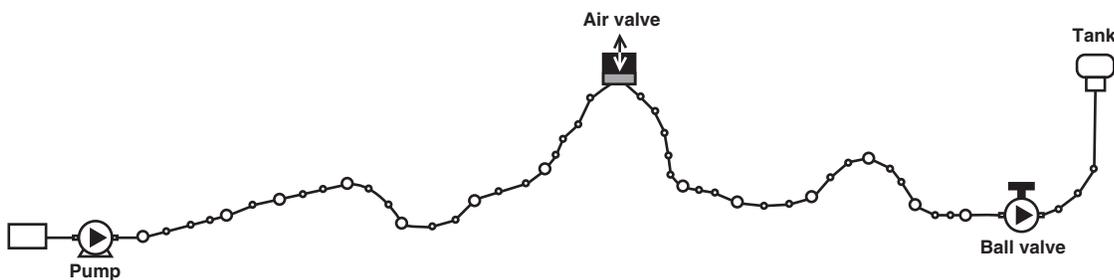FIGURE 10   Pipeline schematic example 2

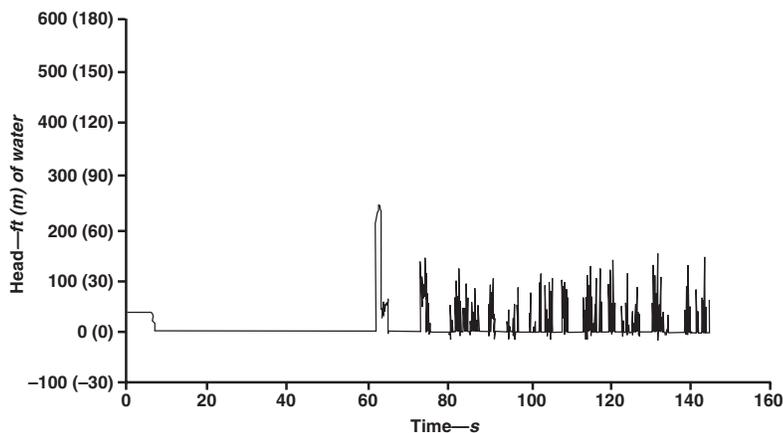**FIGURE 11 Surge analysis for example 2, 3-in. (75-mm) orifice**

FIGURE 12 Surge analysis for example 2, 1-in. (25-mm) orifice
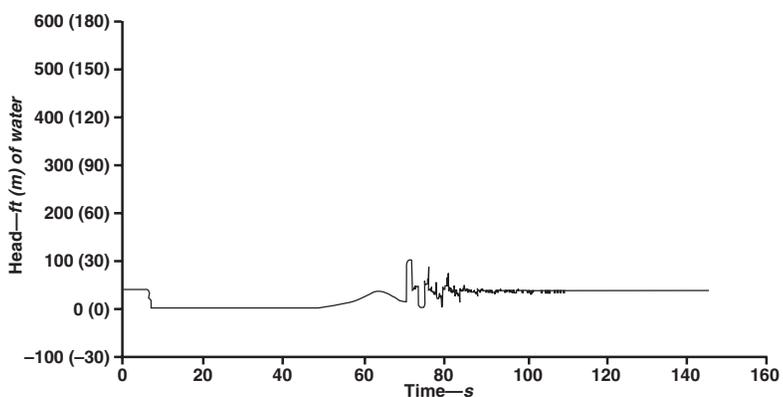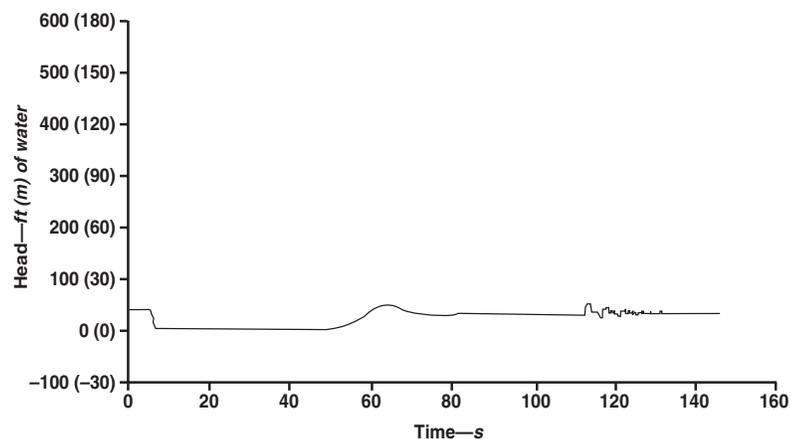

FIGURE 13 Surge analysis for example 2, 0.5-in. (12.5-mm) orifice

the calculations from a transient analysis program that takes the compression effects into account.

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FOOTNOTES
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If you have a comment about this article, please contact us at journal@awwa.org.

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