Practical Aspects of Water Hammer

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THE A.W.W.A. was one of the first organizations in the United States to publish a comprehensive treatise (1) on water hammer, embodying the work of N. Joukovsky on cast-iron water mains in Moscow in 1897.

Joukovsky established the fundamental relations between the velocity of flow, the velocity of the pressure wave and the rate at which flow is cut off. These fundamentals have been confirmed many times during the intervening 50 years or more, and the theory on the subject has been greatly amplified by many writers throughout the world.

Much mystery has surrounded the solution of water-hammer problems, probably because of the complex theory of wave motion and the lack of time or opportunity for most engineers to study the details or to perform the calculations. As a result, a number of approximate formulas were developed, some of which are good within limits, but most of which are dangerous to use. The variations from the true values range from 35 per cent below to 500 per cent above. The graphic method for solving water-hammer problems effects material simplifications, and for some complex cases it offers the only practical means for calculating surge pressures. Much time and effort has been saved by the use of this method, but specialized knowledge is still required to apply it correctly and it is not yet widely used.

How then can the practical aspects be presented in simple form, to enable the average water works man, designer, purchaser or operator to know when a situation is dangerous or when reasonable water-hammer pressure allowances can be used with safety? There is no complete answer to this question, but perhaps it may be helpful to discuss generally some of the fundamental relations that determine water-hammer pressures, omitting involved formulas as far as possible.

Fundamentals

Four fundamental relations are essential for even a preliminary study of the subject of water hammer:

1. *Velocity of flow in the pipeline.* With the size, type and age of the pipe known, and the flow rate established, the water velocity, V, can be computed readily. Water works practice, particularly in distribution systems, has commonly limited the maximum flow rate to approximately 3 fps., with 5 fps. as the top value usually encountered. Higher velocities are sometimes found in pump discharge lines, in long flow lines or in aqueducts.

2. *Length of pipeline.* The length, L, of a single line leading from a pumping unit to a reservoir or standpipe is easily measured. The same determina-

tion can be made on trunk lines or long runs without take-offs. When a distribution system is to be studied, the situation immediately becomes complex and the length of the line can only be guessed at.

3. *Time of valve operation.* The time, T, of valve operation is a factor that can be quite troublesome, as the total elapsed time is not a true measure of the rate of cutting off flow. The behavior of various types of valves in shutting off flow is familiar to all. The first part of the stroke changes the flow very little; then, from about the half-closed position to full-closed, the rate of cutoff is more rapid. The effective time, T_e, for flow cutoff must be found for the particular valve and its service conditions before much can be known about the possible surge pressures.

TABLE 1

Values of Modulus E

Material	Modulus E *1,000,000 psi.*
Steel	28–31
Average	30
Cast Iron	
Pit-cast	10–15
Average	11
Centrifugally cast	12
Average	12
Asbestos Cement	2.8–4.2
Average	3.4

The critical time, $\frac{2L}{a}$ seconds (a being the pressure wave velocity), is the time for one wave cycle to travel up and down the pipe.

4. *Pressure wave velocity.* The pressure wave velocity, a, is a basic requirement and is affected by the thickness of the pipe wall, the diameter, the material of construction and the elasticity of both the material and the flowing water. When these factors are known, the value of the surge wave velocity can be determined by a simple calculation.

Upon the accuracy of these four fundamentals depends the accuracy of water-hammer calculations. In water-hammer design studies, many assumptions are required, and the accuracy of the resulting calculations is affected in various degrees by the correctness of these assumptions.

Practical Considerations

The water works engineer or operator ordinarily is concerned with water hammer due to the operation of a valve in a long conduit or in the distribution system. In addition, he must deal with adverse conditions which may result from the improper adjustment or use of a quick-operating valve, either automatic or manual. The surges which occur when motor-driven pumping units are shut down, either as a routine operation or because of a power failure, are becoming more and more serious as flow line velocities increase.

TABLE 2

Water Elasticity and Pipe Material Modulus Ratio (M_r)

Material	$M_r = \frac{E}{k}$
Steel	100
Cast Iron	
Pit-cast	37
Centrifugally cast	41
Asbestos Cement	11–12

The simplest and safest, although perhaps too conservative, basis of allowing for water-hammer conditions is to consider only the flow line velocity as a finite, easily determined factor and assume that the remaining three fundamentals are at their critical values.

