Waterhammer Considerations for PVC Pipeline in Irrigation Systems

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ABSTRACT

WATERHAMMER pressure develops whenever flow is changed. Flow changes occur by operating valves, by starting or stopping pumps, or by sudden release of entrapped air. Its intensity depends upon the rate of change. On occasion, it damages piping. Waterhammer can be contained by: adequate design; proper installation and responsible use.

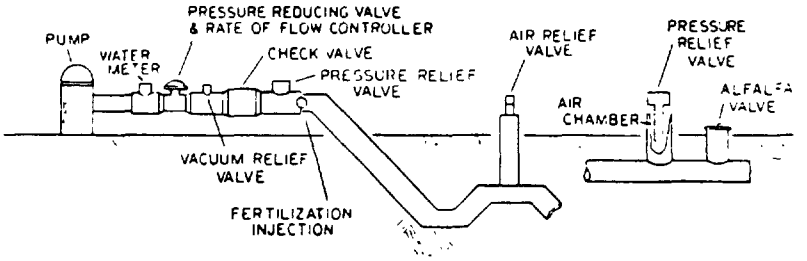

FIG. 1 Underground PVC piping irrigation system.

INTRODUCTION

A good irrigation system, providing satisfactory long term service, should have the lowest investment cost practical. An important part of any irrigation system is the underground piping to deliver the water from its source to the irrigation means (i.e. a sprinkler or the like), Fig. 1.

Poly (vinyl chloride), PVC, is an inexpensive piping material which, like any piping material, when adequately designed, properly engineered, properly installed, and responsibly used, will perform satisfactorily. The ways in which waterhammer is restrained to within acceptable bounds is a major consideration too often ignored.

One purpose of this paper is to draw attention to waterhammer, its causes, its extent and its effect. The second purpose is to emphasize the need to contain waterhammer forces through design, installation and use of an irrigation system.

Everyone has at one time or another experienced waterhammer. You hear it when a spigot is suddenly closed—pipes shake and simultaneously emit a sharp, hammer-like noise. Unbridled, waterhammer often does more than just vibrate and jar the piping; it imposes damage to the system—sometimes to a considerable extent, even to blowing pipe out of the ground, Fig. 2.

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BASIC CONSIDERATIONS

To understand waterhammer and its control, it is necessary to review the basic physical principle involved. Waterhammer occurs when water under pressure in a pipe line is subjected to a change in its rate of flow, (i.e. its velocity). The intensity of the waterhammer, evidenced as a surge in pressure, depends among other things upon the rapidity with which the velocity is altered.

Water flowing through a pipe bears energy. Part of this energy is kinetic, due to the velocity. Part is potential, a result of pressure. The sum of two energies (ignoring friction losses) remains constant throughout the line. Simply explained, whenever the velocity changes there follows a change in kinetic energy. Since the system does not essentially gain or lose energy, a compensating change occurs in potential energy with a corresponding change in pressure. Hence, when a valve is closed quickly and flow is brought to a rather sudden halt, relatively high pressures develop on the upstream side of the valve. This pressure-increase produces pressure-waves which travel the pipe and water system at sonic velocities—an effect designated waterhammer, see Figs. 3 and 4.

Since any change in water velocity produces a change in pressure, the velocity change should be made gradually so as to prevent excessive pressure increases.

CAUSES OF VARYING VELOCITY

Water velocity in a pipe of constant cross-sectional area will vary due to any one of the following conditions:

1. Closing a valve
2. Opening a valve
3. Rythmic valve operation
4. Starting a pump (especially a centrifugal pump, with or without a check valve in the pump discharge)
5. Stopping a pump
6. Pulsation of an operating reciprocating pump
7. Movement of air pockets along a pipe line
8. Sudden or rapid release of air from a pipe line
9. Sudden halt in flow when air has been exhausted out of an air release value
10. Recombination after water-column separation

INTENSITY OF WATERHAMMER PRESSURE

The increase of pressure in a pipeline full of flowing water due to a change in water velocity can be determined by the equation:

$$\Delta P = Ca\ (\Delta V)$$

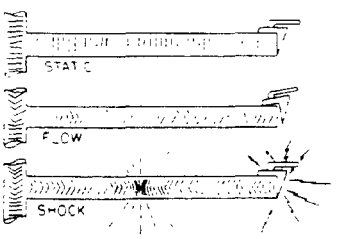

FIG. 2 Waterhammer generation.

