CHAPTER 13

TRANSIENT CONTROL DEVICES AND PROCEDURES

Transients in a pipeline system can cause objectionably high or low pressures. Excessively high pressures can damage pumps, valves, and other pipeline appurtenances, as well as rupturing the pipe itself. However, "failure" may refer only to the inability to meet a given standard of performance; thus it is possible for a failure to occur in the absence of any physical damage. For example, it may be required under all conditions that the pressure in a pipeline remain above atmospheric pressure to prevent air from entering the lines through vacuum valves. If an analysis indicated that the pressure would drop below atmospheric pressure for even a single operating condition, the pipeline has "failed."

Excessively low pressures can lead to the release of large amounts of dissolved air, and extensive vaporization of the liquid can occur if the pressure drops to the liquid vapor pressure. The resulting low pressures, possibly enhanced by external pressures, could cause the pipe to collapse. Also, a vapor cavity closure event occurring at some point in the pipeline can produce high shock pressures which could lead to failure of the pipe. These cavity closure shocks are difficult to predict owing to the difficulty of simulating the actual physical phenomena occurring in the pipe. The approach outlined in Section 10.7 appears to be the most commonly used method of simulating this complex phenomenon. Brittle pipe materials such as concrete are particularly susceptible to this type of problem. For example, some types of reinforced concrete pipe contain a thin steel cylinder which is lined with cement mortar and then wrapped under tension with reinforcing wire (see Section 8.3). If pressure shocks cause the fracture and spalling of the internal cement lining, the thin steel cylinder has little support to prevent wall buckling and collapse. Even under less dramatic circumstances the loss of the mortar lining would potentially expose the steel to corrosion which could ultimately undermine the integrity of the pipe.

Another type of transient condition which can cause problems in a pipeline is vibration. A periodic pressure variation could excite some component of the pipeline which possesses a natural frequency near the pressure fluctuation frequency. Under this condition, large stresses, strains, and displacements could occur which at best would be undesirable and at worst could cause system failure. Because a good understanding of these phenomena requires a knowledge of the natural frequencies of the system components and how they are related to the periodic pressure fluctuations, the method of characteristics may not be as appropriate as other existing techniques for this analysis. Therefore, the analysis of periodic transient flow will not be addressed in this work. The reader may consult Wylie and Streeter (1993) and Chaudhry (1987) for details.

13.1 TRANSIENT PROBLEMS IN PIPE SYSTEMS

In this section we explore the most common causes of transient problems in pipe systems.

13.1.1. VALVE MOVEMENT

Probably the most common and well-known cause of transient flow problems is the movement of a valve. Any valve movement causes pressure waves to propagate through the system. The magnitude of the pressure waves depends on the type of valve, the way in which the valve is moved, the hydraulic properties of the system, and the elastic properties and restraint of the pipe system.

The proper evaluation of the impact of valve movement on the pressures in a system depends strongly on the loss characteristics of the valve. While there are charts and graphs available to *estimate* the effects of valve closure, it is far more reassuring to be able to *calculate* the effects in a specific situation. We have shown how this can be accomplished in Section 10.4.

13.1.2. CHECK VALVES

Check valves can cause large transient pressure differences if the flow backwards through them can occur before the valve closure is complete. Such a case is documented by Purcell (1997), in which check-valve slam was caused by an air chamber at the pump discharge. The high discharge pressure, maintained by the air chamber after pump power failure, caused the pump discharge to drop to zero rapidly, in turn causing the check valve, presum-ably undamped, to close abruptly. In this situation the slamming check valve creates the same problem that is caused by sudden valve closure.

Most modern check valves do not slam. In some cases a spring or weight causes the check valve to close at the instant forward flow ceases, thereby preventing the reverse-flow problem. Another type closes slowly, regulated by a damping mechanism, to bring the reverse flow to rest gradually.

13.1.3. AIR IN LINES

Filling empty lines, particularly in pumped systems, can produce velocities that are well above the expected steady-state velocities. At the low pump head that generally exists early in the filling process, the pump is operating on its curve at a point where the discharge is quite large. If the line ends at any device which acts as a flow obstruction, as Fig. 13.1 shows, e.g., a partially-closed valve or an open air-vacuum valve, then a serious water hammer situation can occur.

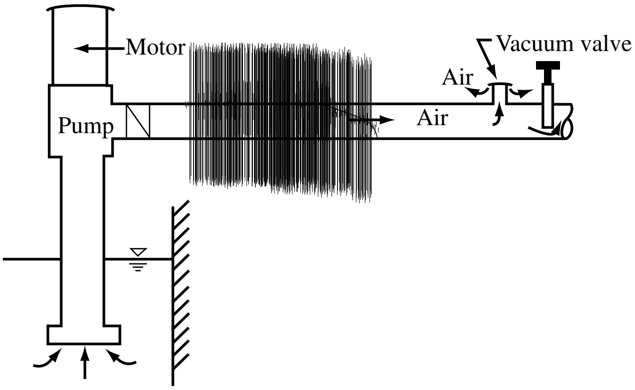


Figure 13.1 Filling an initially empty pump discharge line.

The air being vented from the pipe ahead of the oncoming water will leave the pipe much more easily than will the water behind it. When the last of this air leaves the pipe and the water hits the obstruction, there is a significant drop in water velocity which can cause a large increase in pressure. Research at Colorado State University by Kolp (1968), Andrews (1970), Diaz (1972), and Berlant (1974) has demonstrated the potential severity of the consequences of air exhaustion from pipelines. A Johns-Manville Corporation (1977) technical report nicely summarizes their work.

Another situation wherein air exhaustion can cause significant pressures is depicted in Fig. 13.2. Here the pump discharge column is initially empty, having been vented to the atmosphere by an air-vacuum valve. The water in the pipeline is restrained by a check valve. When the pump starts up, the water rushes up the discharge column and forces the air out through the open air-vacuum valve. When the last air leaves and the valve slams shut, large water hammer pressures can develop.

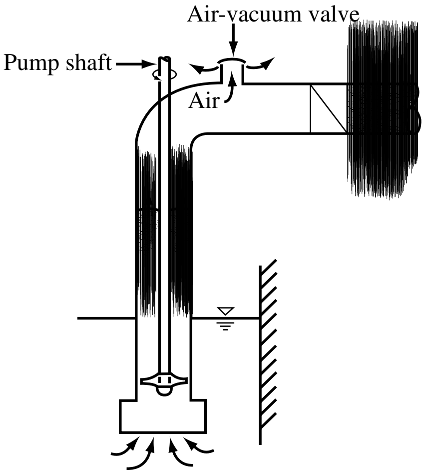


Figure 13.2 Filling a pump discharge column behind a closed check valve.

One other notable situation is a consequence of shutting down a pipeline in such a manner that air-vacuum valves open and large amounts of air enter the line. Upon restarting the flow in the line, care must be taken to insure that the air exhaustion problems discussed above do not occur here. This situation is insidious in that, after the pipeline has been successfully filled, it is easy to overlook the fact that significant amounts of air can be reintroduced by subsequent operation of the line.

13.1.4. PUMP STARTUP

As the pump starts up and comes "on line," a positive pressure surge is created in the downstream line. The magnitude of the pressure increment depends on the sudden increase in velocity which occurs when the check valve is forced open and the liquid in the pipeline begins to move. When there is no air in the line, the pressure increase is generally not large and does not exceed the pump shutoff head. If the pump has an objectionably high shutoff head, then there is a problem. Determining these pressures for various startup procedures using PROG8 was discussed briefly in Section 11.2.

