



Control of air related problems for PVC and aluminum irrigation pipelines
by Jeffery Kishel

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil
Engineering

Montana State University

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Abstract:

Generation of hydraulic transients related to air inlet and air relief was analyzed for pressurized irrigation pipeline systems with PVC and aluminum pipe. Design procedures for sizing air inlet valves and specifying pump discharge valve position during filling were developed. The design procedures were verified by computer modeling and were compared with existing design standards. The existing standards were found to be contradictory and inadequate in some cases.

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Bozeman, Montana

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10/15/84
Date

William A. Hunt
Chairperson, Graduate Committee

Approved for the Major Department

22 Oct 84
Date

Sherrice E. Lang
Head, Major Department

Approved for the College of Graduate Studies

11-2-84
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Mr. Malone
Graduate Dean

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ABSTRACT

Generation of hydraulic transients related to air inlet and air relief was analyzed for pressurized irrigation pipeline systems with PVC and aluminum pipe. Design procedures for sizing air inlet valves and specifying pump discharge valve position during filling were developed. The design procedures were verified by computer modeling and were compared with existing design standards. The existing standards were found to be contradictory and inadequate in some cases.

INTRODUCTION

Failure of sprinkler irrigation pipeline systems generally occurs during system start-up or shutdown (including pump failure) and is often associated with the operation of air inlet and air relief valves. Frequently the air inlet and air relief functions are performed by a combination air inlet and air relief valve known as an air-vac valve or air-vac. Incorrect sizing of these valves and improper system operation may lead to the generation of high pressures within the pipe that may result in pipe failure.

The purposes of this paper are: (1) to review the conditions under which air-vacs operate, (2) to review the existing standards for the selection of air-vacs, and (3) to develop (a) an analytical method for sizing air-vacs and (b) a procedure for specifying pump discharge valve position during the filling of a sprinkler irrigation system pipeline to prevent high, possibly damaging, pressure surges.

A description of a typical sprinkler irrigation system is followed by a discussion of the problems caused by air and the development of design procedures that address these problems. Numerical examples illustrating the design procedures are also included.

AIR-VAC OPERATION

A type of system in which pipe failures have been reported (Figure 1) consists of a pipeline less than 5 miles (8.3 km) in length laid over an undulating ground profile, supplied by a pump and leading to a sprinkler irrigation system. The pipe may be polyvinyl-chloride (PVC) or aluminum. PVC pipelines are normally buried and aluminum pipelines are normally above ground. Valving is frequently limited to a manually-operated gate or butterfly valve at the pump discharge. Systems with large elevation differences between sump and discharge are occasionally equipped with check valves at the pump discharge. Valves with controlled speed, or two-stage opening are sometimes used.

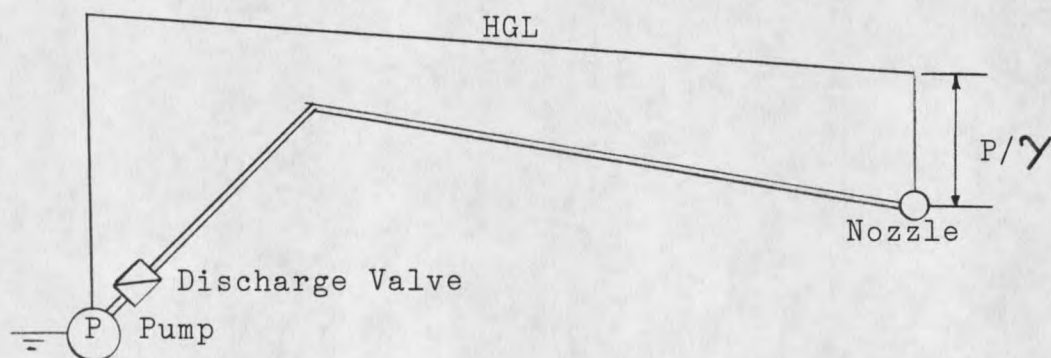


Figure 1. Schematic of typical sprinkler irrigation system.

During normal operation, water flows through the pipeline at a steady rate. When the pump loses power, either deliberately or accidentally, the hydraulic gradeline (HGL) drops first at the pump discharge and is lowered at points downstream along the pipeline as the wave of reduced pressure is propagated downstream (Figure 2). The lowest value attained by the HGL elevation corresponds to vapor pressure at a given point.

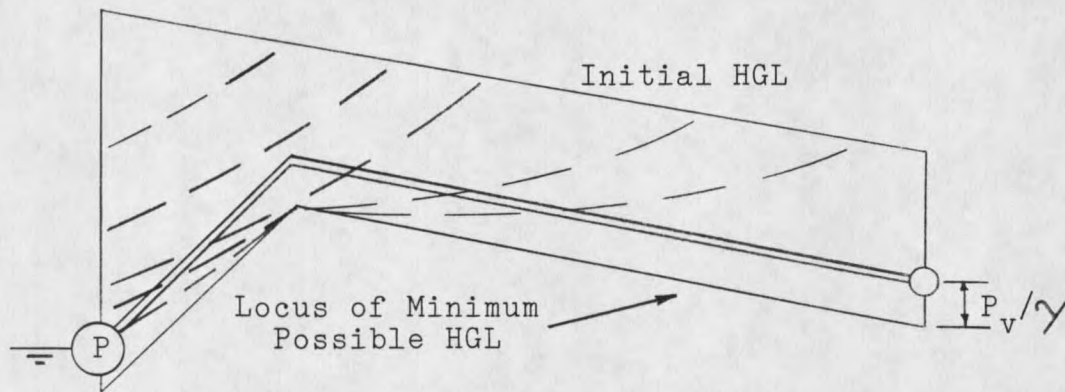


Figure 2. Progression of HGL during pump failure.

When an air-vac is present at the pipeline crest and the HGL drops below the crest elevation, the air-vac opens, admitting air to the pipe and water flows away from the crest. If there is a properly functioning check valve at the pump discharge, water will flow away from the crest in the downstream direction only.

If there is no air-vac at the crest or the installed air-vac is too small, the negative gauge pressure that

occurs upon pump shutdown may be sufficient to cause the collapse of a thin walled pipe. Even when there is no danger of collapse, as is the case with thick walled pipe, the pressure in the pipe may drop to vapor pressure, resulting in the formation of a vapor cavity at the crest.

A vapor cavity in a pipeline represents a discontinuity in the water column, effectively separating it into two columns that act independently. When the direction of one of the columns is reversed, or the relative velocities of the columns are otherwise changed, the columns will meet at the discontinuity, vapor cavity, is filled. When the columns meet, the resulting change in momentum will be manifested by a change in hydraulic head at that point. This may result in pipeline damage due to high pressure.

The mechanics of pipeline collapse due to low pressure and pressure surge due to column separation will be examined in more detail later.

When the system is started and the pipeline is being filled, air in the pipeline is displaced by water and collects at high points along the pipeline profile. The air pockets at the crests present obstructions to flow and must be exhausted to the atmosphere. Air vacs are provided at the crests; these valves open in the absence water and close instantaneously when water reaches them. Air is also displaced in front of the advancing water

column and is exhausted to the atmosphere through the sprinkler nozzles. The sprinkler nozzles, therefore, represent an air-vac of great size.

The air-vac (Figure 3) that accomplishes the air inlet and air relief functions required by sprinkler irrigation system pipelines contains a float that is buoyed up to seal the orifice in the presence of water and falls away from the orifice when pressure at the bottom of the float drops below atmospheric. This type of valve is widely used in on-farm sprinkler irrigation systems because of its relatively low cost. Long water transmission lines and complex irrigation pipeline systems are usually equipped with air-vacs that use two orifices, large for air inlet and smaller for air relief.