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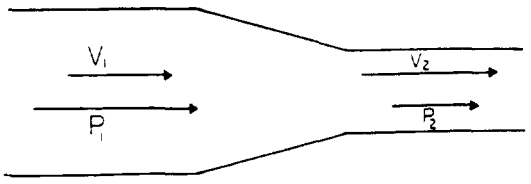

$$P_1/w + V_1^2/2G = P_2/w + V_2^2/2G$$

POTENTIAL ENERGY$_1$ + KINETIC ENERGY$_1$ = POTENTIAL ENERGY$_2$ + KINETIC ENERGY$_2$

FIG. 3 Water flow energy adjustment.

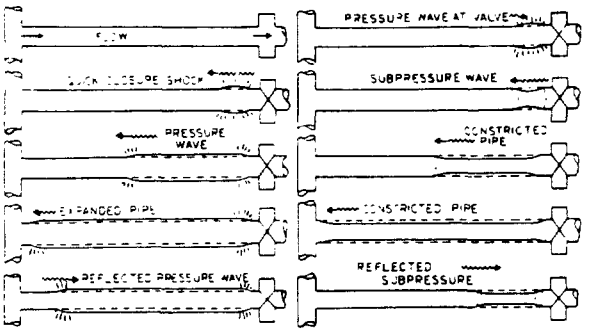

FIG. 4 Pressure wave propagation quick valve closure.

Where:

- ΔP = pressure increase, psi
- ΔV = velocity change, ft per sec
- a = sonic velocity of pressure wave in pipe-water system, ft per sec
- C = w/144g, a constant
- w/144 = weight, lb per sq in. of a 1-ft column of water
- g = acceleration of gravity, 32.2 ft per sec per sec

$$a = \frac{12}{\sqrt{\frac{w}{g}\left(\frac{1}{k} + \frac{C_1 d}{Et}\right)}}$$

Where:

- K = bulk modulus of water, 300,000 psi
- E = modulus of elasticity of pipe material, 425,000 psi Type I PVC
- d = pipe inside diameter, in.
- t = pipe wall thickness, in.
- C_1 = a factor dependent on pipe-end conditions and poisson ratio of the pipe material (anchored one end only for PVC $C_1 = 0.95$; anchored both ends but free at mid-length for PVC $C_1 = 0.85$)

$$SDR\text{-}2 = \frac{d}{t}$$

using $C_1 = 0.91$, for PVC type I

$$a = \frac{5892}{\sqrt{SDR\text{-}0.443}} \quad \text{and}$$

$$\Delta P = \frac{79.22\,\Delta V}{\sqrt{SDR\text{-}0.443}}$$

The pressure (class) rating of PVC Type I, Grade I is determined by

$$\overline{PR} = \frac{\frac{4000}{2}}{\frac{(SDR\text{-}1)}{2}}$$

Where:

$\overline{PR}$ = pressure (class) rating, psi $\frac{4000}{2}$

= design hoop stress, psi with a 2:1 safety factor

EFFECT OF VARYING VELOCITY

If we restrict waterhammer pressure to $\Delta P' = 0.2857\ \overline{PR}$ (based on a 2.8:1 safety factor) thereby allowing the remaining portion of the class rating, i.e. 0.7143 $\overline{PR}$ to represent the maximum operating pressures.

$$0.7143\,\overline{PR} = \frac{\left(\frac{4000}{2}\right)\left(\frac{2}{2.8}\right)}{\frac{(SDR\text{-}1)}{2}} =$$

$$\frac{\left(\frac{4000}{2}\right)(0.7143)}{\frac{(SDR\text{-}1)}{2}}$$

Hence $\Delta P' = \frac{1143}{(SDR\text{-}1)} =$

$$\frac{79.22\,\Delta V'}{\sqrt{SDR\text{-}0.443}}$$

From which $\Delta V' =$

$$\frac{14.43\ \sqrt{SDR\text{-}0.443}}{(SDR\text{-}1)}$$

See Table 1.