If there is air in the discharge column or in the line, then substantial transient pressures can be developed. We have already discussed the problem of air in the discharge column. Martin (1976) analyzed this problem and concluded that head increases greater than ten times the original head can be generated under certain circumstances.

13.1.5. PUMP POWER FAILURE

Systems in which the static lift is large and the pipeline profile rises rapidly immediately downstream of the pumps can be subjected to the most severe transients upon power failure. If power is cut off from the pumps suddenly, either accidentally or purposefully, the pressure just downstream of the pumps drops rapidly, and this pressure drop propagates downstream at the wave speed (see Fig. 13.3). This drop in pressure can cause extensive column separation and lead to subsequent cavity closure shocks of large magnitude. In addition, a flow reversal in the system may also occur and lead to significant overpressures in the system, generally in the vicinity of the pumps, if the transient is not properly controlled.

If the pumps are booster pumps without a bypass line, power failure will initially cause the pressure to increase on the suction side of the pumps and drop on the discharge side.

Subsequent reflections from the upstream and downstream reservoirs may then cause unanticipated high or low pressures on either side of the pumps.

These situations are the most common causes of transient problems in pipe systems. Other situations are often combinations of these basic ones. We will now examine each of these situations individually and investigate the procedures and devices which can be employed to prevent objectionably high or low pressures.

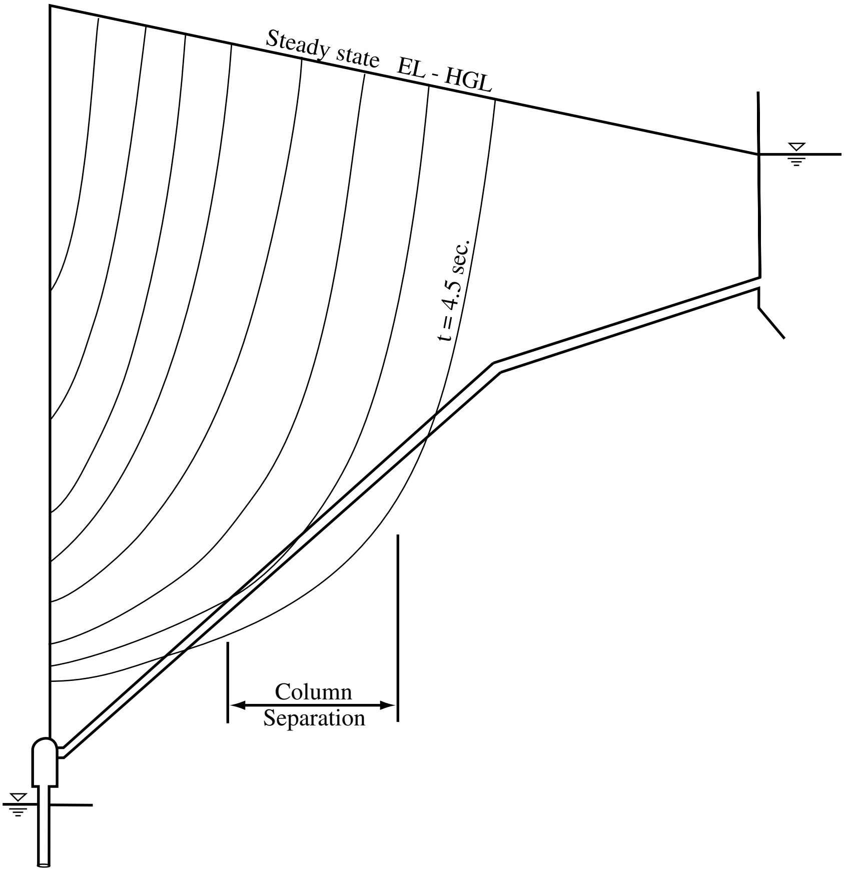


Figure 13.3 Propagation of a negative wave resulting from pump power failure.

13.2 TRANSIENT CONTROL

Transient pressure waves occur in pipelines because of changes in the fluid velocity that are commonly caused, for example, by valve movement, pump power failure, and/or column separation. Because the change in pressure is directly proportional to the change in velocity, the avoidance of sudden velocity changes will generally prevent serious transient pressures from developing. Most control devices and procedures are designed to function in a particular application to achieve this goal. We will now see how this approach can mitigate or sidestep these problems.

13.2.1. CONTROLLED VALVE MOVEMENT

In Section 10.4 we demonstrated how a valve closure schedule could affect the maximum transient pressure. For a gate valve we saw that the last 2-5% of the valve closure motion was critical in determining the maximum pressure. Different results will be found for other kinds of valves. The best way to determine the effect of a valve closure schedule on transient pressures is to obtain loss coefficients for the valve at various openings and conduct computer simulations of the system behavior in response to various proposed closure schedules. Once the proper closure schedule has been determined, a control system must be devised to implement it. The cost and availability of valve closure mechanisms in relation to funding limits will narrow the exploration of various closure schedules. For example, if the only option in closing a valve is to use a constant-speed motor, then two-rate closure schedules are not relevant to the study.

13.2.2. CHECK VALVES

The best check valves to use do not slam shut but instead close at the moment when forward flow ceases. Even in this case there may be some elastic energy in the system which will cause a pressure surge at the check valve. If a damped check valve is used, it must be treated in the same manner as a closing valve during the back flow period. It is important to assure that the valve either closes quickly before a reverse flow can become large or closes slowly over a time interval that is considerably greater than the critical time of closure $2L/a$. Otherwise an objectionably high pressure could occur at the time of check valve closure. Unfortunately, this problem is difficult to analyze; to do so requires a knowledge of the back-flow loss characteristics of the valve, which is rarely available.

13.2.3. SURGE RELIEF VALVES

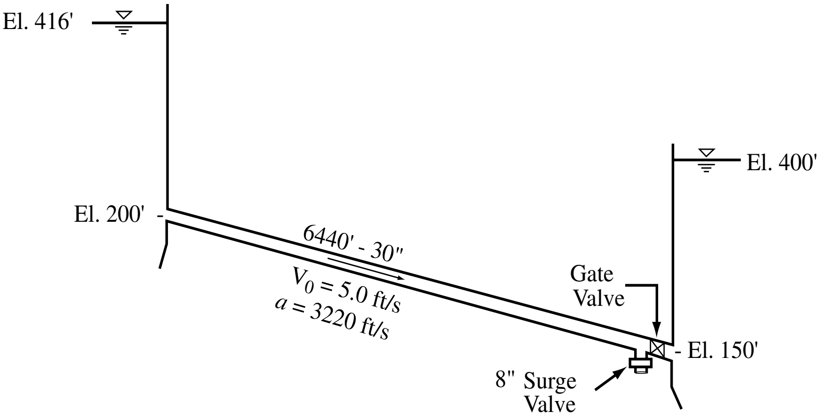
On occasion it is necessary to close valves rapidly or create other obstructions to the flow which cause abrupt decreases in velocity and result in high transient pressures. In these cases the most economical solution is often to use a surge relief valve. As Weaver (1972) describes, these valves open when a prescribed pressure is exceeded; they range from relatively inexpensive spring-loaded devices to rather expensive and complicated systems.