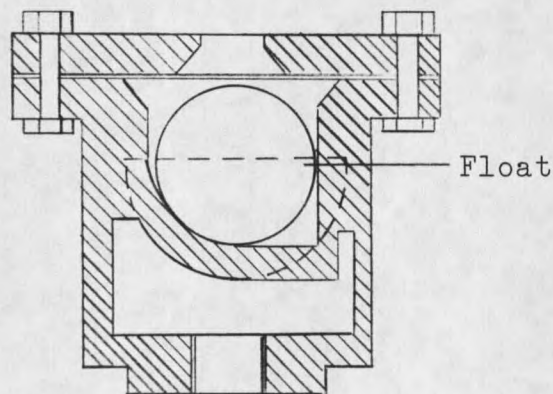


Figure 3. Single orifice air-vac.

Improper sizing of an air-vac may result in pressure in the pipe during pump failure low enough to result in

pipe collapse or the formation of a vapor cavity within the pipe. The reasons for avoiding pipe collapse are obvious. Vapor cavity formation is undesirable because of the possibility of pressure surges (waterhammer) developing when the vapor cavity is refilled by water. The pressure surge is due to the instantaneous velocity change experienced by a water column when it fills a vapor cavity and collides with a water column travelling at a different velocity. This change of momentum results in the instantaneous increase in hydraulic head, or head rise, given by

$$\Delta H = -\Delta V a / g \quad (1)$$

in which H = change in hydraulic head; ΔV = change in velocity of the water column; a = acoustic speed in the water-filled conduit; and g = acceleration of gravity. This increase in hydraulic head is propagated throughout the pipeline system as a hydraulic transient, commonly called a waterhammer.

A hydraulic transient is also generated when an air-vac slams shut when reached by an advancing water column. In the case of the typical sprinkler irrigation system, a hydraulic transient is generated when the system is filled. At the instant that the system is completely filled with water as the last of the air is exhausted

through the sprinkler nozzle, the system flow rate decreases immediately to the normal operating flow as determined by the pump characteristic and the hydraulic nature of the system. The corresponding decrease in flow velocity results in an increase in hydraulic head given by Equation 1 which is propagated upstream (Figure 4). The head rise travels upstream at the acoustic speed in the water filled pipe as a hydraulic transient.

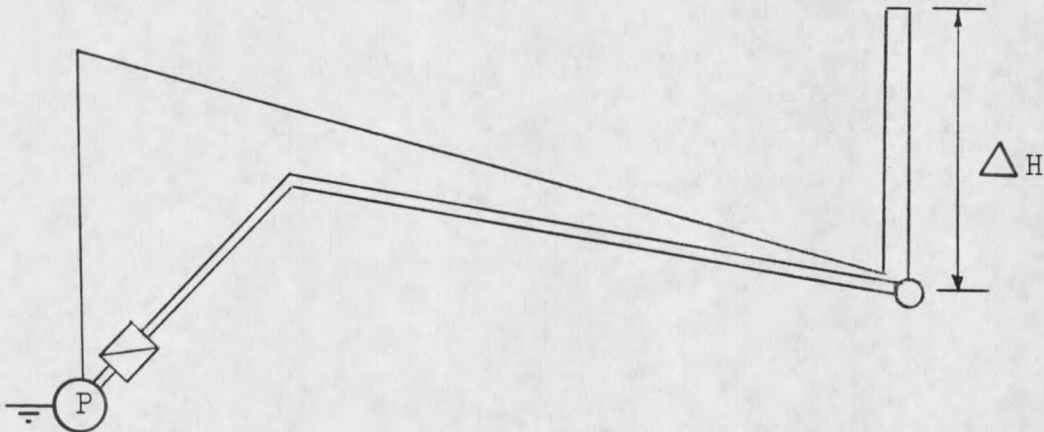


Figure 4. HGL immediately after pipeline filling.

This scenario represents the limiting case for the typical sprinkler irrigation system. Actually, the behavior of the advancing water column during filling may be quite complex, particularly when it travels downhill as in Figure 4. Two-phase flow, air and water, may take place in the form of slug flow or entrained air flow. However, the limiting case is valuable in determining useable design procedures.

Modeling the behavior of hydraulic transients is very system specific and is accomplished by numerical methods that lend themselves to computer solution. Computer models, such as the Stoner Solution Services LIQT simulation (7) are available, but the use of these services is not presently practical for analyzing small, on-farm irrigation systems because of the expense and highly technical nature of such simulation.

By considering limiting cases, design guidelines may be developed based on avoiding situations that could lead to the generation of excessive pressures within irrigation pipeline systems. These situations include (1) sizing air-vacs for the air inlet function so that vapor pressure will never be reached in the pipe, and (2) controlling the fill rate of a sprinkler irrigation system pipeline to limit the pressure surge generated by air relief to an acceptable level.

These conditions are achieved by specifying a minimum air-vac size for a given location in order to maintain minimum allowable pressure during air inlet and by specifying a position for the pump discharge valve that is to be maintained throughout pipeline filling.

A discussion of air-vac sizing to provide required air inlet is followed by a discussion of air relief. The limiting case for air relief is examined and a procedure

for determining safe pump discharge valve position during filling is developed.

AIR-VAC SIZING

Standards for sizing air-vacs have been prepared by the American Society of Agricultural Engineers and the United States Department of Agriculture Soil Conservation Service. The American Water Works Association and the United States Bureau of Reclamation have addressed the subject of air-vac sizing but have prepared no explicit sizing standards, relying instead on general policy statements. These standards and statements are reproduced in Appendix A.

The two existing standards specify minimum air-vac size as a discrete function of pipeline diameter. These two standards are in disagreement over several categories of pipe diameters and apply only to PVC pipelines. There are no standards for sizing air-vacs for aluminum pipe.

A minimum air-vac size is specified for a given pipeline crest in order to ensure that vapor pressure will not be reached at that location or that the pressure will not drop so low as to cause the collapse of the pipe during pump shutdown. The pressure in the pipe during this time, when air flow is occurring, is a function of air mass inflow rate and the rate at which the separate water columns are retreating from the crest. Air mass inflow rate is a function of air-vac size and the

difference in pressure between the atmosphere and that inside the pipe. The maximum rate of air mass inflow corresponds to the minimum allowable pressure in the pipe. The rate at which the water columns retreat from the crest depends on the hydraulic parameters of the system, pipe diameter and slope, pipe roughness and boundary conditions.

The minimum allowable pressure for a given pipe and the rate at which the water columns retreat from a pipeline crest will now be examined.

Minimum Allowable Pressure

The minimum allowable pressure in a sprinkler irrigation pipeline is the maximum of: (a) vapor pressure and (b) that given by

$$P_m = P_a - P_c/N \quad (2)$$

in which P_m = minimum allowable pressure in the pipe; P_a = local atmospheric pressure; P_c = pressure difference required to collapse the pipe; and N = a safety factor appropriate for the pipe material.

The selection and application of the safety factor in Equation 2 merits a brief discussion. When determining a maximum allowable pipeline pressure, the operating pressure is specified as some percentage of: (a) the pressure class rating of PVC pipe, or (b) the pressure

producing a certain allowable tensile fiber stress in aluminum pipe. When PVC pipe was first developed, maximum allowable operating pressure was considered to be equal to the pipe's pressure class rating, which is defined as 50 percent of the pressure that will result in yield of the pipe wall in tension. This represents a safety factor of 2. Experience with PVC pipe in typical, on-farm applications showed that working pressure based on 50 percent of the pressure causing yield is inadequate. Subsequently, the Soil Conservation Service adopted the recommendations of PVC pipe manufacturers (6) that the maximum allowable operating pressure for PVC pipelines be limited to 72 percent of the pressure class rating of the pipe, representing a safety factor of 2.8.