Hence a sudden change in velocity of 2.92 ft per sec ($\Delta V' = 2.92$) will produce a maximum waterhammer pressure in an SDR 26 PVC pipe of

$\Delta P = 15.67 \times \Delta V' = 15.67 \times 2.92 =$

45.5 psi

EFFECTS FROM AIR MOVEMENT

A very important factor affecting waterhammer pressures is that due to movement of air pockets. The seriousness of entrapped air is not generally realized nor understood. When an air pocket becomes suddenly dislodged, as by a stream of flowing water, the extent of changes in "local" fluid velocities and

TABLE 1. WAVE VELOCITY, WATERHAMMER, WATER VELOCITY CHANGE ~VS~ PVC SDR

SDR	$\overline{PR}$	a	P	$\Delta V'$
OD/wall ratio	Pressure rating, psi.	Surge velocity ft per sec	Waterhammer, psi per $\Delta V'$	Instant velocity change max. ft per sec
81	50	656	8.8	1.6
51	80	829	11.1	2.1
41	100	925	12.4	2.3
32.5	125	1040	14.0	2.6
26	160	1165	15.7	2.9
21	200	1300	17.5	3.3

$\overline{PR}$ = 4000/(SDR-1)
SDR = D/t = (d/t)+2
a = $5892/\sqrt{SDR\text{-}0.443}$
P = $79.22\,\Delta V/\sqrt{SDR\text{-}0.443}$
$\Delta V'$ = $14.43\sqrt{SDR\text{-}0.443}/SDR\text{-}1$

NOTE: The instantaneous velocity change produces $P = 0.2857 \times \overline{PR}$

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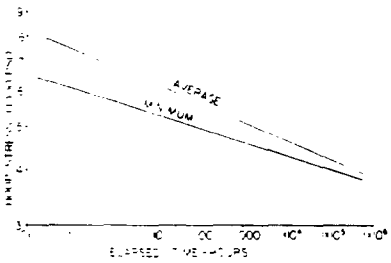

FIG. 5 PVC pipe, type I, grade I hoop stress regression (at 73.4 F).

the consequent waterhammer pressures are often much in excess of that accounted for by the general theory. Sometimes waterhammer pressures of several hundred psi or more are believed to develop. With PVC, as with any plastic piping, the effect of air entrapment is suspected to be more pronounced because air bubbles appear to "stick" more to plastic surfaces, hence the quantity of air entrapped at a particular point would be greater than that at surfaces of more wettable material. If such is the case, the larger quantity of air when finally dislodged would have the more devastating effect. For this reason, it is most important to rid PVC piping of air and to prevent air from getting into the system. Avoiding or getting rid of air is particularly difficult for an irrigation system because of the many times throughout the irrigation season the system is started and stopped.

WATERHAMMER DAMAGE

Unless steps are taken to restrict waterhammer pressures, damage may occur to one or many of the irrigation system elements, such as pumps, valves, or piping. Depending upon the intensity of the waterhammer pressure will determine the severity of the damage. Piping may suffer a hydrostatic burst, confined to the area of the waterhammer origin. More often, however, the pressure wave will propagate with little loss of intensity ahead of an ensuing burst propagation, thereby continuing to rend the pipe up to that point where it meets sufficient resistance to restrain its damaging force. Such a point of resistance may be at a joint. If the joint is of monolithic construction, i.e. one pipe length welded to the next or a pipe socket welded into an adjacent bell, the resistance to burst propagation is minimal and too frequently the damaging force will continue on through one or more such joints. Discontinuous joints, represented by rubber-gasketed seals, usually offer adequate resistance to stop a burst propagation. While gasketed joints do not remedy waterhammer damage, at least they generally reduce the extent of the damage considerably.

ADEQUATE DESIGN: PVC SAFETY FACTOR

A very misunderstood concept in PVC pipe design is its pressure (class) rating, and the safety factor attended thereto. The graph, Fig. 5, is a typical regression plot of PVC pipe, in which the ordinate is the log of pipe wall hoop stress in psi and the abscissa is the log of the time to failure, hour.

On this plot, when the stress is elevated to 6400 psi (3.2 times the class rating), the pipe will burst hydrostatically in 0.018 hr (65 sec) or longer. If pressured to a hoop stress of 4000 psi, burst will not occur before 100 000 hr. If, however, the pipe is stressed at 4000 psi for a period less than 100 000 hr, say 20 000 hr, it will still retain its original strength, i.e. it will burst at 6400 psi at or in excess of 65 sec.