The surge relief valve is generally located adjacent to the device that is expected to cause the high pressure. The purpose of the valve is to provide an escape for the flowing liquid so that a sudden change in velocity and the consequent high pressures do not occur. A high-quality surge relief valve has little inertia in its actuating mechanism, so it can open almost instantaneously. It can be adjusted to operate to minimize the loss of liquid from the system and yet avoid unnecessarily high pressures during the closure process. These requirements can lead to a rather expensive valve which must be adjusted in the field for proper performance.

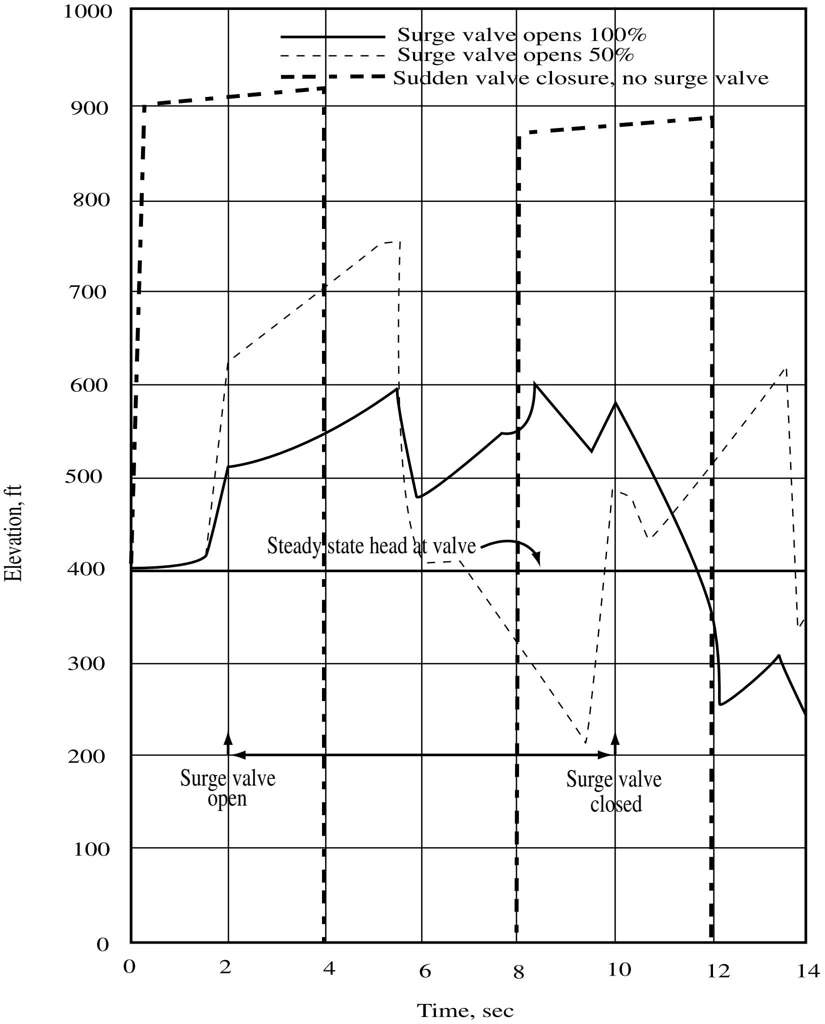
Large pipelines can be fitted with small surge relief valves because these valves can tolerate extremely high velocities for a short time period. To explore further the effectiveness of surge relief valves, we will look at an example.

Example Problem 13.1

This 30-in steel pipeline carries 11,020 gal/min between the two reservoirs. The gate valve closes in 2 sec, which is half of the critical closure time. The 8-in surge relief valve is set to open when the pressure exceeds 130 lb/in^2, and it will then close 8 sec later.



The results from three analyses are displayed in the plot and described in the paragraphs which follow.



The first analysis of the system assumed a sudden valve closure and an inoperative surge relief valve. The other two analyses treated cases with the relief valve (a) opening fully or (b) opening only 50 %.

With sudden valve closure and an inoperative surge relief valve, we obtain a typical nearly-square wave form similar to the one found in Chapter 7. When the surge relief valve is operative, the gate valve is closed in two seconds. If the surge relief valve only opens 50% of its full stroke, some pressure attenuation is achieved. However, to achieve a sig-nificant pressure reduction it is necessary to open the valve completely. The surge relief valve has reduced the potential surge pressure from over 500 ft to less than 200 ft.

The surge pressure can be regulated by the choice of surge relief valve size, opening pressure, percent of initial opening, and/or by the choice of closure schedule. Some surge relief valves are designed to close at the end of the surge in direct response to the pressure reduction in the line (spring-loaded). Others are designed to close after a specified (approximate) time interval has passed. Simulating well the behavior of a particular valve requires an intimate knowledge of the operational characteristics of that valve.

* * *

13.2.4. AIR VENTING PROCEDURES

Filling empty lines

The key to filling the empty lines of a pipeline system safely is *caution*. A means must be provided to introduce liquid slowly into the system at velocities of 1.0 ft/s or less (Johns-Manville Corp., 1977). Air release and air-vacuum valves must be located so that all air can be removed from the system slowly. Normally valves must be provided at the ends of lines so each line can be pressurized and all air can be forced out. This feature is also needed so that pressure tests can be conducted for leaks. Whatever the situation, operational procedures for the system must provide a way to control the rate of change of velocity so that severe transients do not occur.

The problem of air in the pump discharge column can be solved by replacing the vacuum valve on the pump discharge line with a valve which opens on sensing a vacuum but then closes slowly after the air is exhausted. Such a valve, much like a surge relief valve, can also be set to open at a prescribed high pressure, thus preventing the pump from ever operating at shutoff head.

In some pumped pipelines it may be necessary to provide a discharge bypass back to the sump to avoid the need to operate the pump under no-flow conditions. This bypass can prevent high pressures from developing, and it can also reduce the electrical load on the pump motor and the heat buildup in the pump itself. This feature is almost always required for axial-flow pumps.

Removing Air From Lines

Proper location and sizing of air-release and air-vacuum valves is an important consideration in pipeline design. Lescovich (1972) discusses this topic thoroughly. Seipt (1974) describes some operating techniques and addresses problems related to installation that can minimize air-related problems.

If the line is mostly filled with only relatively small pockets of air created by a shutdown, caution must still be used when the pumping system is restarted. The best approach is first to fill the empty lines by using the technique above and not resume normal operation until every air-vacuum and air-release valve has closed.

13.2.5. SURGE TANKS

Surge tanks can be used to mitigate both high and low pressures. They may act as temporary storage devices for excess liquid which has been diverted from the main flow. Such a diversion permits a much more gradual temporal change in velocity in the pipeline and a reduction in the magnitude of transient pressure waves. Surge tanks can also supply liquid to the pipeline to prevent excessive deceleration and objectionably low pressures. They may also act as damping devices on a pipeline where velocities surge back and forth frequently. There are numerous different types of surge tanks, each tailored to a particular purpose. The types that are most commonly used to protect pipelines are open-end, one-way, vented surge tanks, and air chambers. We will address each in turn.

Open-end surge tanks

The open-end surge tank is the simplest of the various types of tanks. Unfortunately, as a consequence of this simplicity, it is not commonly used in pipeline systems. The tank is connected to the pipeline so that the steady-state EL-HGL passes through the sur-face of the liquid in the tank. Any fluctuation in pressure at the surge tank connection causes flow to or from the tank, thereby moderating the pressure surges in the system. Unless the tank is quite tall and possibly rather large, it cannot accommodate large or extended pressure fluctuations. It is this disadvantage that limits its usefulness. It finds its greatest application in hydroelectric power projects where the damping features are valuable and the pressures are such that a reasonably sized tank, chamber, or tower can be employed. The cost of this type of project is generally so large that even a large surge tank or air chamber can be justified.

