Simplified Analysis of Water Hammer

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Use this graphical method to quickly and reliably determine the main data — wave celerity, critical time, maximum head developed in the maximum pressure time and the minimum head developed in the critical time — produced by water hammer.

Water hammer is generally defined as a pressure surge or wave caused by the kinetic energy of a fluid in motion when it is forced to stop or change direction suddenly, such as in the slow or abrupt startup or shutdown of a pump system. It can also occur because of other operating conditions, such as turbine failure, pipe breakage or electric power interruption to the pump's motor.

Today, informatics methods are commonly used to perform complex water hammer calculations. However, the lack of information about certain physical flow properties, as well as the intricacy in handling complicated equations make this phenomena analysis difficult. The objective of this paper is to provide a practical and simplified methodology to calculate four main phenomenon parameters of water hammer:

- velocity of the pressure wave or celerity
- phenomena critical time
- maximum head developed in the maximum pressure time
- minimum head developed in the critical time.

Equations and basic considerations

One of the most basic equations for the maximum pressure gradient calculation is Joukowsky's equation:

$$h_{w\,max} = (a)(v)/g \tag{1}$$

where: $h_{w\,max}$ is the maximum fluid elevation head to water hammer, ft; a is the wave celerity, ft/s; v is the flow velocity, ft/s; and g is the gravitational acceleration constant, ft/s^2.

The volumetric flow is given as:

$$Q = vA \tag{2}$$

where A is the flow area, ft^2. A can be defined as:

$$A = \pi D_i^2/4 \tag{3}$$

where D_i is the internal diameter of the pipe, in. Substituting Eqs. 2 and 3 into Eq. 1 and solving for a, yields:

$$a = \left(\frac{g\,\pi}{4}\right)\left(\frac{h_{w\max}\varepsilon^2}{Q}\right)\left(\frac{D_i}{\varepsilon}\right)^2 \tag{4}$$

where ε is the pipe thickness, in.

Eq. 4 can then be rewritten as:

$$a = \left(\frac{1}{\left(\frac{\rho}{g}\right)\left(\frac{1}{K}+\left(\frac{D}{\varepsilon}\right)\left(\frac{C_1}{E}\right)\right)}\right)^{1/2} \tag{5}$$

where ρ is the density, lb/ft^3; K is the liquid compressibility volume factor, lb/in^2; C_1 is Poisson's ratio; and E is the maximum yield stress, lb/in^2. These equations were used to generate Figures 1–3.

When the valve that stops the fluid flow is closed in a time slower than the critical time (this reduces the effect of water hammer), the Allievi equation is used:

$$\Delta h = \frac{h_o}{2}\left(C^2 \pm C\left(4 + C^2\right)^{0.5}\right) \qquad (6)$$

$$C = \frac{LV}{gh_0 t_c} \qquad (7)$$

$$v = \frac{4Q}{\pi D_i^2} \qquad (8)$$

where: C is a valve constant; h_0 is the head pump, ft; L is the length, ft; V is the velocity, ft; and t_c is the time to close the valve. Substituting Eqs. 7 and 8 into Eq. 6 results in:

$$\Delta h = \frac{h_o}{2}\left(\left(\left(\frac{1}{h_o}\right)\left(\frac{4}{g\pi}\right)\left(\frac{LQ}{D_i^2 t_c}\right)\right)^2 \pm \left(\left(\frac{1}{h_o}\right)\left(\frac{4}{g\pi}\right)\left(\frac{LQ}{D_i^2 t_c}\right)\right)\left(4 + \left(\left(\frac{1}{h_o}\right)\left(\frac{4}{g\pi}\right)\left(\frac{LQ}{D_i^2 t_c}\right)\right)^2\right)^{0.5}\right) \qquad (9)$$

the right side to determine the quotient value t_c/L. The value of $h_{w\,max}\varepsilon^2/Q$ is determined by observing the value of the vertical curve at which D/ε and the density in °API meets. With the knowledge of the value of $h_{w\,max}\varepsilon^2/Q$, the maximum pressure with instant valve closing time can be obtained. This value should be added to the system's pressure to determine the system overpressure.

The maximum and the minimum head, with different valves closing can be calculated using Figure 4, which plots the pump head against the maximum pump head to water hammer. It also shows a family of curves with different LQ/D^2t_c values. Knowing the values for the pump head and LQ/D^2t_c, the maximum and minimum pressure that the system can handle can be determined by drawing a horizontal line from the point that the pump head and LQ/D^2t_c intersects.