Hence, the hydrostatic design basis has been established as 4000 psi. Then, by applying a 2:1 safety factor, the hydrostatic design stress is 2000 psi. Based upon the hoop stress formula, the pressure (class) rating of the pipe is determined from a hoop stress of 2000 psi.

$$\overline{PR} = \frac{\frac{4000}{2}}{\frac{(D-t)}{2t}} = \frac{4000}{(SDR-1)} \quad \text{(ISO Formula)}$$

Therefore after 10 years at the pressure rating, it can be said with certainty, and even after 100 years at the pressure rating it is reasonable to expect that PVC Type I, Grade I pipe will still retain all of its original strength.

Many manufacturers of PVC pipe advocate the use of a 2:1 safety factor, which means that they promote the use of their pipe at a maximum operating pressure equal to the pressure (class) rating of the pipe. No provisions are thereby made to allow for waterhammer pressures within the pressure (class) rating of the pipe. However, we at Certain-teed believe strongly that the maximum operating pressure *plus surge allowance* should not exceed the pressure (class) rating. Experience has taught that a 2:1 safety factor is not adequate. For irrigation pipe, we recommend the maximum operating pressure not exceed 72 percent of the pressure (class) rating. This corresponds to a hoop stress of 1430 psi, or a safety factor of 2.8:1, see Table 2.

TABLE 2. PVC MAXIMUM OPERATING PRESSURE FORMULA

$$\overline{MOP} = \frac{\overline{HDB}/S.F.}{(D-t)/2t} = \frac{4000/2.8}{(SDR-1)/2} = \frac{1430}{(SDR-1)/2} = \frac{2860}{SDR-1}$$

$\overline{MOP}$	=	Max. operating pressure, psi.
$\overline{HDB}$	=	Hydrostatic design basis, psi.
S.F.	=	Safety factor
D	=	Pipe outside dia., in.
t	=	Pipe wall thickness, in.
SDR	=	Std. Dimensional Ratio

Hucks (1972) has shown that PVC exhibits also a cyclic stress regression curve, completely independent of the steady-state regression curve already discussed. Wilging(1972) in discussing Hucks' paper, graphically depicts the 2.8:1 safety factor, Fig. 6.

Using a 2.8:1 safety factor with a maximum hoop stress of 1430 psi plus a peak cyclic stress of 570 psi on top of that (a total of 2000 psi stress), the expected number of cycles to failure is 500 000. With an irrigation service life of 50 years, and a growing season of 80 days per year, this would allow 120 cycles per day, a factor probably 10 times that expected. Hence a 2.8:1 safety factor appears adequate.

In designing an irrigation system, it is important therefore to select pipe of an adequate pressure (class) rating. For example, if the maximum operating pressure is 90 psi, then a pipe of 125 psi rating (SDR 32.5) would be selected in order to provide a 2.8:1 safety factor.

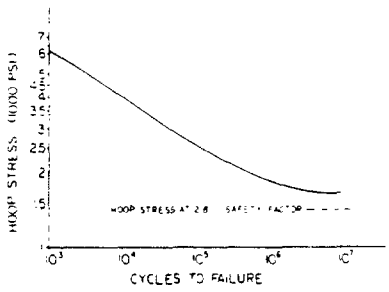

FIG. 6 PVC pipe, type I, grade I hoop stress versus cycle to failure.

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TABLE 3. PVC MAXIMUM OPERATING PRESSURE ~VS~ SDR

SDR	PR	MOP
OD/wall ratio	Pressure (class) rating	Max. operating pressure psi
81	50	35
51	80	55
41	100	70
32.5	125	90
26	160	115
21	200	145

$$SDR = \frac{D}{t}$$

$$PR = \frac{4000}{SDR-1}$$

$$MOP = 0.71 \times PR = \frac{2840}{(SDR-1)}$$

D = Pipe outside diameter, in.
t = Pipe wall thickness, in.
SDR = Standard dimensional ratio
PR = Pressure (class) rating, psi.
MOP = Maximum operating pressure, psi.