One-way surge tanks

In pumped flows in pipelines the one-way surge tank is commonly used because the EL-HGL is usually too far above the pipeline to employ an open-end surge tank. The one-way surge tank is used to prevent objectionably low pressures downstream from it. This tank can not prevent high pressures because the only flow is from the tank. A check valve in the connection prevents any return flow to the tank.

During normal steady-state operation the one-way surge tank is isolated from the system by the check valve. Figure 13.4 shows a typical one-way surge tank configuration. When transients occur which cause the pressure head at the tank connection to drop below the liquid level in the tank, the check valve will open, and flow from the tank into the line will occur. As a result, the liquid column is not required to decelerate so rapidly, and the pipeline EL-HGL is fixed nearly at the surge tank liquid surface. Figure 13.5 shows qualitatively how a series of one-way surge tanks placed along an uphill pipeline can prevent the column separation that is a common result of a pump power failure.

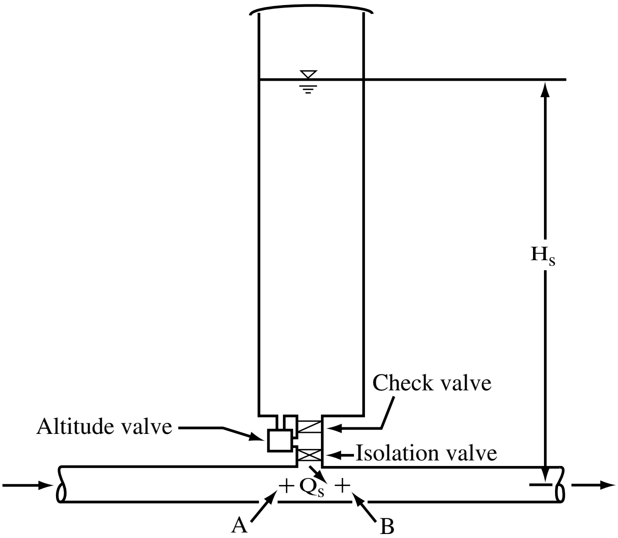


Figure 13.4 Diagram of a one-way surge tank.

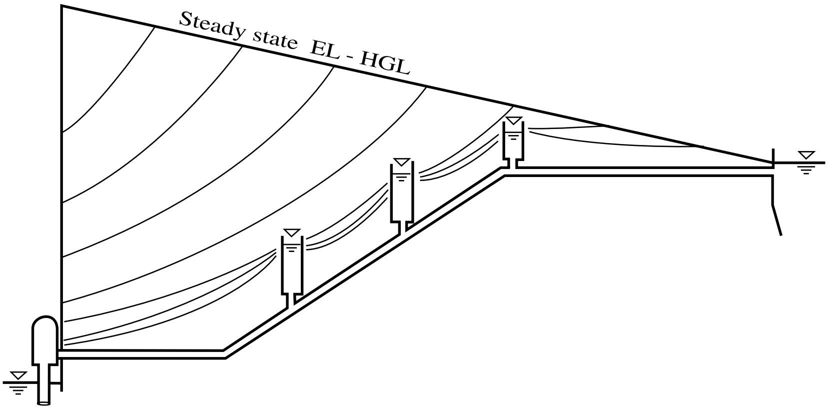


Figure 13.5 One-way surge tanks in a pumped pipeline.

To include one-way surge tanks in a transient analysis, it is necessary to model them with a particular set of interior boundary conditions. Input data to a computer program must specify the locations of the tanks, their geometry, and their hydraulic characteristics. We will now develop the equations to simulate the operation of these tanks.

We first assume that the surge tank is always sited at the junction of two series pipes. This is not a restrictive assumption, because we can always divide any pipe into a convenient number of series pipes, "breaking" the pipe at any convenient location. Referring to Fig. 13.4, we can write the following equations for the internal boundary conditions:

Upstream C^+ $$V_{P_A} = C_3 - C_4 H_P \tag{13.1}$$

Downstream C^- $$V_{P_B} = C_1 + C_2 H_P \tag{13.2}$$

Conservation of mass $$V_{P_A} A_A + Q_s = V_{P_B} A_B \tag{13.3}$$

Work-energy $$Q_s = C_{out} A_{out} \sqrt{2g\left(H_s + z_{AB} - H_P\right)} \tag{13.4}$$

Here C_{out} is the loss coefficient for the connecting pipe, A_{out} is the cross-sectional area of that connection, H_s is the height of the tank liquid surface above the centerline of the pipeline, and z_{AB} is the elevation of the center of the pipeline. The H_P's are not subscripted because the values of the head at locations A and B are identical. To determine when to activate this internal boundary condition, we continually monitor the pressure head at the surge tank connection. When the pressure head drops below the liquid level in the surge tank, flow from the tank begins, and the four equations must then be activated to simulate this condition.

In Eq. 13.4 the short-tube orifice equation describes the flow from the tank. The values of C_{out} can be calculated from the more readily available values for K_L for the components of the tank connection by using

$$C_{out} = \frac{1}{\sqrt{1.0 + \sum K_L}} \tag{13.5}$$

in which ΣK_L is the sum of the loss coefficients for the entrance, bends, check valve, and isolation valve, and 1.0 is the coefficient associated with the loss of one velocity head as the fluid from the tank enters the flow in the pipe. The pipe friction coefficient fL/D for the connector must be included if it is long. For a very well-designed connection C_{out} could be as large as 0.80; for a poorly designed connection C_{out} may be as low as 0.40.

In this surge tank model we have five unknowns but only four equations, so we need another equation. We resolve this problem by monitoring the height H_s of the liquid in the tank. Calling the initial height H_{s_0}, the height H_s at any later time can be found by direct integration via the equation

$$H_s = H_{s_0} - \frac{1}{A_s}\int_0^t Q_s dt \tag{13.6}$$

in which A_s is the cross-sectional area of the surge tank.

However, instead of performing the integration, we will keep a running record of the liquid height by finding the change at each time step and recomputing the new height. Thus H_s becomes known in the equation set. The relation which does this is

$$H_s(t + \Delta t) = H_s(t) - \frac{\Delta t}{A_s} Q_s(t) \tag{13.7}$$

Here we have treated the flow from the tank as a quasi-steady flow by neglecting inertial effects and assuming that the steady-flow equation of motion applies.