No corresponding safety factor exists for aluminum pipe.

The safety factor in Equation 2 is applied to the pressure difference required to collapse the pipe and not to the minimum allowable pressure, because it is this pressure difference that is actually acting on the pipe. Similarly, the safety factor is applied to the pressure difference that would result in vapor cavity formation for thick walled pipe and not to the vapor pressure itself.

Although the mechanisms of failure associated with low and high pressures are different, because the safety

factor is used to set an allowable pressure as a percentage of a disallowable pressure, it is reasonable to specify the same safety factor for minimum allowable pressure as has been found to be adequate for maximum allowable pressure.

The pressure difference required to collapse a circular pipe of uniform wall thickness is given by Staunton as cited by Boresi (3) as

$$P_c = 2.66E(t/D)^3 \quad (3)$$

in which P_c = pressure difference (pressure outside - pressure inside) required to collapse the circular pipe; E = modulus of elasticity of the pipe material; t = pipe wall thickness; and D = average pipe diameter (average of inside and outside diameters). Equation 3 was developed empirically and yields values for critical pressure that are 17 percent less than those obtained by analytical solution (3).

For PVC pipe, which is commonly classified according to standard dimension ratio (SDR), Equation 3 may be approximated by

$$P_c = 2.66E(SDR)^{-3} \quad (4)$$

in which SDR = standard dimension ratio (outside diameter/wall thickness). The modulus of elasticity for type I PVC is 6.09×10^5 psi (41.96×10^5 kPa).

Table 1 gives minimum allowable internal pipe pressures for PVC and aluminum pipe of various classes based on Equation 2 and a safety factor of 2.8 at sea level. These are absolute pressures.

Table 1. Minimum allowable internal pipe pressures to avoid pipe collapse.

SDR	PVC		Aluminum		
	Pressure Class	P_m	Diameter	Thickness	P_m
	psi (kPa)	psi (kPa)	in (mm)	in (mm)	psi (kPa)
81	50 (345)	3.9 (26.5)	6 (152)	.051 (1.29)	11.01 (75.79)
51	80 (551)	-16 (-110)	8 (203)	.051 (1.29)	13.16 (90.67)
41	100 (689)	-44 (-303)	8 (203)	.072 (1.83)	10.37 (71.45)
32.5	125 (861)	-103 (-710)	10 (254)	.051 (1.29)	13.91 (95.84)
26	160 (1100)	-313 (-2160)	10 (254)	.094 (2.39)	9.76 (67.25)

The theoretical minimum allowable pressures in Table 1 indicate that most classes of PVC pipe will not collapse

even when a complete vacuum exists within the pipe. The negative absolute pressures calculated indicate the rare case of water in tension, which cannot be expected to occur under normal operating conditions in sprinkler irrigation pipeline systems.

The class 50 psi (345 kPa) PVC pipe in Table 1 indicates a positive absolute minimum allowable pressure, meaning that it could collapse under partial vacuum. However, experiments conducted at Utah State University by Watkins (10) have shown that negative gauge pressure within a plastic pipe cannot collapse that pipe when it is properly encased in a soil envelope and exposed to normal service temperatures.

Since PVC pipe is normally buried, it is not subject to collapse due to negative gauge pressure and the minimum allowable pressure in the pipe should be based on vapor pressure. Using a safety factor of 2.8 and assuming a water temperature of 60 degrees Fahrenheit (15.4 degrees Celsius), the pressure in the pipe should be maintained at or above 2.59 psi (17.85 kPa) to insure against vapor cavity formation.

The positive absolute minimum allowable pressures given in Table 1 for aluminum pipe indicate that pressure in aluminum pipes cannot be allowed to drop very far

below atmospheric pressure, otherwise the danger of collapse is present.

Air inlet must be provided to maintain pressure in the pipe at or above the minimum allowable pressure. Although some types of gasketed aluminum pipe are inherently vented by the gasketed joints themselves, this contribution to air inlet has not been quantified by experiment and it has been the author's experience that the joints cannot be relied upon, under all conditions, to provide adequate air inlet.

By considering the limiting case of pressure in the pipe equal to the minimum allowable pressure, the air mass inflow through an open air inlet valve is a function of valve diameter and the difference of atmospheric and minimum allowable pressures. This air mass inflow rate must result in sufficient air mass to occupy the void space created by the retreating water columns at minimum allowable internal pipe pressure. The void volume created by the retreating water columns increases at a rate equal to the summation of volumetric liquid flows away from the pipeline crest (Figure 5).

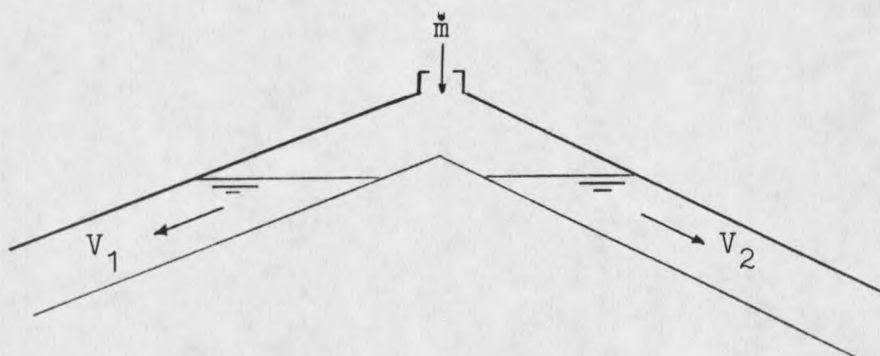


Figure 5. Pipeline crest during air inlet operation.

Air Inflow

From continuity, the air mass inflow rate required to fill the void space depicted in Figure 5 is

$$\dot{m} = \rho(A_1V_1 + A_2V_2) \quad (5)$$

in which \dot{m} = mass air inflow rate; ρ = density of atmospheric air; A = cross sectional area of the pipe; V = velocity of retreating liquid column and the subscripts 1 and 2 refer to areas and velocities to the left and to the right of the pipeline crest respectively.

The column retreat velocities in Equation 5 can be determined by applying the energy equation to a given system. Some system boundary conditions may be difficult to evaluate, for example, a pump during run down. However, conservative results for use in design can be obtained by

considering the limiting case in which both pipes discharge freely to the atmosphere (through their own diameters). The retreat velocity of each column may then be expressed by Manning's equation

$$V = (1.49/n)R^{0.66}s^{0.5} \quad (6)$$

in which V = column retreat velocity; n = Manning's roughness coefficient; R = hydraulic radius ($\frac{1}{4}$ the diameter of a pipe flowing full); and s = slope of the hydraulic gradeline (net elevation difference between discharge and top of water column/horizontal length over which it occurs).

Equations 5 and 6 are used to calculate the mass air inflow rate required at a given location and the air-vac size is based on this requirement.

Air Relief

Because the air-vac also performs as an air relief valve, sizing the air-vac on the basis of air inlet may result in oversizing from the point of view of air relief. An air relief valve is oversized when it allows air to be released very quickly in front of an advancing water column that is moving at a high velocity. When the water column reaches the air relief valve, the valve slams shut, generating a hydraulic transient of increased pressure.

This is the limiting case for the scenario described by Figure 4 in which a pressure surge and hydraulic transient is generated upon the completion of pipeline filling. The magnitude of the pressure rise depends on the velocity of the water column at the moment that it reaches the valve.