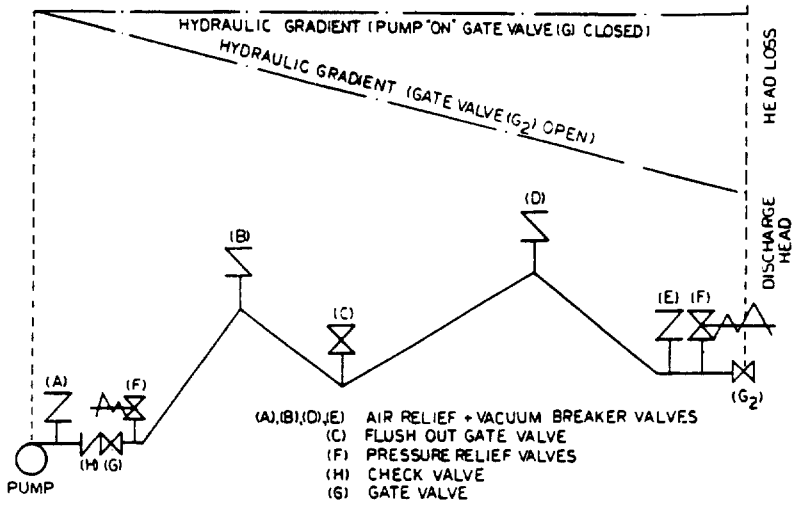

FIG. 7 Pipeline valving.

The Table 3 of maximum operating pressures, comply with the 2.8:1 safety factor:

Low head (50-ft) irrigation pipe should be used only for gravity flow systems, and should not have a valve in the discharge end of the line. Where a head gate or an entrance valve is used to stop or throttle flow, a vacuum-breaker valve should be installed immediately downstream from the entrance valve.

ADEQUATE DESIGN: VELOCITY AND PRESSURE

Waterhammer pressure due to closing a valve: the time required upon closing a valve for the pressure wave to travel from the valve to the pressure source and reflect back to the valve is given by the equation:

$$T_c = \frac{2L}{a}$$

Where

T_c = critical valve closure time, sec
L = Length of Line, ft
a = "sonic" velocity of pressure wave, ft per sec

The maximum waterhammer pressure will occur at the closed valve provided the time to complete valve closure is less than $\frac{2L}{a}$

The amount of waterhammer pressure, the pressure increase, is constant and maximum for valve closure times equal to or less than the critical time:

$$T \leq \frac{2L}{a}$$

Where:

T = valve closure time, sec

Since the maximum waterhammer pressure possible at the closed valve occurs when valve closure time does not exceed

$\frac{2L}{a}$

the critical time of valve closure which produces a maximum waterhammer pressure rise becomes of interest. As the following summary for PVC pipe shows, this close-time period increases with increasing length of pipe line.

The critical flow-stoppage time, T_c, in seconds yielding a maximum increase of waterhammer pressure at the valve is shown in Table 4 for various pipe SDR's and pipeline lengths:

By stopping flow at rates slower than critical time, waterhammer pressures will be reduced from their maximums. Charts and graphs are available to determine the time of flow-stoppage for various valve types and flow conditions which will provide acceptable waterhammer pressures (Kephert and Davis 1961, Kerr 1958). However, some indication of valve closure time to obtain a percentage of the maximum waterhammer pressure (force) $\frac{aV}{g}$

may be obtained by, first determining the pipe-line constant, P_c:

$$P_c = \left(\frac{aV}{2gPo}\right)\left(\frac{62.37}{144}\right) = \frac{aV}{148.8Po}$$

& Since $a = \frac{5892}{\sqrt{SDR-0.443}}$ for PVC

$$P_c = \left(\frac{V}{Po}\right)\left(\frac{39.6}{\sqrt{SDR-0.443}}\right)$$

Where:

P_c = pipeline constant
a = "sonic" velocity of pressure wave, ft per sec

TABLE 4. CRITICAL FLOW STOPPAGE TIMES ~VS~ SDR

SDR	a	Tc = 2L/a, seconds		
OD/wall ratio	Surge velocity, ft per sec.	L=100 ft	L=1000 ft	L=10,000ft
81	656	0.31	3.05	30.5
51	829	0.24	2.41	24.1
41	925	0.22	2.16	21.6
32.5	1040	0.19	1.92	19.2
26	1165	0.17	1.72	17.2
21	1300	0.15	1.54	15.4

$$a = 5892/\sqrt{SDR-0.443}$$

SDR = Std. dimensional ratio
a = Surge velocity, ft per sec
Tc = Critical flow-stoppage time, sec
L = Pipeline length, ft

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V = velocity of pipeline flow, ft per sec

P_o = pipeline pressure before valve closure, psi

g = acceleration of gravity, 32.2 ft per sec per sec

Generally when closing a valve, most of the flow is stopped between one-quarter and three-quarters of valve closure. Hence, actual valve closing time is twice that given by

$$T = \frac{2L}{a}$$

Therefore, the actual valve closing time to produce critical flow-stoppage is approximately

$$T = \frac{4L}{a}$$

sec. But to reduce the surge by four-fifths the maximum (i.e. to 20 percent of maximum) the above mentioned charts show that valve closure times must be increased by multiplying the critical flow-stoppage time, T_c, by the following factors, N:

When P_c	N
1	6.4
10	11.6

Hence, valve closing times should be those shown in Table 5.