In pursuing this line of reasoning, only one formula is needed:

$$h = 2.3p = \frac{aV}{g} \ldots\ldots (1)$$

in which h, in feet, or p, in pounds per square inch, is the water-hammer pressure in excess of the normal pipe pressure; a is the velocity of the pressure wave, in feet per second; g is the familiar 32.2 fps. per second; and V is the flow line velocity, in feet per second, cut off by the valve or other action in the critical time or less.

On distribution systems fed from reservoirs or elevated storage tanks, if an effective cutoff time (T_o) is assumed short enough to be equivalent to the so-called instantaneous stoppage of flow, Formula (1) applies. The length and time factors are not then important, since the pressures computed from Formula (1) are the *maximums* that could ordinarily result. The only exception involves wave resonance found infrequently where the "hunting" of valve controls may amplify surges or where dead ends and branch pipes may pile up wave reflections under extreme conditions. For ordinary installations these need not be considered as critical. At most, they can cause pressures 50–100 per cent in excess of those given in Formula (1) in all but the most exceptional situations.

Since the flow line velocity (V) is known or can be determined and g is a known constant, the only factor yet to be arrived at is a and Formula (1) becomes:

$$\left.\begin{aligned} h &= \frac{aV}{32.2} \\ p &= \frac{aV}{74} \end{aligned}\right\} \ldots\ldots\ldots (1a)$$

If some simple means of determining a (the pressure wave velocity) can be found for all the different types of pipe used in water supply lines, the problem can be solved by referring to tables or charts rather than to complex mathematical formulas.

Surge Wave Velocity

The research and test work on water hammer carried out in the last half century have established a significant fact—the velocity of the water hammer or surge wave is the same as the velocity of sound in a fluid-filled pipe. The elastic properties of the pipe are fairly well known, and water is compressible on the order of 3½ ppm. Thus there is an elastic system in which the relationship of the physical dimensions and elastic values can be established, and hence the wave velocity can be calculated with a great degree of accuracy.

The formula is:

$$a = \frac{4{,}660}{\sqrt{1 + \frac{k}{E} \cdot \frac{d}{e}}} \ldots\ldots (2)$$

in which a is the wave velocity (fps.), k the modulus of compression of water (psi.), E the modulus of elasticity of the pipe material (psi.), d the internal diameter (in.) and e the wall thickness (in.).

Examination of Formula (2) will show that the maximum wave velocity a is 4,660 fps. (sometimes given as 4,720) for a rigid conduit such as a rock tunnel. The relations between the modulus of elasticity of water and the modulus of the pipe walls, as well as the ratio of the inside diameter to the thickness of the pipe, may tend to reduce this velocity but cannot increase it.

The value of k has been reported as 290,000 to 300,000 psi. The modulus of the pipe material, E, depends upon many factors and the values vary to some extent, but Table 1 gives those usually accepted.

Based on the average values of E, Table 2 gives the ratio, M_r, of the modulus of elasticity of water to that of the pipe material. Then Formula (2) becomes:

$$a = \frac{4{,}660}{\sqrt{1 + \frac{d}{e} \cdot \frac{1}{M_r}}} \quad \ldots\ldots (2a)$$

From the tables of standard pipe sizes, the ratio of the internal diameter to the wall thickness can be calculated, and by the use of the chart in Fig. 1 the surge wave velocity can be obtained. The numbers at the right of the curves in the chart represent the modulus of elasticity, E (in 1,000,000-psi. units), for the various pipe materials.