Methodology

The simplified graphic methodology is based on the simple nomograms developed for pipeline transportation of hydrocarbons (piping API-5L-X52 of carbonated steel). Figures 1–3 plot the wave celerity on the y-axis and the diameter divided by the pipe thickness in the x-axis for commercial LPG, crude oil and water, respectively. Also plotted in Figures 1–3 are the different values of density in degrees (°API) and the quotient value, $h_{w\,max}\varepsilon^2/Q$. Using Figures 1, 2 or 3, the maximum head at the instant the valve closes or the pump stops can be calculated.

Given the values of D/ε and the density in °API, the wave celerity, $h_{w\,max}\varepsilon^2/Q$ and t_c/L can be determined. This is done by drawing a horizontal line from the intersection to the left side of the figure to determine the wave celerity, and to

Nomenclature

a	= wave celerity, ft/s	L	= length, ft
A	= flow area, ft^2	Q	= volumetric flow, ft^3/s
C	= valve constant as defined by the Allievi Eq.	t_c	= close time valve, s
C_1	= Poisson's ratio	v	= flow velocity, ft/s
D_i	= internal diameter, in.	V	= velocity, ft/s
E	= maximum yield stress, lb/in^2	X	= value of the quotient obtained in Figure 4
g	= gravitational acceleration constant, ft/s^2		
h_o	= pump head, ft	**Greek Letters**	
h_w	= fluid elevation head to water hammer, ft	μ	= pipe thickness, in.
K	= liquid compressibility volume factor, lb/in.^{2}	ρ	= density, lb/ft^3