Not only is it important in design, but in actual operation as well, to insure that value closing times be of the order of magnitude shown in Table 5. One means for ensuring safe waterhammer pressures is to limit the maximum velocity in the pipe line. Also shown in Table 5 (second column) are those velocities which will produce a maximum waterhammer pressure equal to 20 percent of the pipe's pressure (class) rating. Hence, we recommend that the design water velocity when operating at system capacity does not exceed 5 ft per sec, unless additional measures or ancillary equipment are used to ensure waterhammer pressures not in excess of 20 percent pipe's pressure (class) rating and that in no case should the velocity exceed 10 ft per sec.

TABLE 5. VALVE CLOSING TIMES ~VS~ SDR

SDR	V'	Valve closing time, T, seconds			
		L=1000 ft		L=10,000 ft	
OD/wall ratio	Max. vel. change, ft per sec	Pc=1	Pc=10	Pc=1	Pc=10
81	5.7	19.5	35.4	195	354
51	7.2	15.4	28.0	154	280
41	8.0	14.0	26.0	140	260
32.5	9.0	12.3	22.3	123	223
26	10.2	11.3	20.5	113	205
21	11.4	9.9	17.9	99	179

P_c	N
1	6.4
10	11.6

$T = N(2L/a)$

$P_c = (V/P_o)(39.6/\sqrt{SDR-0.443})$

$V' = 50.5\sqrt{SDR-0.443}/(SDR-1)$

P_c = Pipe line constant

P_o = Pressure in pipeline (before valve closure) psi.

V = Velocity in pipe line, ft per sec

V' = Max. velocity change producing waterhammer, P=0.20 PR, as by valve closure times shown

ADEQUATE DESIGN: AIR RELIEF

Air trapped in a water line can, and often does, spell trouble. If trapped at the top of a rise, it can seriously impede flow.

Air is compressible and, if carried along a pipeline can act like a spring, being compressed at the bottom of a draw and expanding at the top of a rise. Such alternate compression and expansion produces velocity fluctuations and pressure variations which, if great enough, can produce serious waterhammer pressures.

Investigations of asbestos–cement pipelines have, for example, indicated that a sudden release of entrapped air can produce pressure increases which may be as much as 10 times the normal operating pressure of the lines. Similar magnitudes of pressure increase in PVC are believed also to occur–as witnessed when damaged pipelines were examined.

Water-column separation can also result in excessive waterhammer pressures when the separated column rejoins at high velocity. Furthermore, when the minimum pressure at any point in a line drops to the vapor pressure of water, the waterhammer solution is no longer valid. (Kephert and Davis 1961)

To prevent damage as a result of air entrapment during initial filling of a pipeline and to keep air from getting into the line from operating pumps, provisions should be made to remove air from the line at all high points. Combined air-relief and vacuum-breaker valves should be located at high points, (A), (B), (D), and (E) indicated in the diagram, Fig. 7.

A pressure-relief valve at (F) will limit waterhammer pressure which might result from too rapidly closing the gate valve–at the right end of the diagram. A flush valve (C) will help remove possible debris from the line's low point.

Reasons for locating the several combined air-relief and vacuum-breaker valves are as follows:

1 Air has a tendency to accumulate at crests and along the downstream side of the crest. Hence, several air vents should be located downstream of the crest and vented, through a manifold, into the air release valve located at the crest.

2 The valve at (A) is to eliminate air from a deep-well-pump column at startup and limits waterhammer at the check valve.

3 The valve at (B) is to eliminate air between the pump and (B) upon initial line-fill, to vent air accumulation with the system in operation under pressure and to avoid column separation if the pressure should drop below atmospheric.

4 The valve at (D) is to eliminate air between (C) and (D) and to avoid column separation.

6 The valve at (E) is to eliminate air between (D) and (E) and to avoid possible pipe collapse (in the case of thinner wall pipe, such as SDR 32.5 or higher (SDR) due to high water velocity which may exist going through the gate valve at the downstream end of the line. (Sturm 1970, Lescovich 1972).