This velocity can be reduced to an acceptable level by the presence of an air cushion at the air relief valve or air-vac. The air cushion acts as a spring damper to slow the advance of the water column just prior to air-vac closure. The cushion is maintained at adequate size when the air-vac is small enough. This requirement and the requirement for adequate air inlet are usually mutually exclusive. This is the case when a pipeline contains a dramatic change, but not reversal, of grade (Figure 6). In this situation, the downstream water column may, upon pump shutdown, reverse direction and travel toward the knee. An air-vac at the knee acts first in its capacity as an air inlet valve, admitting air to the pipeline, then as an air relief valve as the downstream column reverses direction. When a properly functioning check valve is present at the pump discharge, the downstream water column overtakes the stopped upstream water column. When the columns meet, the downstream column is instantaneously slowed, which results in a pressure rise.

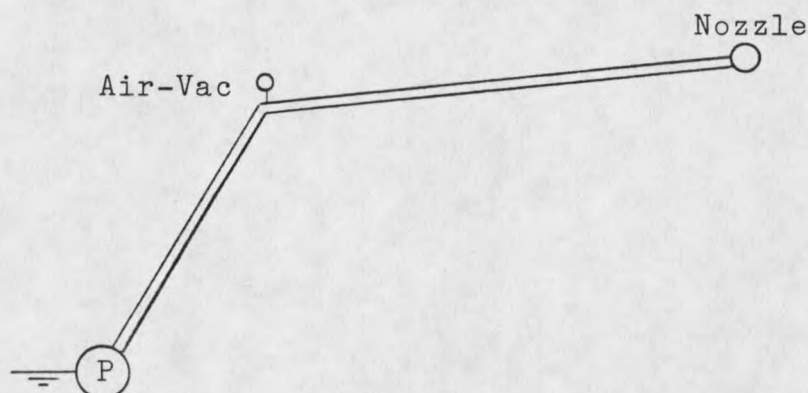


Figure 6. Air-vac at pipeline knee.

The speed at which the downstream column strikes the upstream column is controlled by the rate at which air is relieved at the knee. This situation indicates the need for a dual orifice air inlet and air relief valve. The sizing of these valves often requires a complete transient analysis of the system and is discussed by Kroon, Stoner and Hunt (4).

A conservative alternative to sizing air-vacs for the air relief function and for controlling the hydraulic transients generated upon pipeline filling is to control the velocity of the advancing water column during filling by specifying a pump discharge valve position to be maintained during the filling operation.

The behavior of pipeline systems will be discussed and will be followed by a brief discussion of the hydraulic

behavior of pump discharge valves.

PUMP DISCHARGE VALVE POSITION DURING START-UP

The velocity of the advancing water column at the instant that it reaches the sprinkler nozzle (Figure 7) is a function of the pump characteristic, discharge valve position, pipeline properties and system configuration. A system fill curve can be written of the form:

$$H = Z + RQ^x \quad (7)$$

in which H = total dynamic pump head; Z = elevation difference between sump water surface and sprinkler nozzles; R = system resistance factor which includes loss coefficients for pipe and discharge valve; and x = head loss exponent.

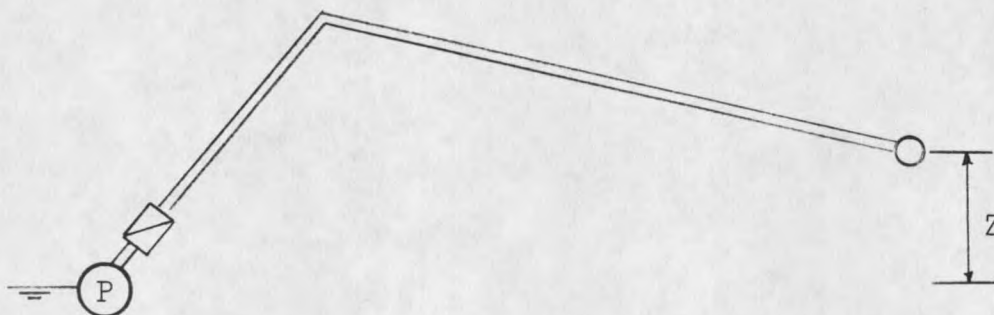


Figure 7. Schematic of sprinkler irrigation system.

Using the Darcy-Weisbach head loss equation, Equation 7 may be written

$$H = Z + (fL/D + 1/C_d^2)Q^2/(2gA^2) \quad (8)$$

in which f = Darcy-Weisbach friction factor; L = pipeline length; D = pipe diameter; A = cross sectional pipe area and C_d = valve discharge coefficient. The valve discharge coefficient is defined as

$$C_d = (Q/A)(2gh)^{0.5} \quad (9)$$

in which A is the cross sectional area of the pipe in which the valve is installed; and h = head loss across the valve.

The ratio of the product of C_d and the valve flow area at any valve position to that for a fully open valve is referred to as τ , a dimensionless discharge coefficient. τ is equal to 1 when the valve is fully open and 0 when the valve is fully closed. For most valves τ , or percent open, does not correspond directly to valve stem position. Curves relating discharge coefficient to valve stem position are occasionally available from valve manufacturers for specific valves. Streeter (8) and Seipt (6) give curves for general types of discharge valves.

Equation 8 is a system fill curve that represents the systems response at the instant of filling for any given

discharge valve position. When this curve is plotted on the pump characteristic curve (Figure 8), the point of intersection of the two curves indicates the point at which the pump is operating at the instant that the water column reaches the sprinkler nozzle. The flow rate at this point is the terminal fill flow rate. The terminal fill flow rate from Figure 8, when divided by the pipe cross sectional area, yields the terminal fill velocity for the system. The normal system operating curve intersects the pump characteristic at the normal operating flow. The corresponding water velocity is the velocity at which water travels through the pipe during normal system operation.

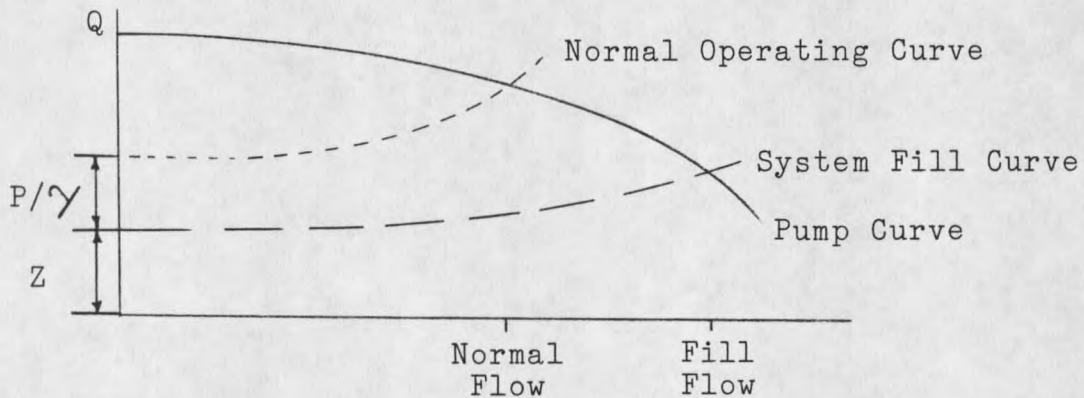


Figure 8. Pump characteristic, system fill curve and system operating curve.

The difference between the terminal fill velocity and the normal operating velocity is used to calculate the

subsequent head rise from Equation 1. This head rise is then propagated upstream to the pump. A conservative approach is to ignore the effects of frictional attenuation on the hydraulic transient and to assume that the head rise remains parallel to the fill HGL as it travels upstream (Figure 9).