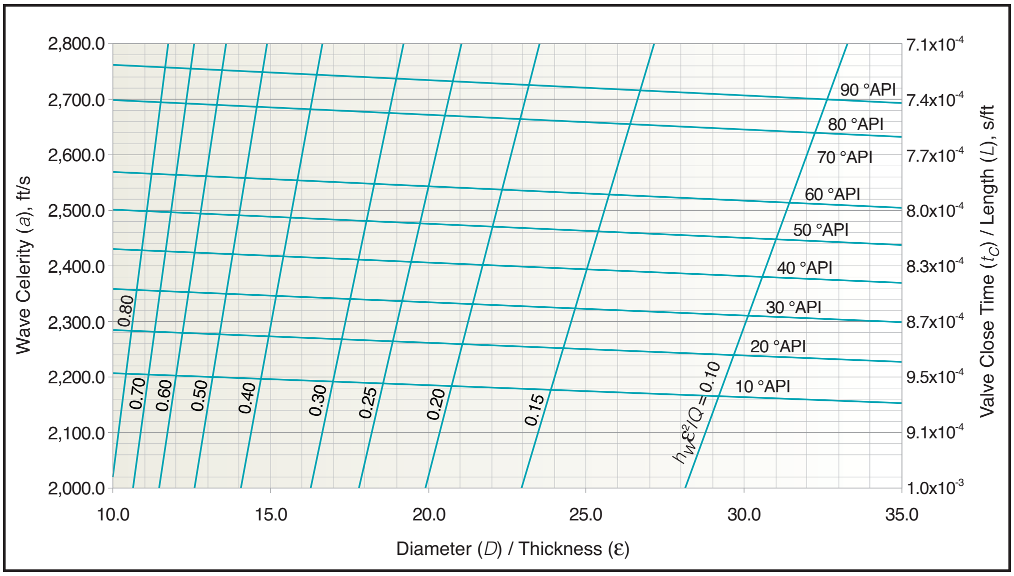
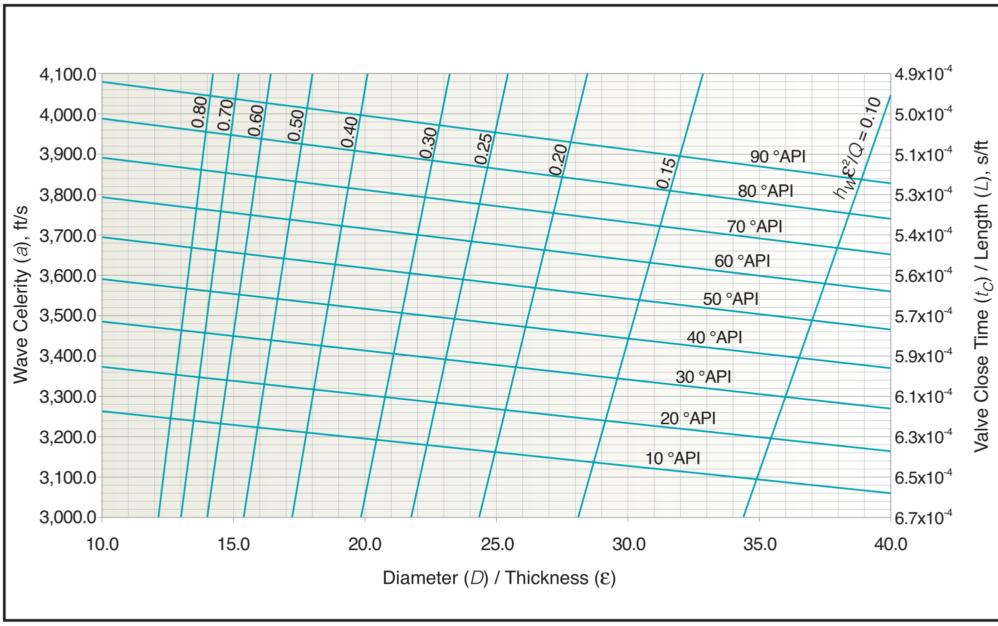
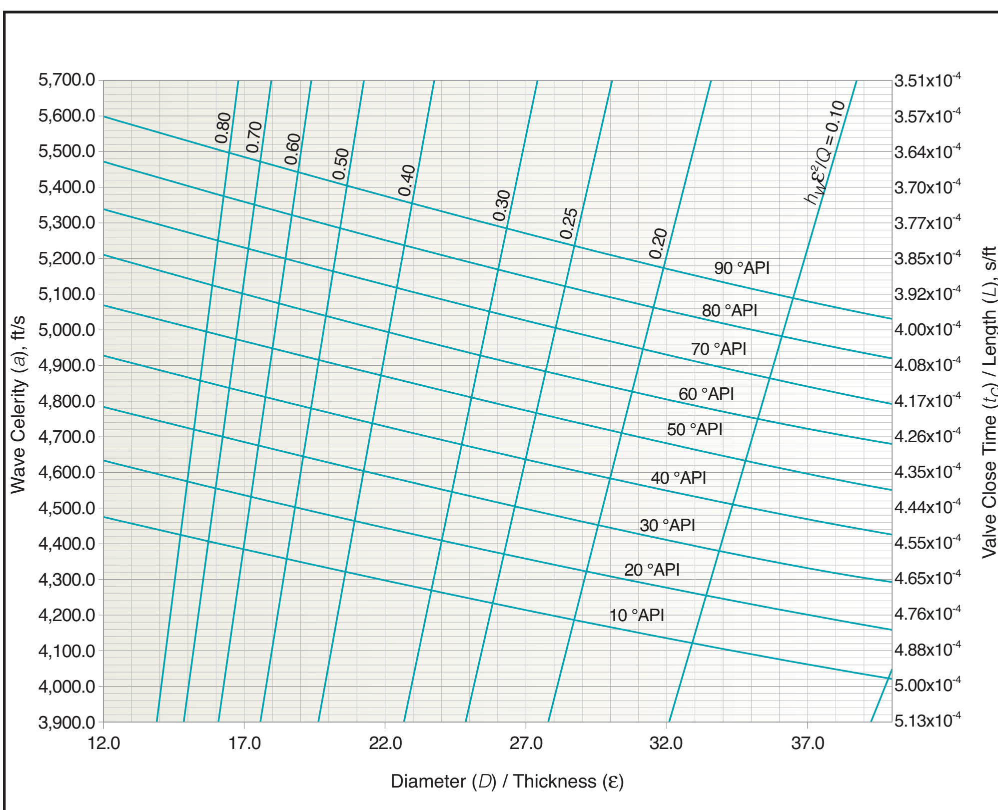


Figure 1. Wave celerity vs. D/ε vs. valve close time for commercial liquefied propane gas (LPG; volume factor = 67,000 lb/in.^{2}) in carbon steel pipe.



■ Figure 2. Wave celerity vs. $D/ε$ vs. valve close time for crude oil (volume factor = 150,000 lb/in.^{2}) in carbon steel pipe.



■ Figure 3. Wave celerity vs. $D/ε$ vs. valve close time for water (volume factor = 300,000 lb/in.^{2}) in carbon steel pipe.

Sample calculation

A 12-in. pipe used to transport hydrocarbons (commercial LPG with a density of 51.4 lb/ft^3) with 40°API has a length of 12 km and a flow of 25,000 bbl/d. The pipe is constructed from carbonated steel API-5L-X-52 and has a constant thickness of 0.406 in. The pump's discharge pressure is 400 lb/in.^{2} and the valve section closing time is 60 s. Calculate the: maximum pressure; maximum pressure critical time; maximum pressure with a valve closing time of 30 s; and overpressure.