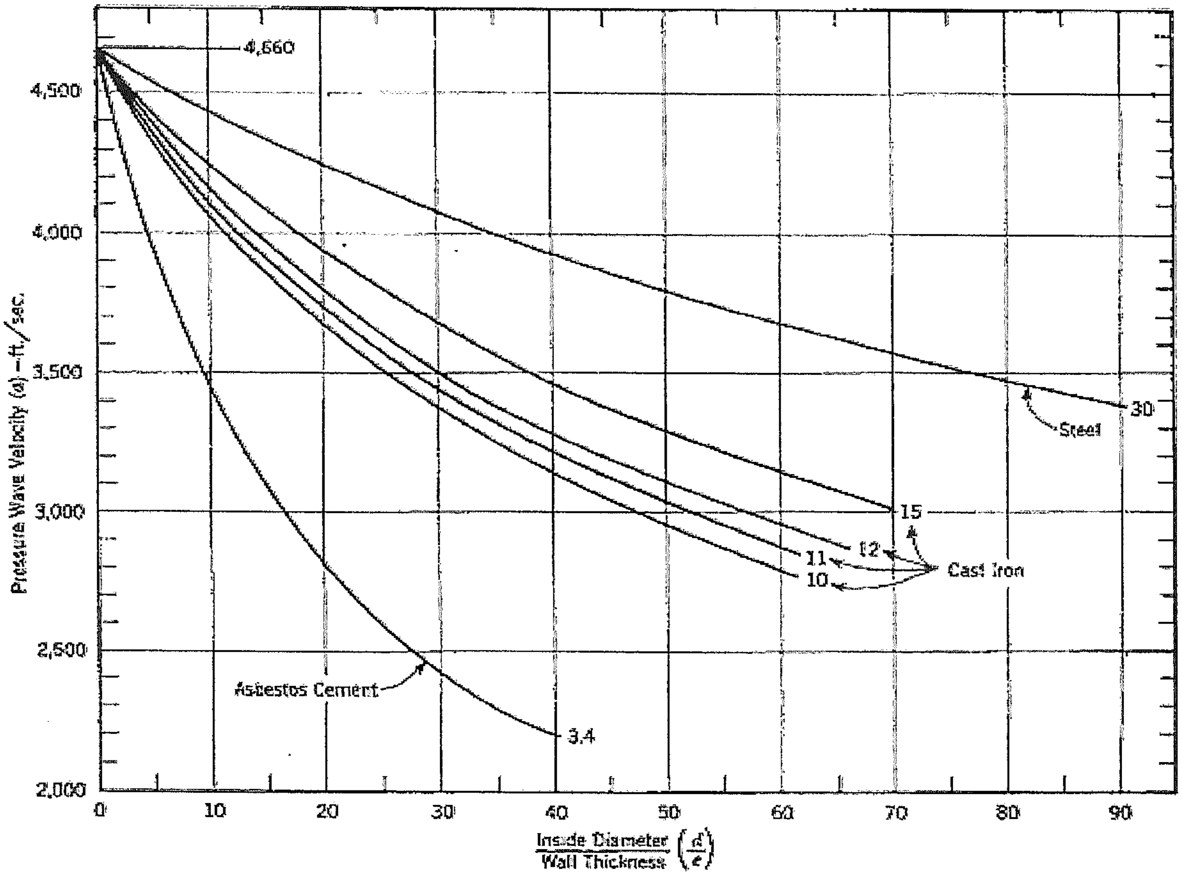

FIG. 1. Surge Wave Velocity Chart

Comparative Wave Velocities

Taking the equivalent diameter and pressure specifications for steel, asbestos-cement and cast-iron pipe for the same service, and utilizing the simplified analysis previously described—again assuming a practically instantaneous cutoff of flow—the corresponding results would be as given in Table 3. Standard published tables of dimensions have been used throughout. The physical characteristics of the pipe walls are from the literature and the allowances for barrel thickness over machined-end thickness have been obtained from published articles and from data supplied by manufacturers of asbestos-cement pipe.

An examination of Table 3 shows that for the same general specifications the velocity of the pressure wave in 4-in. pipe is in the range of from 3,600 to 4,300 fps. The corresponding water-hammer pressure is approximately 48–58 psi. for each foot per second of pipeline flow cut off instantaneously.

TABLE 3

Wave Velocities of Various Pipes

Material	Inside Diam. (d) *in.*	Wall Thickness (e) *in.*	$\frac{d}{e}$	Modulus E *1,000,000 psi.*	Wave Velocity (a) *fps.*
4-in. Pipe (150-psi. service)					
Steel (standard weight)	4.026	0.237	17.8	30.0	4,290
Cast Iron (pit-cast)	4.000	0.40	10.0	11.0	4,120
Cast Iron (centrifugally cast)	4.012	0.34	11.8	12.0	4,090
Asbestos Cement (ends)	3.950	0.45	8.8	3.4	3,570
Asbestos Cement (barrel)*	3.950	0.59	6.7	3.4	3,780
14-in. Pipe (150-psi. service)					
Steel (standard weight)	13.25	0.38	34.8	30.0	4,010
Cast Iron (pit-cast)	14.39	0.63	22.8	11.0	3,660
Cast Iron (centrifugally cast)	14.20	0.55	25.8	12.0	3,620
Asbestos Cement (ends)	14.00	1.13	12.4	3.4	3,270
Asbestos Cement (barrel)*	14.00	1.27	11.0	3.4	3,390

* Average 0.10–0.13-in. overrun on barrel compared with machined ends. Barrel is approximately 75–80 per cent of the total length per section.