In many instances, manually operated globe and gate valves have been installed on pipelines to eliminate air at high points. While cheaper than combined air-relief and vacuum-breaker valves, their use should be discouraged because they must be opened (and closed) manually. The automatic protection provided by the more sophisticated air-relief and vacuum-breaker valves is well worth their additional cost Performance proves it.

If a line is laid in relatively flat terrain, provide at least three combined air-relief and vacuum-breaker valves. One should be in the pump discharge line ahead of the check and gate valves. A second should be near the middle of

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the line and the third at the downstream end of the line. If several laterals take off from the main supply line, each one should have a combined air-relief and vacuum-breaker valve at its outermost end.

Everett (1967) points out that: "a popular misconception concerning waterhammer in a pumping system involves the relative gradient and system pressure. It is assumed that a low flat gradient and a low pressure will minimize the shock pressure. Conversely, a steep gradient and a high pressure on the system will produce an excessive shock pressure. This misconception should be reversed. Long flat lines with a small amount of gradient develop more shock pressure and are more susceptible to line failure than steep gradients at high pressure."

ADEQUATE DESIGN: PROTECTIVE EQUIPMENT

Many installations of PVC piping are supplied by motor-driven centrifugal pumps. These will be either horizontal-shaft pumps or vertical-shaft deep well turbine pumps, both driven by constant speed squirrel cage induction motors. In general, 10HP and smaller will have full-voltage across-the-line starter units. Motors of greater horsepower will generally be provided with reduced-voltage starting. Hence, a pump-control of the flow in such cases is not possible. Flow control can be achieved by the opening or closing of a gate valve in the pump discharge, but must be done slowly and with due caution to the operating characteristics of the pump-drive system.

The designer of a PVC piping system supplied by the above mentioned pumping facilities, must consider the following features to ensure satisfactory performance:

1 Remove air from the line as it is being filled using automatic air-removal valves, properly sized and located at:
- (a) the pump discharge.
- (b) high points in the pipeline.
- (c) the downstream end of the pipeline.

2 Remove air from the riser pipe on deep well turbine pumps at start-up by a suitable air removal valve.

3 Provide pressure-relief valves at:
- (a) ahead of the gate valve in the pump discharge line.
- (b) at the downstream end of the pipe lines.

4 It may be necessary to install surge arrestors or automatic pressure reducing valves at:
- (a) flow regulators.
- (b) pump discharge.

5 It may be necessary to provide flow controllers so as to keep down the rate of filling and to reduce the start-up surge in a filled lined at:
- (a) pump discharge.
- (b) at downstream end of pipe line.

6 Always use a non-slam and preferably a controlled closing-rate check-valve at the pump discharge.

7 Besides protecting the pipe at pump start-up, provisions should be considered for reducing waterhammer at pump shut-down or at emergency shut-off as can occur from a power outage.

8 When shutting the system off, especially if it is to be started up again within several hours, the system should be designed, if possible, so as to keep out all air, then restart can begin with a completely, water-filled system.

9 Where the level of draw-down in the water supply can drop below that of the pump intake-line, air could be drawn in. This should be avoided and can be accomplished by the use of a pump-feed level-control.

10 The pump drive should operate at a relatively constant speed and not capable of suddenly racing to excessive speeds. A drive provided with throttled speed control is an advantage at start-up and at shut-off.

Check valves are used to protect the pump and drive from damage by a flow reversal and/or waterhammer. To protect the pipe line, use a non-slam check valve at a centrifugal-pump discharge so as to limit waterhammer pressure to a minimum. The check valve should close at the point of zero velocity, before the reflected surge wave returns from the downstream end. For even further protection, a surge-relief device (pressure-relief valve, surge chamber, etc.) should be located just downstream of the check valve.

Each type of irrigation system has its peculiarities of operating pressures and potential for surge which must be taken into account. Every system must be analyzed in the light of its own performance behavior and requirements, allowable water velocity, hydraulic gradient and pipeline profile (especially that leaving the pump discharge), pipe diameter, pipe wall thickness, and the needs for protective equipment selected to provide a satisfactory, economic system.

Where waterhammer pressures could develop with sufficient magnitude to damage PVC pipe, joining methods should be considered having one of the two following possibilities:

1 Use gasketed joints to confine the damage.

2 Where solvent-weld joints are used, install gasketed joints periodically to restrict the length of line damage should excessive waterhammer pressures develop.