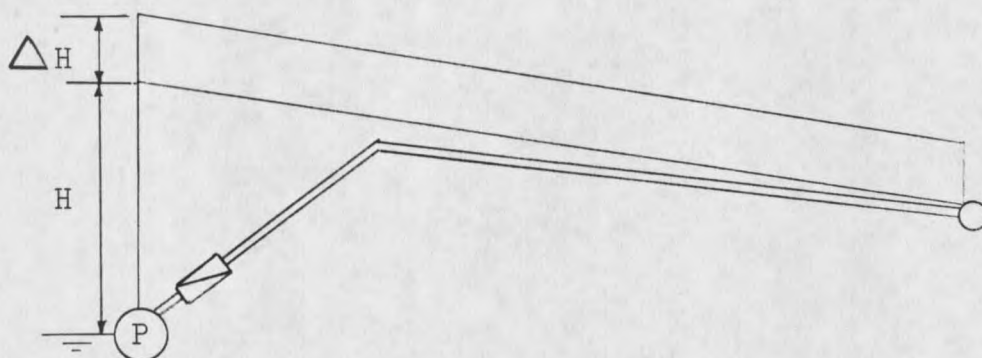


Figure 9. Hydraulic gradeline L/a seconds after filling.

If the HGL shown in Figure 9 represents pressures less than the design pressure all along its length, then there is no danger of pipe failure due to overpressure at this discharge valve position. If, however, the pressures represented in Figure 9 exceed allowable pressures, the head rise must be attenuated by controlling the line fill rate. This is accomplished by positioning the pump discharge valve so as to limit the terminal fill flow to the point at which the head rise is kept within allowable limits.

DESIGN PROCEDURES

Air Inlet and Air Relief

When pressure in a pipe at an air inlet falls below atmospheric, the valve opens and air flows into the pipe. From compressible flow theory, when the pressure in the pipe is between atmospheric and 53 percent of atmospheric, the air inflow is subsonic or subcritical. Assuming isentropic flow and using the continuity equation, energy equation and equation of state, the air mass inflow rate in this pressure difference zone is given by Streeter (8) as

$$\dot{m} = CA(7P_a((P/P_a)^{1.4286} - (P/P_a)^{1.714}))^{0.5} \quad (10)$$

in which C = air inlet valve discharge coefficient; A = cross sectional area of air inlet orifice; P = absolute pressure inside the pipe; and P_a = absolute atmospheric pressure.

When the pressure in the pipe falls to 53 percent of atmospheric, the air flow becomes sonic, or critical and further reduction of pressure in the pipe will have no effect on air mass inflow rate. Critical air mass inflow rate is given by Streeter (8) as

$$\dot{m} = .686CAP_a (rT)^{-0.5} \quad (11)$$

in which r = gas constant; and T = absolute temperature of the atmospheric air.

Similarly, when there is no water at an air relief valve and air pressure in the pipe rises above atmospheric, air relief takes place and air flows out of the pipe, through the air relief valve and into the atmosphere. When the air pressure in the pipe is between atmospheric and 1.894 times atmospheric, air outflow is subsonic and is given by Streeter (8) as

$$\dot{m} = -CAP(7/rT((P_a/P)^{1.4286} - (P_a/P)^{1.714}))^{0.5} \quad (12)$$

When air pressure in the pipe reaches 1.894 times atmospheric, air outflow becomes sonic or critical and further increases in air pressure in the pipe will have no effect on air mass outflow. Sonic, or critical air mass outflow is given by Streeter as

$$\dot{m} = -.686CAP(rT)^{0.5} \quad (13)$$

in which T = absolute temperature of air inside the pipe.

Sizing Air Inlet Valves

The procedure for sizing air-vacs for their air inlet function begins with determining water column retreat velocities for the limiting case for a given location

from Equation 6. These velocities are substituted into Equation 5 with the local air density to determine the required air mass inflow rate. The required air mass inflow rate and the minimum allowable pressure from Equation 2 are substituted into either Equation 10 or Equation 11 depending on the air flow regime defined by the ratio of minimum allowable pressure to atmospheric to find the required air inlet area. A reasonable value for air inlet valve coefficient, C , is suggested by Parmakian (5) to be 0.5.

Example

A 10 in. (254 mm) PVC pipeline approaches a crest on a 10 percent positive grade and descends a 1 percent grade on the other side. The crest is at 5000 ft (1525 m) above sea level and the air temperature is 70 degrees Fahrenheit (21 degrees Celsius). What is the minimum required air-vac diameter to provide adequate air inlet?

1. Calculate column retreat velocities from Manning's Equation with $n=.009$ and assuming open ends (Equation 6), (Figure 5).

$$V_1 = 1.49/.009(.83/4)^{0.66}(0.1)^{0.5} = 18.30 \text{ fps (5.6 m/s)}$$

$$V_2 = 1.49/.009(.83/4)^{0.66}(.01)^{0.5} = 5.79 \text{ fps (1.8 m/s)}$$

2. Atmospheric air density for the conditions given is equal to .00196 slugs per cu.ft (.104 kgm/m³), so the required air mass inflow rate is calculated from Equation 5.

$$\dot{m} = .00196(.54(18.3) + .54(5.79)) = .0255 \text{ slugs/s} \\ (1.3531 \text{ kgm/s})$$

3. Because this is PVC pipe and is not in danger of collapse due to low pressure, the minimum allowable pressure in the pipe is based on the vapor pressure and a safety factor of 2.8 in Equation 2, where P_c is the difference between atmospheric and vapor pressure at the location.

$$P_m = 2.59 \text{ psia } (17.8 \text{ kPa})$$

4. The ratio of minimum allowable pressure to atmospheric pressure is less than .53, therefore, sonic air inflow will occur at the minimum allowable pressure and Equation 11 governs. Equation 11 is solved for the required air inflow area.

$$A = ((.03(1715(530))^{0.5}) / (.686(.5)12.4(144)))^{0.5}$$

$$A = .0398 \text{ sq ft } (.0037 \text{ m}^2)$$

This corresponds to an air inlet orifice opening with a diameter equal to 2.7 in. (68.6 mm), therefore a 3 in. (76 mm) air-vac would be specified for this location.

Comparison to Existing Standards.

Using the procedure outlined in the foregoing example, minimum required air inlet valve diameters were calculated for several diameters of PVC pipe for pipeline crest locations with combined grades (sum of approach and departure grades, with grades the same on both sides of the crest) of 2 and 50 percent (Table 2).

Table 2. Minimum required air inlet valve sizes, in. (mm).

Pipe Diameter in. (mm)	Air Inlet Valve Diameter Combined Grade	
	2 percent	50 percent
6 (152)	1.01 (26)	2.26 (57)
8 (203)	1.48 (38)	3.32 (84)
10 (254)	1.98 (50)	4.20 (107)

Table 2 is based on a minimum allowable pressure in the pipe of 2.59 psia (17.8 kPa) and an air density based on an elevation of 5000 ft (1525 m) above sea level and

an air temperature of 70 degrees Fahrenheit (21 degrees Celsius).

The United States Department of Agriculture Soil Conservation Service standard for air inlet valve sizing (9) specifies that a minimum air inlet valve diameter of 1 in. (25 mm) be used for PVC pipelines from 6 in. (152 mm) to 10 in (254 mm) in diameter. The American Society of Agricultural Engineers' standard for air inlet valve sizing specifies a minimum required air inlet valve diameter of 2 in. (51 mm) for 6 in. (152 mm) pipelines and 3 in. (76 mm) for 7 in. (178 mm) through 10 in. (254 mm) pipelines.

The discrepancies between the two existing standards and the results shown in Table 2 indicate that the specification of minimum required air inlet valve diameter as a discrete function of pipeline diameter may be inadequate under some design conditions. Neither of the existing standards address the effect of grade on required air inlet valve size.

No corresponding standards exist for aluminum pipe.

Specifying Pump Discharge Valve Position During Start-Up

The procedure for determining the position of the pump discharge valve during pipeline filling is (a) determine an allowable head rise that will occur upon the

completion of filling; (b) relate the allowable head rise to a corresponding safe fill rate; (c) calculate the C_d required to ensure the safe fill rate; and (d) relate the C_d required to a specific valve opening position.