For the 14-in. pipe, the range is lower, being from about 3,300 up to 4,000 fps., equivalent to pressures of 45–54 psi. for each foot per second of flow line velocity cut off. The differences are not great and the rough average could be taken as approximately 50-psi. water-hammer pressure for each foot per second of pipeline velocity cut off in the critical time or less.

Many factors tend to reduce these surge pressures, and the average figure given above can be affected greatly if the flow is cut off at a much slower rate than the critical time, or if branch pipes are still flowing freely and acting as points of relief for surge pressures. The actual water hammer above normal may be only one-third to one-half of the maximum suggested and may sometimes be even less.

Allowances for Water Hammer

The "American Recommended Practice Manual for the Computation of Strength and Thickness of Cast-Iron Pipe" (2) includes recommended allowances for water-hammer pressures in addition to the static pressure. These allowances vary with the diameter of the pipe, but no adjustment has been made for the thickness variations due to different normal pressure ratings or to the velocity of flow in the pipe. If it is assumed that Class C pipe for a 300-ft. head (143 psi.) would represent an average value, then, utilizing the analysis previously set forth, the equivalent velocities cut off within the critical time would, for these allowances, correspond to the values shown in Table 4.

TABLE 4

*Cast-Iron Pipe Water-Hammer Allowances and Estimated Equivalent Flow Cutoff**

Pipe Diameter *in.*	Water Hammer *psi.*	Flow Cutoff† *fps.*
4–10	120	2.5
12–14	110	2.0
16–18	100	1.9
20	90	1.7
24	85	1.6
30	80	1.6
36	75	1.5
42–60	70	1.4

* Water-hammer allowances based on ASA tables (2).

† Values based on Class C cast-iron pipe and with assumed valve closure in less than critical time where $p = \frac{aV}{2.3g}$.

It is interesting to note that in the smaller sizes the water-hammer allowance corresponds to a flow velocity cutoff of about $2\frac{1}{2}$ fps., while in the larger sizes the water-hammer allowances would correspond to an instantaneous cutoff of about $1\frac{1}{2}$ fps. in the pipeline velocity.

Conclusions

It is evident from an inspection of Fig. 1 and Table 3 that the differences in the surge pressures resulting from stopping any given flow in a pipeline depend upon the diameter, thickness and material of construction of the pipe. To set up arbitrary allowances for water-hammer pressures without considering these additional factors would seem at times to impose a severe penalty, while at others the arbitrary allowances might not be great enough.

Once the flow conditions and size recommendations have been established for a given pipeline, whether it is in the distribution system or in a long flow line or trunk main (exclusive of pump discharge lines), the maximum instantaneous water-hammer pressures above normal can be computed readily from the charts and tables included in this paper.

If the allowances appear to be excessive and tend to increase the cost of the pipe by a substantial amount, the potential savings due to the use of lighter pipe would justify a further study of the water-hammer conditions.

Particular attention should be paid to the valves installed for controlling flow. It is usually possible to adjust the time of closure to a matter of minutes rather than seconds, so that the *effective* time (T_e) will be long enough to avoid a heavy pressure rise. Automatic operating valves should be carefully regulated to prevent rapid closing or opening and special precautions should be taken to avoid either slamming shut or "hunting."

Pressure-regulating valves, altitude valves and other types of line controls can cause dangerous surges if not adjusted to sufficiently slow operating speeds. The use of an oversize valve may cut off the flow too rapidly at the end of the stroke and the resulting surge may be many times greater than the full stroke timing might indicate. Much more test and performance information on the behavior of control valves needs to be made available.

For pump discharge lines, particularly where adverse profiles are present, standard allowances for water hammer should not be used. Many other factors must be considered, such as the parting and rejoining of water columns, the effect of the pump and motor characteristics, the inertia of the rotating element, the ratio of the length of line to the head acting on it, and the rate of reversal of flow as compared with the critical time of the line.

For large-diameter mains, 30 in. and over, the potential savings in the cost of pipe will usually justify some detailed study of water-hammer conditions. As the size of the conduit increases, it becomes even more important to make careful analyses of surge conditions.

For ordinary flow lines up to 24 in. in diameter, and for distribution systems, it would be desirable to revise present thinking in relation to standard allowances for water hammer, so that all four of the fundamental factors could be considered in selecting the proper weight of pipe.

References

1. Simin, Olga. Water Hammer. Proc. A.W.W.A., p. 335 (1904).
2. American Recommended Practice Manual for the Computation of Strength and Thickness of Cast-Iron Pipe—ASA A21.1–1939. Am. Water Works Assn., New York (1939); Jour. A.W.W.A., **31**: *following* p. 2194 (Dec. 1939).