While the use of air chambers can protect a line by limiting waterhammer pressures, they must be properly sized, correctly located and adequately maintained.

Pressure relief valves are actuated by a small increase in pressure above a preset value. They open to discharge water, thereby relieving pressure somewhat and restraining its build-up to a degree.

Since there are many appurtenances for pipeline protection and because of the varied flow conditions associated with a pipeline system, calculations to determine and control waterhammer can be complex. Analysis and treatment of the problem must be tempered with judgment and experience. This paper is concerned essentially with elementary elastic wave theory to determine the magnitude of waterhammer pressures. It is limited in its application to single lines of constant cross-section, containing valves and gates. The determination of waterhammer pressures and associated variations in lines supplied by pumps or supplying turbines cannot be adequately treated in a paper as limited in scope as this one.

An excellent treatment of valves used for surge control has been given in an article by Weaver (1972). Additional references are also given (Ref: Commercial Catalogues).

PROPER INSTALLATION

Properly installed pipe is a subject not to be ignored or overlooked, but will not be covered to any extent except to note that it should be done by accepted practices and in such a way as to permit safe operation. PVC pipe, like any piping material should be handled and treated with reasonable care. Rough handling, dropping the pipe, allowing it to strike or be struck by objects either before or after installation can seriously damage and weaken the pipe. Such impact damage, unfortunately, is not always apparent. If the pipe line gradient is steep, laying the pipe closer to grade will help to reduce the accumulation of air pockets. More detailed instruction in pipe line installation can be found in several references noted (SCS

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432-D, SCS 432-E, ASTM D 2321, ASTM D 2774).

RESPONSIBLE USE

A very important factor in the responsible use of an irrigation system is proper system start-up. With an empty pipe line, fill as slowly as possible, observing the following cautions:

1 Never completely close the gate valve in the discharge of a deep well turbine type pump, because of the excessive shut-off head that develops.

2 Open all manual valves except in the pump discharge. Start filling the line slowly. It is suggested not to fill at a velocity in excess of 1 ft per sec. If it should be necessary to interrupt pumping while in the process of filling a pipe line, upon restart slow down the input rate even more (a velocity of 1/2 ft per sec maximum is recommended). When restarting into a partly filled line, the approaching steep water front (i.e. the approaching wall of water) may slam into the back of a stationary wall or into a more slowly moving water boundary with sufficient force to cause a rapid slow down of advancing water rate, particularly if air becomes entrapped between the fronts, and often results in damaging waterhammer pressures.

3 When water begins to discharge from the downstream end, there will most likely still be pockets of entrapped air. Continue to pump water through at a slow rate until no air is evident for at least a fifteen minute period. Then, if possible, shut off the pump while closing the system to keep air from getting in. Wait about 15 min before starting to pump again. Maintain the slow rate of flow until no air can be seen or heard at the discharge end for a least 15 min.

4 Close all manual valves slowly so as to increase the pressure slowly to the full operating line pressure, taking at least 10 min to do so. For larger diameter pipe (6 in. or larger), for longer lines (more than 1000 ft) and for the higher operating pressures (in excess of 100 psi) proportionately more than 10 min should be taken to bring the pressure up.

No valve should ever be closed in less than 10 sec (i.e. no less than 5 sec from one-quarter to three-quarters closed), preferably 30 sec or more would be a far safer valve-closure time.

Starting to pump into a filled line requires that velocity buildup and its attendant pressure rise be done gradually. The water should be started into the line slowly by either manual control or by automatic control and once assured that the line is free of air, the flow should be increased at a rate slow enough to limit waterhammer pressure.

Many times an irrigation system will be interrupted momentarily (i.e. shut off for a period of from 10 min to possibly several hours). It is just as important then to slow down flow as when slowly increasing flow at start-up. In so doing, close all valves to keep water in and to keep all air out. Then when restarting, it will not be necessary to repurge the line of air.

When stopping an irrigation system at any time for any reason, it is just as important that it be done with the same due care and caution as that for start-up. However, provisions should be made to assure protection from excessive waterhammer pressures, automatically at emergency shut-down (as by power outages, etc.). While such automatic means are protective, they generally do not reduce waterhammer pressure enough to be relied upon for repeated, routine shut-offs. In such cases, additional manual slow down or automatic throttling should be employed.

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