The allowable head rise is related to the terminal fill flow and the normal operating flow by the classic waterhammer equation (Equation 1). The terminal fill flow is related to the valve discharge coefficient by Equation 8 and the pump characteristic curve. The valve discharge coefficient, C_d , is related to valve stem position by the dimensionless parameter τ . In equation form:

$$\tau = C_d A / C_{do} A_o \quad (14)$$

in which the subscript o refers to conditions for the fully open valve. Graphical or tabular representations of the relationships between C_d and τ and τ and valve stem position are sometimes available from a valve's manufacturer for a specific valve. Streeter (8) presents C_d as a function of percent valve opening for various types of discharge valves. C_d versus percent valve opening for a 12 in. (305 mm) butterfly valve is given in Figure 10. C_d is determined experimentally and is defined as the ratio of flow velocity in the pipe to the square root of the product of twice the acceleration of gravity and the head loss across the valve.

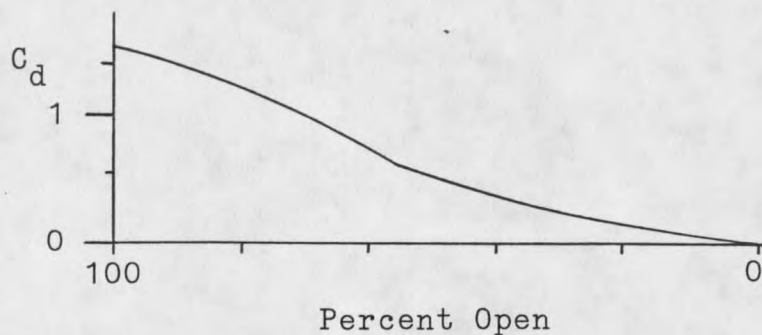


Figure 10. Discharge coefficients for 12 in. (305 mm) butterfly valve.

The numerical example in the following section demonstrates the procedure used to specify pump discharge valve position during pipeline filling.

Example

The 2000 ft (610 m), 10 in. (254 mm), PVC class 100 psi (689 kPa) pipeline (Figure 11) contains a pump with the characteristic shown (Figure 12). The system operating curve and the system fill curve have been plotted using a Darcy-Weisbach friction factor of .01 in Equation 8. The system operating curve is displaced upward from the system fill curve by a distance of 50 ft (16 m) which represents the pressure head corresponding to an operating pressure at the sprinkler nozzle of 22 psi (158 kPa).

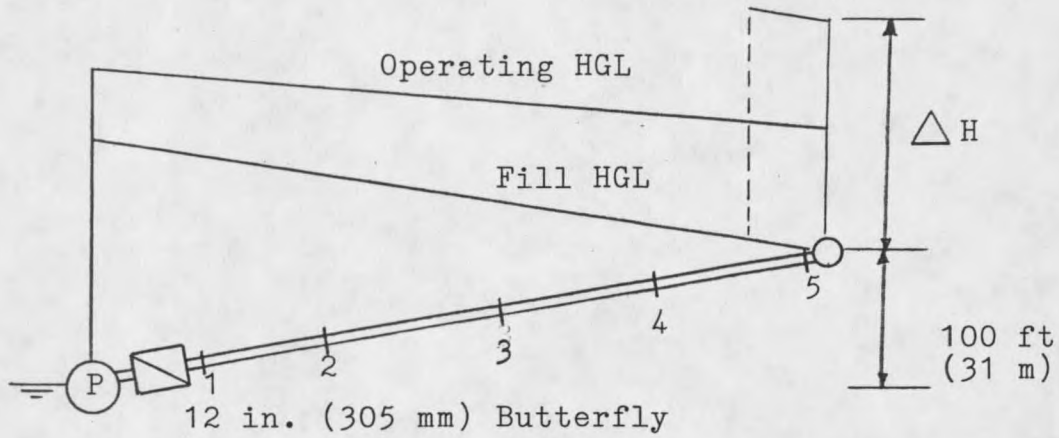


Figure 11. Irrigation pipeline system.

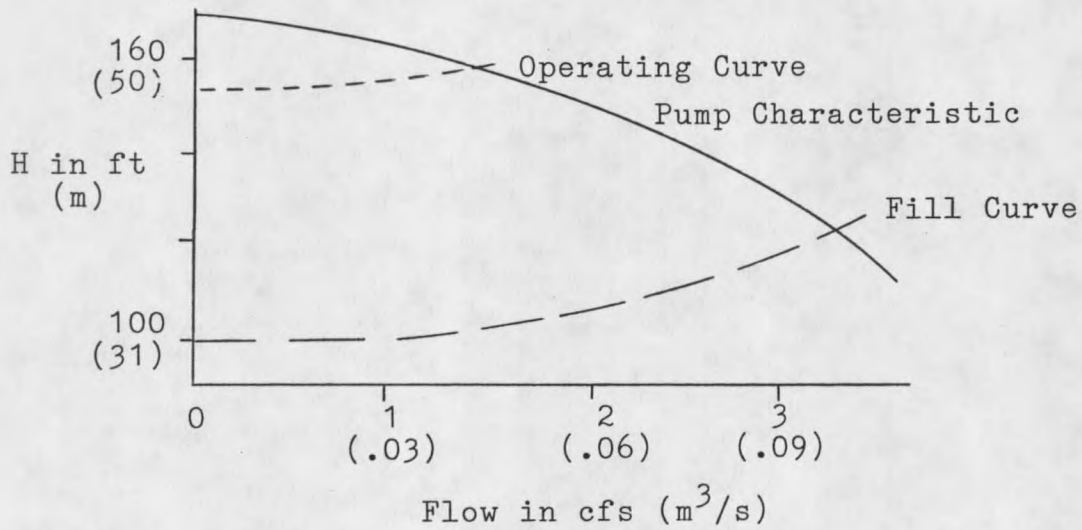


Figure 12. Pump Characteristic, system operating and fill curves.

The head at the pump at the completion of filling is, from Figure 12, 120 ft (37 m). The head corresponding to the pressure class rating of the 100 psi (689 kPa) pipe is 231 ft (70 m) therefore, the maximum allowable head rise (neglecting attenuation) is

$$\Delta H = 231 - 120 = 111 \text{ ft (33 m)}.$$

This is the ΔH shown in Figure 11 and corresponds to a maximum allowable velocity change (From Equation 1) of

$$\Delta V = 111(32.2)/925 = 3.8 \text{ fps (1.2 m/s)}$$

where 925 is the wavespeed in the class 100 pipe.

From Figure 12, the terminal fill flow is 3.4 cfs ($0.1 \text{ m}^3/\text{s}$) and the normal operating flow is 1.2 cfs ($.03 \text{ m}^3/\text{s}$). This change in flow corresponds to a decrease in velocity of 4.1 fps (1.3 m/s) in the 10 in. (254 mm) pipe. This velocity change is greater than the allowable velocity change previously calculated.

The maximum allowable safe terminal fill velocity is then the normal operating velocity plus the allowable velocity change

$$V = 2.2 + 3.8 = 6 \text{ fps (1.8 m/s)}.$$

From continuity, the safe fill flow is

$$Q = 6(.54) = 3.2 \text{ cfs } (0.1 \text{ m}^3/\text{s})$$

where .54 is the cross sectional area of the pipe. From Figure 12, this flow corresponds to a pump head of 127 ft (39 m). When frictional attenuation of the hydraulic transient is neglected, the HGL elevation at L/a seconds must be based on this terminal fill head. Therefore, the determination of a safe fill flow rate is accomplished by an iterative procedure. In this case, the elevation of the HGL at L/a seconds after filling is

$$H = 127 + 3.8(925)/32.2 = 236 \text{ ft } (72 \text{ m}).$$

This elevation of the HGL corresponds to a pressure of 101 psi (689 kPa) at the pump discharge, which is acceptable for the class 100 pipe. If this pressure had been unacceptably high, an additional iteration would have been required to determine a safe fill flow rate.