Calculate the maximum pressure. First, determine $D/ε$. Start by calculating the internal diameter:

$$D = 12 \text{ in.} - ((2)(0.406 \text{ in.})) = 11.18 \text{ in.} = 0.93 \text{ ft}$$

Therefore:

$$D/ε = (11.18 \text{ in.})/(0.406 \text{ in.}) = 27.53$$

The maximum system pressure is:

$$\text{System pressure} = (400 \text{ lb/in.}^2)(144)/(51.4 \text{ lb/ft}^3) = 1{,}120.6 \text{ ft}$$

Calculate the maximum pressure critical time. Using Figure 1, starting at $D/ε = 27.53$, draw a vertical line until it intercepts the 40°API line. At this intersection, the following information is obtained:

a = 2.389 ft/s
$h_{w\,max}\,\varepsilon^2/Q = 0.124$
t_c/L = 0.00083 s/ft

Solve for $h_{w\,max}$, given Q = 25,000 bbl/d = 1.78 ft^3/s and ρ = 51.4 lb/ft^3 = 0.029 lb/$in.^3$:

$h_{w\,max} = XQ/\varepsilon^2$ = 0.124(1.78ft^3/s)/(0.406 in./12 in./ft)^2 = 192.8 ft

The maximum overpressure is:

1,120.6 ft + 192.8 ft = 1,313.4 ft

Calculate the maximum pressure critical time:

$t_c = (t_c/L)L$ = (0.00083 s/ft)(39,370 ft) = 32.6 s

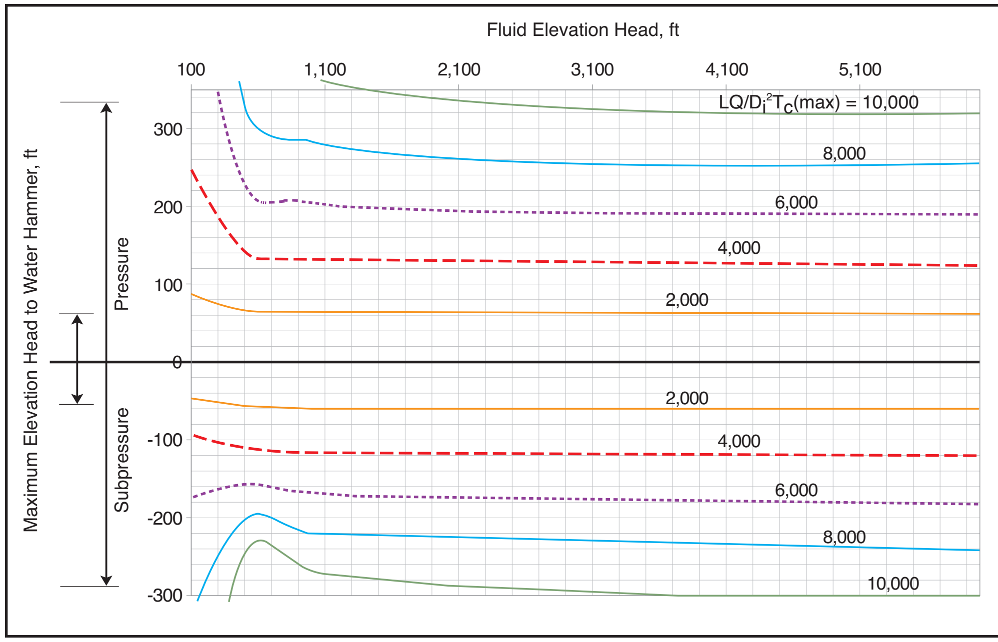


Figure 4. Maximum fluid elevation head to water hammer.

Calculate the maximum pressure with a valve closing time of 30 s.

$LQ/D_i^2t_c$ = (39,370 ft)(1.78 ft^3/s) / (0.93 ft)^2 (30 s) = 2,700.8 ft^2

Calculate the overpressure and subpressure. Knowing the maximum pump head value system, as well as $LQ/D_i^2t_c$, the overpressure can be determined by using Figure 4. The overpressure is 108.8 ft. Therefore, the total system's overpressure is 1,120.6 ft + 108.8 ft = 1,229.4 ft. Similarly, using Figure 4, the subpressure is 104.5 ft. Thus, the total system's subpressure is 1,120.6 ft – 104.5 ft = 1,016.0 ft.

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