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

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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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.

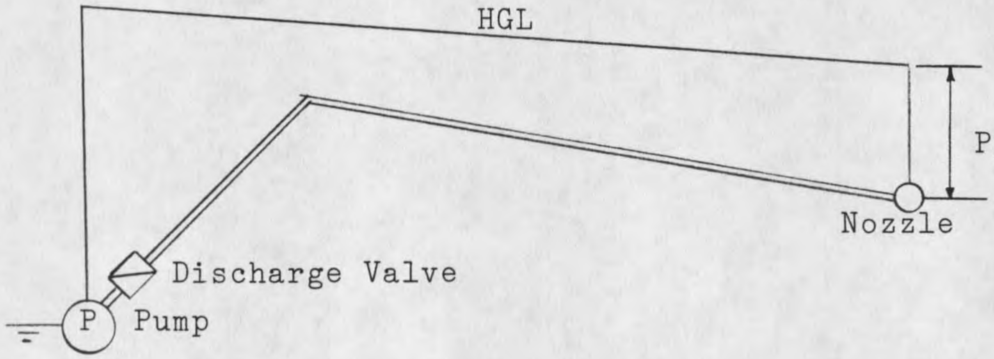

Figure 1. Schematic of typical sprinkler irrigation system.

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 attaind by the HGL elevation corresponds to vapor pressure at a given point.

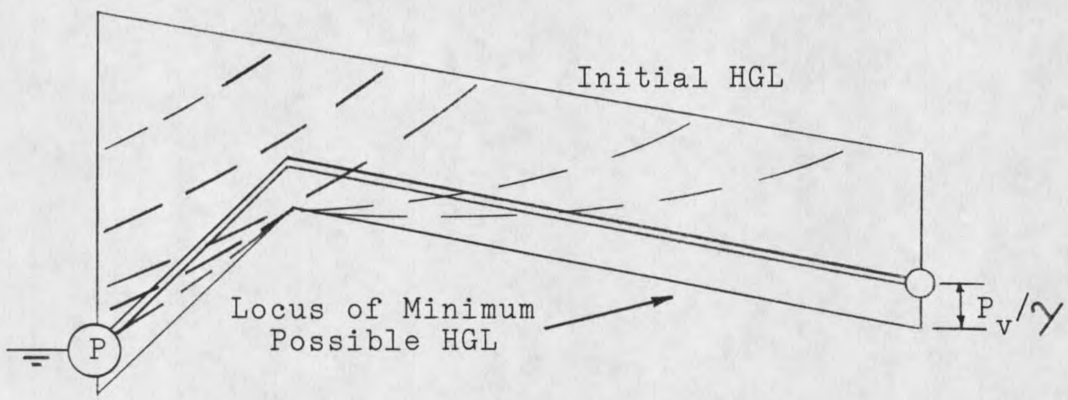

Figure 2. Progression of HGL during pump failure.

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 as 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.

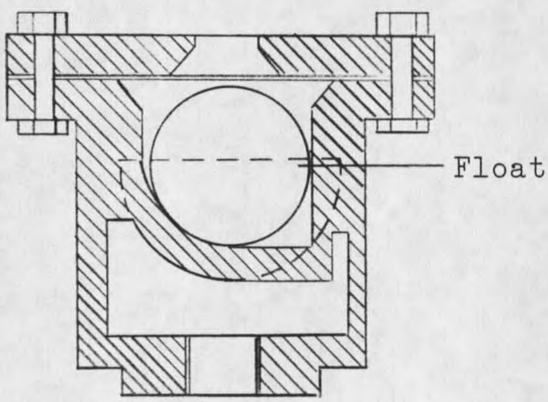

Figure 3. Single orifice air-vac.

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

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

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.

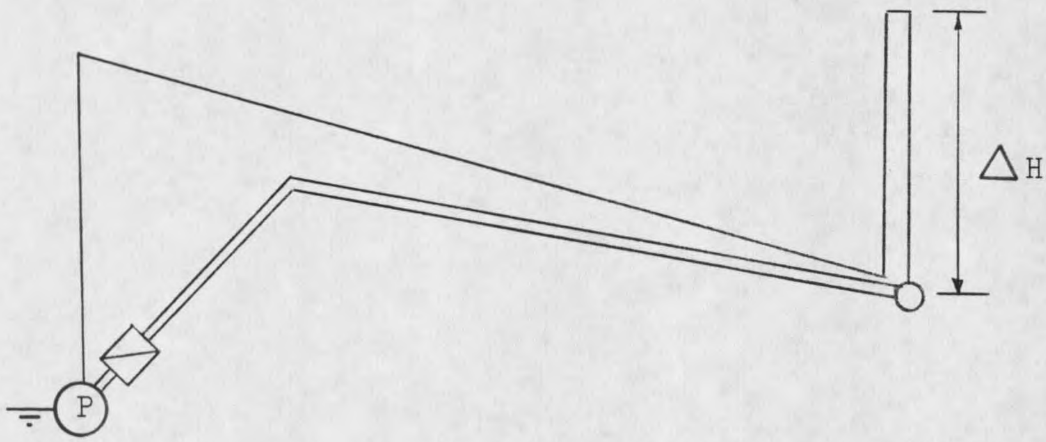

Figure 4. HGL immediately after pipeline filling.

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 occuring, 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

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

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 Eqaution 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

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

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

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