The safe fill flow rate of 3.2 cfs ($0.1 \text{ m}^3/\text{s}$) at a pump head of 127 ft (39 m) can be used to calculate a discharge coefficient for the butterfly valve that will assure these conditions. Equation 8 is solved for C_d using a flow of 3.2 cfs ($0.1 \text{ m}^3/\text{s}$) and a pump head of 127 ft (39 m)

$$C_d = ((64.4/6^2 (127-100) - (.01(2000)/.83))^{-0.5} = 0.2.$$

From Figure 10, the C_d of 0.2 corresponds to a 12 in. (305 mm) butterfly valve 43 percent open, or a valve lever angle of 39 degrees from the fully closed position. For a gear driven valve, 43 percent open corresponds to 43 percent of the turns required to open the valve from its fully closed position.

VERIFICATION

This paper presents procedures for determining adequate in-line air-vac sizes for irrigation pipeline crest locations and for determining safe pump discharge valve position during pipeline filling.

The method presented for sizing in-line air-vacs bases the required size on the air inlet function of the air-vac. Because no consideration is given to the air relief function, the possibility that in-line air-vacs may be oversized by this procedure was addressed by a computer model study.

The method for controlling pressure surges by specifying pump discharge valve position during pipeline filling was verified by computer simulation as well.

In both cases, the LIQT transient analysis modeling procedure from Stoner Associates (7) was used.

In-Line Air-Vacs

In order to determine whether the size of an air-vac at an in-line pipeline crest location had a significant effect on the magnitude of pressure surges, a generic irrigation pipeline system (Figure 13) was modeled using LIQT procedure.

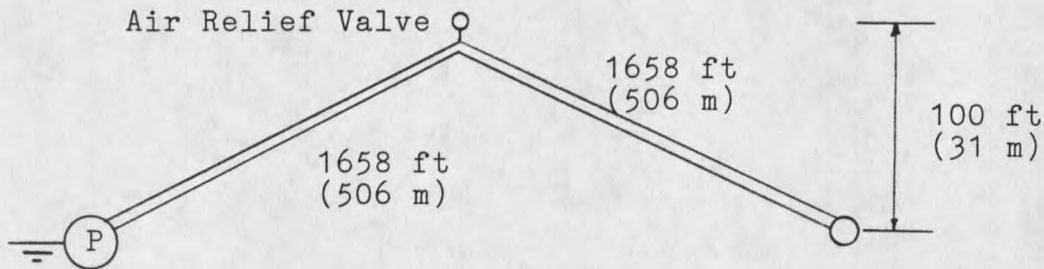


Figure 13. Generic irrigation pipeline system.

System start-ups for pipelines of 6 in. (152 mm), 8 in. (203 mm) and 10 in. (254 mm) diameters were modeled with in-line air-vacs of 2 in. (51 mm), 3 in. (76 mm) and 4 in. (102 mm) orifice diameters. Pressure at the pump discharge was plotted as a function of time for all simulations.

The results of the simulations indicated that in-line air-vac size has no significant effect on the magnitude of head rise experienced by an irrigation pipeline system during start-up. Representative plots of pressure at the pump discharge as a function of time are given in Appendix B.

Valve Position During Filling

The system shown in Figure 11 and used as the basis of an example problem earlier was modeled by the LIQT

procedure. The system was modeled during pump start-up with a fully open pump discharge valve ($C_d = 1.8$) and with a pump discharge valve 43 percent open ($C_d = 0.2$). Maximum pressure summaries for the two simulations are shown Table 3.

Table 3. Maximum pressure summaries for valve position procedure verification.

Section	Maximum Pressure	
	100% open	psi (kPa) 43% open
1	104 (717)	104 (717)
2	145 (999)	91 (627)
3	131 (903)	67 (462)
4	119 (820)	57 (393)
5	109 (751)	55 (379)

From Table 3, the maximum pressure experienced by the system with the pump discharge valve fully open during pipeline filling was 145 psi (999 kPa) and with the valve open 43 percent was 104 psi (717 kPa), an acceptable level for the class 100 pipe.

CONCLUSIONS

The results of this study of the control of air-related problems for PVC and aluminum pipeline systems show that (1) in-line air-vacs can be sized so that pipe collapse and/or vapor cavity formation will not occur; (2) existing standards for sizing in line air-vacs are in disagreement with each other and with the sizing procedure presented by this paper; (3) in-line air-vac size has no significant effect on pressure surges that occur upon system start-up ; and (4) pressure surges caused by the filling of irrigation system pipelines can be kept to acceptable levels by specifying pump discharge valve position throughout the line filling process.

Recommendations to assist practice in the area of air-related problems in irrigation pipeline systems are (1) reexamine existing standards for the sizing of air inlet valves with an objective of creating a single standard that addresses the effects of grade on required air inlet size; and (2) perform extensive tests to develop C_d versus τ information for a wide variety of discharge valves. The completion of these two recommendations will make it practical for irrigation system designers to avoid many air-related problems.

NOTATION

NOTATION

The following symbols are used in this paper:

- A = cross sectional area
- a = acoustic wavespeed
- C = discharge coefficient
- D = inside pipe diameter
- E = Young's modulus of elasticity
- f = Darcy-Weisbach friction factor
- g = acceleration of gravity
- H = hydraulic head
- h = head loss across a valve
- L = pipeline length
- \dot{m} = air mass flow rate
- n = Manning's roughness coefficient
- P = pressure
- Q = volumetric flow rate
- R = hydraulic radius
- r = gas constant
- s = slope
- SDR = standard dimension ratio
- t = pipe wall thickness
- V = velocity

z = elevation difference

Δ = change

ρ = density

τ = dimensionless discharge coefficient

Subscripts

a = atmospheric

c = critical

d = discharge

m = minimum allowable

o = open

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REFERENCES CITED

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APPENDICES

APPENDIX A

EXISTING STANDARDS FOR SIZING AIR INLET VALVES

EXISTING STANDARDS FOR SIZING AIR INLET VALVES

American Society of Agricultural Engineers Standard S-376

Section 4.6.2 Air-vacuum release valves shall have a 51 mm (2 in.) nominal minimum diameter. The valves shall be used as follows:

4.6.2.1 For pipeline 152 mm (6 in.) diameter or less, a minimum valve outlet diameter of 51 mm (2 in.).

4.6.2.2 For pipeline 178 to 254 mm (7 to 10 in.) diameter, a minimum valve outlet diameter of 76 mm (3 in.).

4.6.2.3 For pipelines 305 mm (12 in.) and larger, a minimum valve outlet diameter of 102 mm (4 in.).

United States Department of Agriculture Soil Conservation Service Standard 430-DD

The large orifice (opening that controls air flow during filling and emptying) of an air-and-vacuum valve shall equal or exceed that specified below for the appropriate pipeline diameter:

1/2 in. for 5 in. or less pipelines,

1 in. for 6 to 10 in. pipelines,

1 3/4 in. for 12 to 15 in. pipelines.

United States Department of the Interior, Bureau of
Reclamation

Has no explicit standard, sizes air inlet valves
on a job-to-job basis by no standard method or rule.

American Water Works Association Standard C900-81

Section A.7.3 Negative or vacuum pressure...cannot
collapse an underground plastic pipe that is properly
encased in a soil envelope and exposed to normal
service temperatures.

APPENDIX B

REPRESENTATIVE AIR RELIEF VALVE TRIAL RESULTS

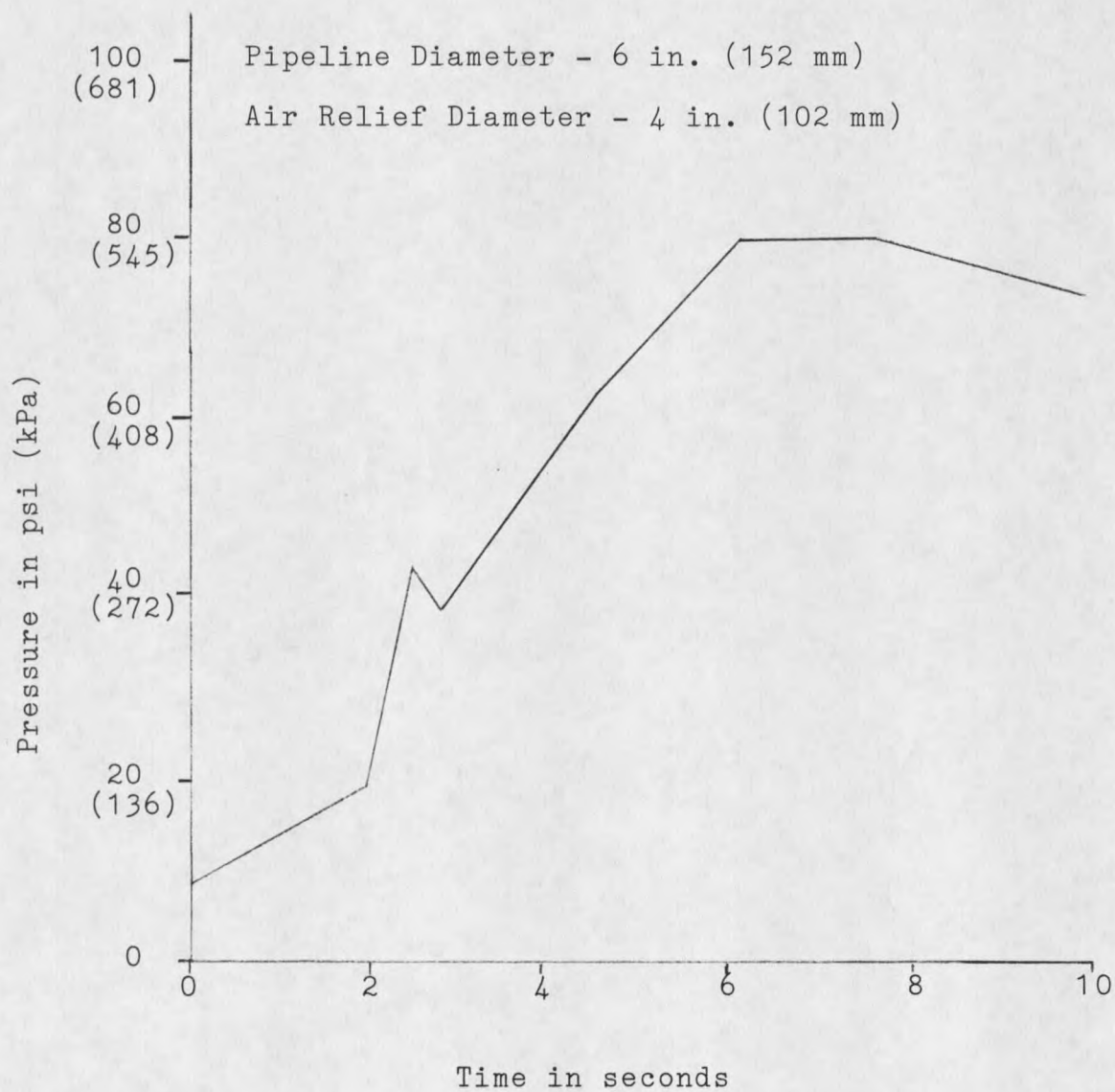


Figure 14. Pressure at pump discharge after start-up.

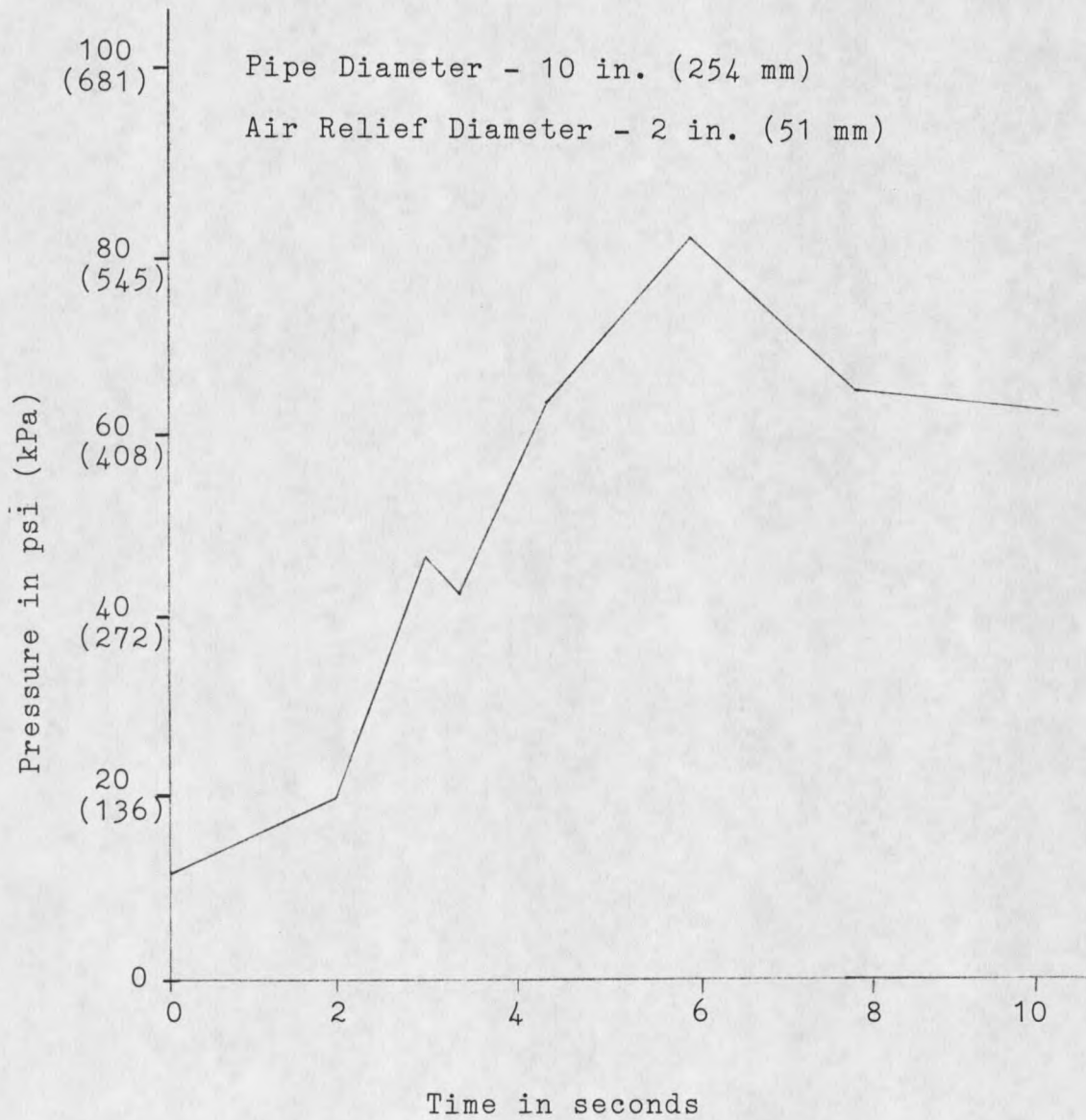


Figure 15. Pressure at pump discharge after start-up.

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