Solving Eqs. 13.1 through 13.4 simultaneously for the discharge from the tank, we obtain

$$Q_s = 0.5\, C_5\left(-1 + \sqrt{1 + \frac{4C_6}{C_5^2}}\right) \tag{13.8}$$

in which

$$C_5 = \frac{2gC_{out}^2 A_{out}^2}{C_2 A_B + C_4 A_A} \tag{13.9}$$

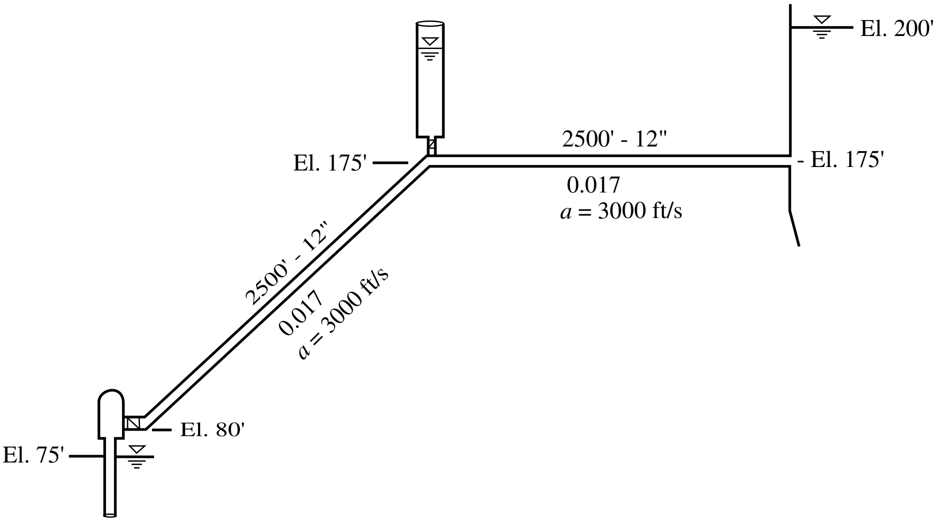
$$C_6 = \frac{2gC_{out}^2 A_{out}^2}{C_2 A_B + C_4 A_A}\left[C_1 A_B - C_3 A_A + \left(C_2 A_B + C_4 A_A\right)\left(H_s + z_{AB}\right)\right] \tag{13.10}$$

Once the surge tank begins to empty, the value of C_6 is continually tested to determine whether Q_s is going to become negative. If $C_6 < 0$, then Q_s is set to zero, thereby closing the surge tank check valve. An example is presented to show the input data that are required for a one-way surge tank and to illustrate their effect on transient pressures.

Example Problem 13.2

Two five-stage Johnston 14BC pumps with 10-in impellers (see Appendix B) are used to pump water from a river at elevation 75 ft to a reservoir with a surface elevation of 200 ft. The ductile iron pipeline is 12 in inside diameter with a friction factor of 0.017 and a wave speed of 3000 ft/s. The pipeline profile is shown on the next page.

The one-way surge tank is located at the end of the uphill run of the pipe from the pump station. The tank is connected to the pipeline with a short 12-in-diameter pipe incorporating a slant-disk check valve and an isolation gate valve. The connection loss coefficient is estimated to be $C_{out} = 0.6$.



The input data file for the final analysis follows:

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DEMONSTRATION OF PROGRAM NO. 8 - INPUT DATA FILE "EP132.DAT"
USE OF A ONE-WAY SURGE TANK TO ELIMINATE COLUMN SEPARATION
&SPECS NPIPES=2,NPARTS=5,IOUT=1000,NSURGE=1,HRES=200.,
       HSUMP=75.,HATM=33.,ZEND=175.,TMAX=50.,QACC=0.5,AIR=F,
       PFILE=F,HVPRNT=T,PPLOT=F,GRAPH=T/
1  12.  2500.  0.017  3000.   80.
2  12.  2500.  0.017  3000.  175.
&PUMPS NPUMPS=2,NSTAGE=5,RPM=1175.,WRSQ=125.,
       QN=0.,200.,400.,600.,900.,1300.,
       HNSQ=43.,40.,38.,36.,26.,0.,
       TNSQ=4.,4.8,6.,7.2,8.,4./
1  25.  3.  12.  0.6
&GRAF NSAVE=4,IOUTSA=5,PIPE=1,1,2,2,NODE=1,4,1,3/
```

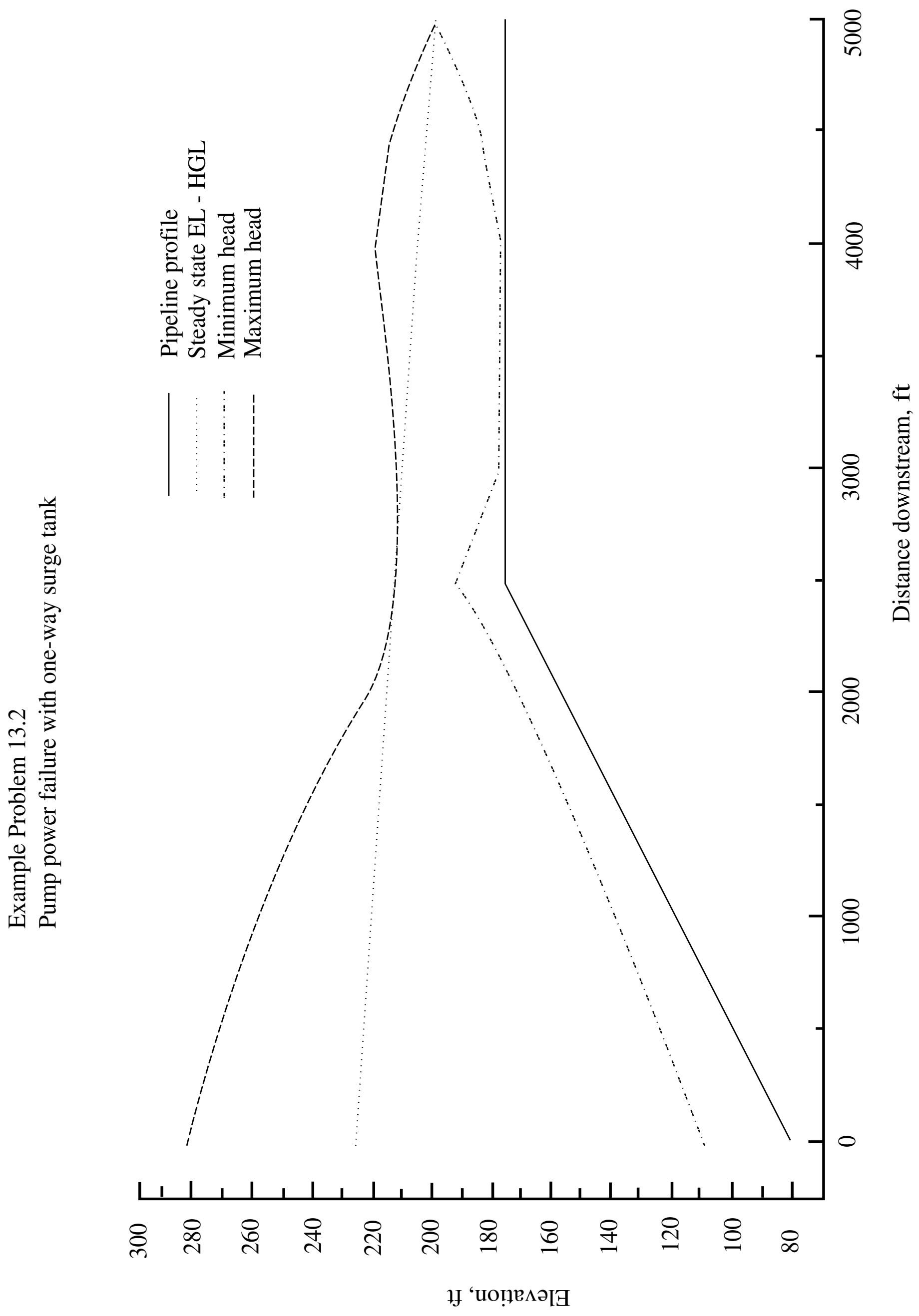
A one-way surge tank 25 ft high and 3 ft in diameter will meet the requirements. The minimum pressure of 1 lb/in^2 occurs in the horizontal section of pipe downstream of the surge tank. A plot of the maximum and minimum pressures along the pipeline is presented on the following page.

* * *

13.2.6. AIR CHAMBERS

An open-end surge tank placed on the discharge side of a pump station would be an excellent device for the control of both positive and negative surges. However, because the discharge pressure of the pumps is often quite high, the surge tank would have to be very tall to extend above the EL-HGL. This height requirement generally causes the open-end surge tank to be uneconomical, not to mention unsightly. However, there is a device which can play the role of an open-end surge tank without the height problem. The device is an air chamber (sometimes called a hydro-pneumatic tank, an air bottle or a shock trap). It is a relatively small pressurized vessel, containing both air and liquid, which is connected to the discharge line from the pump station.

The primary purpose of the air chamber is to prevent negative pressures and column separation in the pipeline downstream of the pump station during power failure rundown. However, the device can be an excellent positive surge suppresser as well. As Fig. 13.6



shows, the chamber is sealed and compressed air overlays the liquid in the chamber. After power failure occurs, liquid is drawn into the pipeline from the chamber, permitting the flow in the pipeline to decelerate more slowly and keeping the pressure relatively high. As the amount of liquid in the chamber decreases, the air volume expands, decreasing the pressure at the pump discharge. The rate at which the air pressure drops is dependent on the

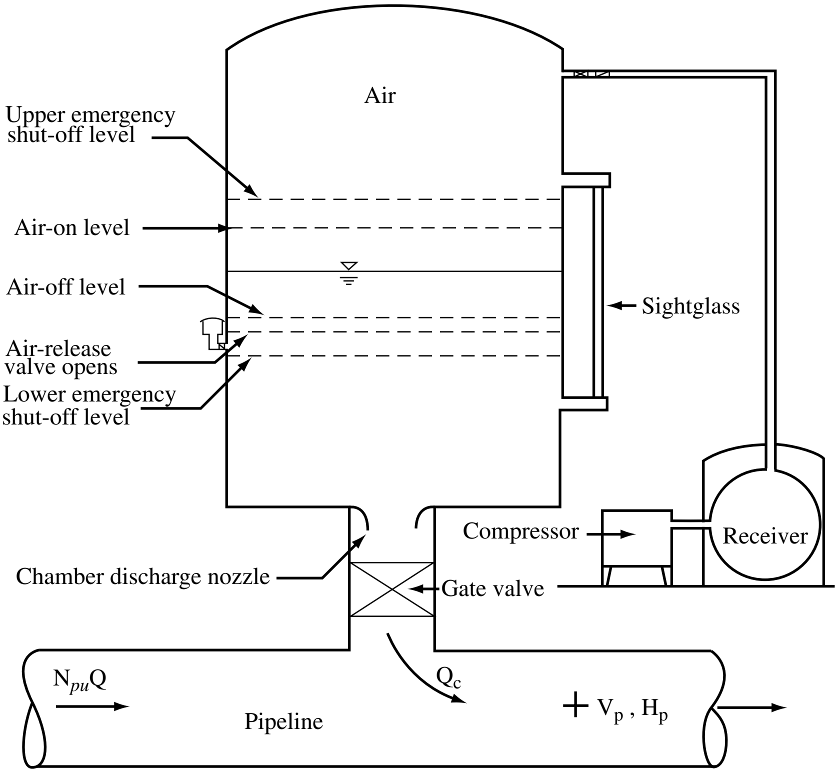


Figure 13.6 Diagram of an air chamber and its appurtenances.

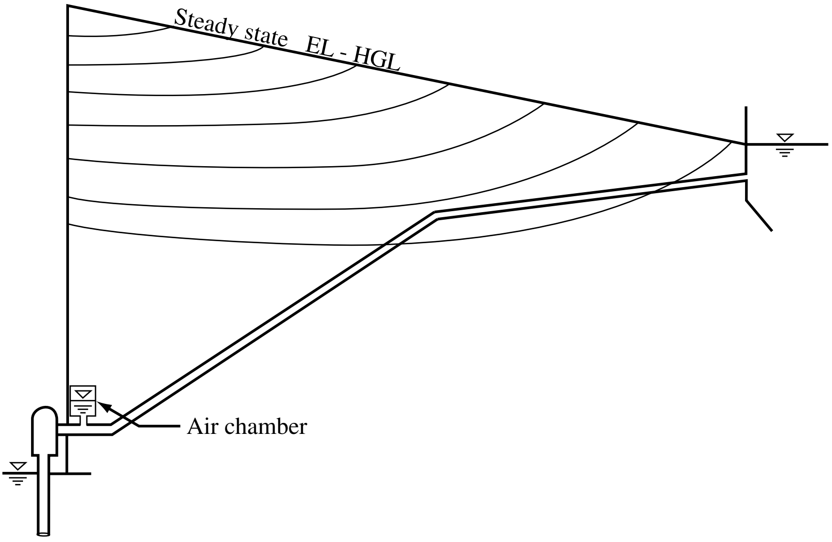


Figure 13.7 Propagation of a negative wave after pump power failure with an air chamber at the pump.

initial air volume, the rate at which liquid is drawn from the chamber, and the thermodynamic process which the air undergoes. This process simulates the dropping liquid level of an open-end surge tank and in many cases is able to bring the pipeline flow gently to rest without causing objectionably low pressures. Figure 13.7 illustrates how the air chamber affects the pressure profile during a transient incident. Compare this behavior with the scenario shown in Fig. 13.3.

The air chamber must be sufficiently large to supply the needs of the pipeline without emptying and permitting air to enter the pipeline. Also, the initial air volume must be large enough to prevent the rate of pressure drop from being excessively high. An initial air volume that is too small will cause the pump discharge pressure to behave as if the air chamber is absent, thereby giving little or no assistance in preventing low pressures. When the flow finally reverses and begins to move back toward the pumps, the check valve closes (actually it usually is already closed), and flow occurs into the chamber. To provide some damping for the system, the losses for flow *into* the chamber are deliberately made higher than the losses for flow *from* the chamber. This can be done by using a nozzle similar to the one shown in Fig. 13.6 or by having two connections to the chamber, one with a low loss for outflow and one with a higher loss for inflow. Generally, good damping can be accomplished without causing high pressures during the backflow phase.

Occasionally the air chamber alone is not adequate to prevent column separation. Low pressures can occur at local summits along the pipeline where the effect of the air chamber at the pump is inadequate. In these cases a one-way surge tank at each summit can be used to "drape" the EL-HGL above the pipeline on both sides of the summit. Figure 13.8 illustrates this technique.

The set of equations describing the behavior of an air chamber is rather complex. We will assume that the air chamber is at the upstream end of the pipeline so the boundary condition at this point will consist of the relations for both the pumps and the air chamber. We will assume that all of the pumps fail simultaneously.

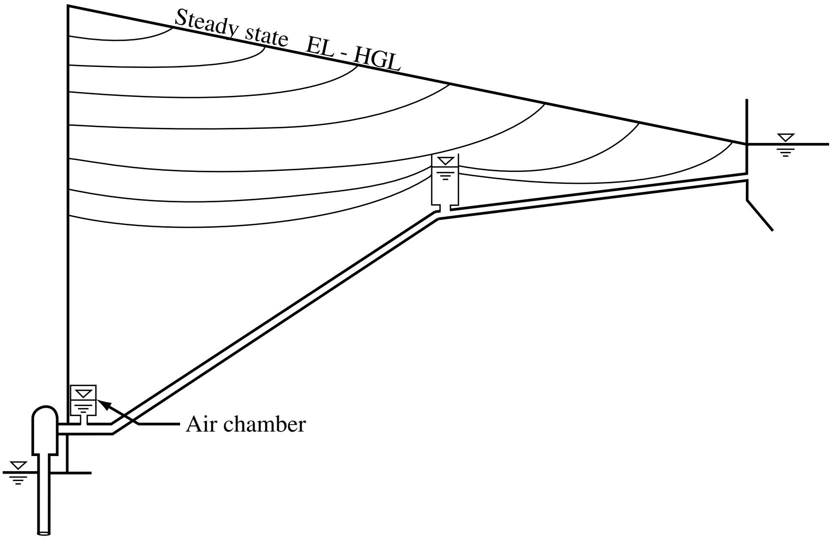


Figure 13.8 Propagation of a negative wave after power failure with an air chamber and a one-way surge tank.

The appropriate equations are the following:

C$^-$ $V_P = C_1 + C_2 H_P$ (13.11)

Conservation of mass $N_{pu}Q + Q_c = V_P A$ (13.12)

Pump work-energy $$H_{sump} + h_p = H_P \tag{13.13}$$

Chamber work-energy $$Q_c = C_{out} A_{out} \sqrt{2g\left(H_c - H_P\right)} \tag{13.14}$$

Pump head increase $$h_p = N^2 N_{st}\left(C_7 \frac{Q}{N} + C_8\right) \tag{13.15}$$

In these equations H_c is the head in the chamber, C_{out} is the outflow coefficient, A_{out} is the outflow cross-sectional area, and Q_c is the discharge from the chamber.

We have six unknowns in these five equations, so another relation is required. This equation will describe the thermodynamic process that the air in the chamber undergoes. The most commonly used process is the polytropic process

$$\frac{p}{\gamma^{\eta}} = \frac{p_o}{\gamma_o^{\eta}} \tag{13.16}$$

in which p_o and γ_o are the absolute pressure and specific weight of the air in the chamber under steady-flow conditions, p and γ are those values at a later time, and η is the polytropic exponent, generally chosen to be 1.2. There is some disagreement over the appropriateness of this value. Graze (1972) and Graze et al. (1976) have shown that this process does not describe precisely the thermodynamic behavior of the air. One complicating feature during the air expansion process is that the freezing temperature of the liquid is often reached. The latent heat released by the freezing of condensed liquid vapor complicates the thermodynamic process beyond the simplicity of the polytropic model. However, in light of the many other uncertainties in the analysis, we will continue to use the polytropic equation until a better model that is reasonably easy to use appears.

With H_{atm} as the atmospheric pressure head, the polytropic equation can be written

$$\frac{\left(H_c + H_{atm} - z_P\right)\gamma_w}{\gamma^{\eta}} = \frac{\left(H_{c_o} + H_{atm} - z_P\right)\gamma_w}{\gamma_o^{\eta}} \tag{13.17}$$

If the initial air volume is $\rlap{-}V_{c_o}$ and the volume at a later time is $\rlap{-}V_c$, the equation can be written as

$$H_c = z_P - H_{atm} + \left(H_{c_o} - z_P + H_{atm}\right)\left(\frac{\rlap{-}V_{c_o}}{\rlap{-}V_c}\right)^{\eta} \tag{13.18}$$

in which the air volume at any time can be calculated in a way that is similar to the fluid volume computations for the one-way surge tank:

$$\rlap{-}V_c\left(t + \Delta t\right) = \rlap{-}V_c\left(t\right) + Q_c\left(t\right)\Delta t \tag{13.19}$$

Now we solve the six equations simultaneously.

For the most general case we assume flow continues both through the pumps and from the chamber. Knowing $\rlap{-}V_c$ from Eq. 13.19, we can calculate H_c from Eq. 13.18, reducing the number of unknowns to five. Solving the five equations for Q_c produces

$$Q_c = 0.5C_5\left(1-\sqrt{1-\frac{4C_6}{C_5^2}}\right) \tag{13.20}$$

in which

$$C_5 = \frac{2gC_{out}^2A_{out}^2NN_{st}C_7}{N_{pu}-NN_{st}AC_7C_2} \tag{13.21}$$

and

$$C_6 = 2gC_{out}^2A_{out}^2\left[-H_c+\frac{H_{sump}+\left(NN_{st}/N_{pu}\right)\left(C_1C_7A+NN_{pu}C_8\right)}{1-\left(NN_{st}AC_2C_7\right)/N_{pu}}\right] \tag{13.22}$$

After calculating Q_c, Q is found from

$$Q = \frac{1}{N_{pu}}\left[AC_1+AC_2\left(H_c-\frac{Q_c^2}{2gC_{out}^2A_{out}^2}\right)-Q_c\right] \tag{13.23}$$

If $Q \geq 0$, then the solution is acceptable, and the remaining unknowns may be calculated from Eqs. 13.11 through 13.15.

If $Q < 0$, then the pump check valves must be closed, and Q must be set to zero. Now Q_c must be calculated from

$$Q_c = 0.5C_5\left(-1+\sqrt{1+\frac{4C_6}{C_5^2}}\right) \tag{13.24}$$

where

$$C_5 = \frac{2gC_{out}^2A_{out}^2}{C_2A} \tag{13.25}$$

and

$$C_6 = 2gC_{out}^2A_{out}^2\left(H_c+\frac{C_1}{C_2}\right) \tag{13.26}$$

Once the pumps are off line and the check valves are closed, they are never reopened. Flow from the air chamber will continue until the flow reverses its direction.

To represent flow into the air chamber correctly, a different set of equations must be solved. With flow into the chamber, the pumps are not a factor, so the following equations are used:

C^- $V_P = C_1 + C_2H_P$ (13.27)

Conservation of mass $Q_c = V_PA$ (13.28)

Chamber work-energy $Q_c = -\ C_{in}A_{in}\sqrt{2g\left(H_P-H_c\right)}$ (13.29)

Here C_{in} is the discharge coefficient for flow into the air chamber, and A_{in} is the inflow cross-sectional area.

Solving these equations simultaneously for Q_c leads to

$$Q_c = 0.5C_5\left(1 - \sqrt{1 - \frac{4C_6}{C_5^2}}\right) \tag{13.30}$$

in which

$$C_5 = \frac{2gC_{in}^2A_{in}^2}{AC_2} \tag{13.31}$$

and

$$C_6 = 2gC_{in}^2A_{in}^2\left(H_c + \frac{C_1}{C_2}\right) \tag{13.32}$$

The values of C_{out} and C_{in} can be estimated from Eq. 13.5.

Sizing the air chamber

At the upstream end of a pipeline where an air chamber is located, the variation of pressure with time depends primarily on the initial air volume in the chamber when the power failure occurs. The pressure drops more rapidly with a smaller initial air volume.

The first step in the sizing procedure is to try successive values of the initial air volume until the minimum pressures along the pipeline are acceptable. This air volume establishes the upper emergency level (see Fig. 13.6). If power failure occurs when the air volume is smaller than this, undesirably low pressures will occur.

Because pressures fluctuate during the normal operation of the system, there must also be some space in the air chamber to accommodate this variation. Evans and Crawford (1953) recommend 25% of the initial air volume at the upper emergency level for this purpose; however, the chosen value can be based on the actual operation of the pumping system.

Because it is possible for the power to fail when the initial air volume corresponds to the upper emergency level plus 25%, we must make sure the chamber is sufficiently large that it will not empty during the downsurge. Hence we make one last analysis using this larger air volume as the initial air volume. This initial air volume is associated with the lower emergency level (see Fig. 13.6). The maximum air volume which exists during this analysis establishes the minimum total volume of the air chamber. This value should be increased by another 10% or more as a factor of safety against emptying the air chamber.

While the configuration in Fig. 13.6 may be a typical schematic design for a small chamber, it may not be appropriate when large chambers are required. If a large chamber is needed, it can be replaced with several smaller chambers similar to the one in Fig. 13.6. Or it can be fabricated as a single horizontal tank that looks much like a large propane tank. Both approaches are commonly used.

Air chamber appurtenances

Air chambers do require some special appurtenances for proper operation. Because the liquid level in the chamber must be kept between the bounds of the upper and lower emergency levels (except for short term fluctuations), some provision must be made to accomplish this. If the liquid level gets too high and remains there too long, compressed air from the receiver (see Fig. 13.6) is injected into the chamber to force the liquid down. Conversely, if the water level drops too low, air is removed from the chamber via an air release valve to raise the liquid level.

Should the liquid level move above the upper emergency level and resist all efforts to bring it back down, the system should be shut down carefully to determine the cause. If the system cannot be shut down, an alarm should be sounded to alert personnel of the problem so corrective action can be initiated.

Flow from the chamber should be achieved with minimum head loss so that the pressure in the pipeline downstream remains as high as possible. If the smooth nozzle shown in

Fig. 13.6 is not practical, at least the outflow connection should be sufficiently large that the fluid velocity in it is moderate. Because the air chamber may take over for the pumps rather quickly, a good estimate of the initial flow from the chamber is the steady-state discharge from all of the pumps.

Flow into the chamber typically is designed to undergo a greater head loss than is experienced by an outflow. This situation will damp the oscillatory flow over time. The nozzle in Fig. 13.6 will accomplish this. However, there are other ways to reach the same end. Separate inflow and outflow connections can be used, with the inflow connection being smaller to create higher velocities and greater losses.

A sight glass is needed to permit observation of the liquid surface in the chamber. Water level sensors are needed to determine when to turn the compressed air flow on or off and when to signal a violation of the upper or lower emergency levels. They can be located externally to the chamber via connecting piping so that maintenance or replacement of these sensors can be done easily. A man-door is generally provided on larger chambers. A variety of drains, pressure regulators, pressure gages, air release valves etc. complete the list of devices. In cold climates the chambers are usually enclosed in a heated structure to prevent their freezing.

Example Problem 13.3

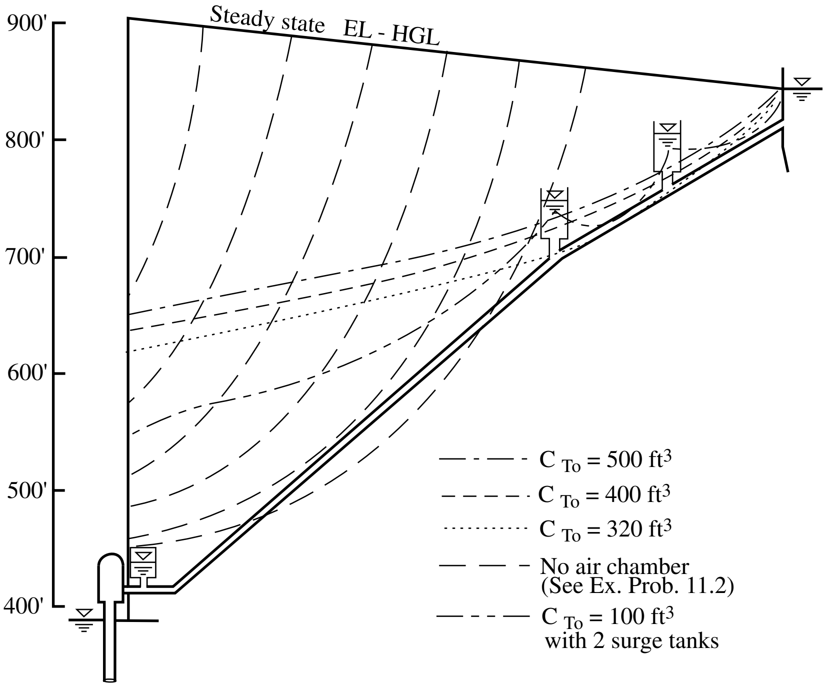
Example Problem 11.2 is reconsidered here with the objective of providing corrective devices to prevent column separation. In fact, we will attempt to eliminate negative pressures from the entire pipeline. We will present the results of five different analyses using PROG7. The five analyses consider the following scenarios:

(a) No corrective devices.
(b) Air chamber with an initial air volume of $320\ ft^3$.
(c) Air chamber with an initial air volume of $400\ ft^3$.
(d) Air chamber with an initial air volume of $500\ ft^3$.
(e) Air chamber with an initial air volume of $100\ ft^3$ and two one-way surge tanks.

The input data file for run (e) is presented here:

```
DEMONSTRATION OF PROGRAM NO. 7 - INPUT DATA FILE "EP133.DAT"
USE OF AN AIR CHAMBER & ONE-WAY SURGE TANKS TO ELIMINATE
COLUMN SEPARATION
&SPECS NPIPES=4,NPARTS=3,IOUT=1000,NSURGE=2,HRES=840.,
       HSUMP=395.,HATM=32.,ZEND=810.,TMAX=50.,QACC=0.50,
       AIR=T,NOPUMP=F,PFILE=F,HVPRNT=T,PPLOT=T,
       GRAPH=T,RERUN=F/
1  30.   2000.  0.013  3590.  415.
2  30.  15840.  0.013  3590.  415.
3  30.   5280.  0.019  3490.  700.
4  30.   5280.  0.019  3490.  755.
&PUMPS NPUMPS=4,NSTAGE=5,RPM=1775.,WRSQ=475.,
       QN=0.,1000.,2000.,3000.,4000.,4500.,
       HNSQ=129.,127.5,121.,103.5,67.5,0.,
       TNSQ=50.,58.,78.,92.,97.,80./
&CHAMB CTZERO=100.,COUT=0.80,CIN=0.50,DNOZ=12.00,EXPON=1.20/
2  40.  6.  12.  0.80
3  50.  6.  12.  0.80
&GRAF NSAVE=3,IOUTSA=2,PIPE=1,3,4,0,NODE=1,1,1,0/
```

The curves for analysis (a) were copied from Example Problem 11.1 and depict the progression of the negative wave downstream. Included in this plot are the results from runs (b) through (e) which represent the lower bound on pressure heads along the pipeline for that configuration.



The initial air volumes each differ in size by 25%. This approach is useful in determining the final size of the air chamber. For example, in the cases where the initial air volume was 500 ft^3, the pressures were found to be well above zero. The next air volume was 500/1.25 = 400 ft^3. This analysis still gave positive pressures so we next tried 400/1.25 = 320 ft^3. This time the minimum pressure was about zero at one point in the line, so we have now established the initial air volume at the upper emergency level. Following the 25% rule for pressure fluctuation space, we next conduct an analysis for 1.25x320 = 400 ft^3. However, this analysis has already been completed, and the information for sizing the tank is already available.

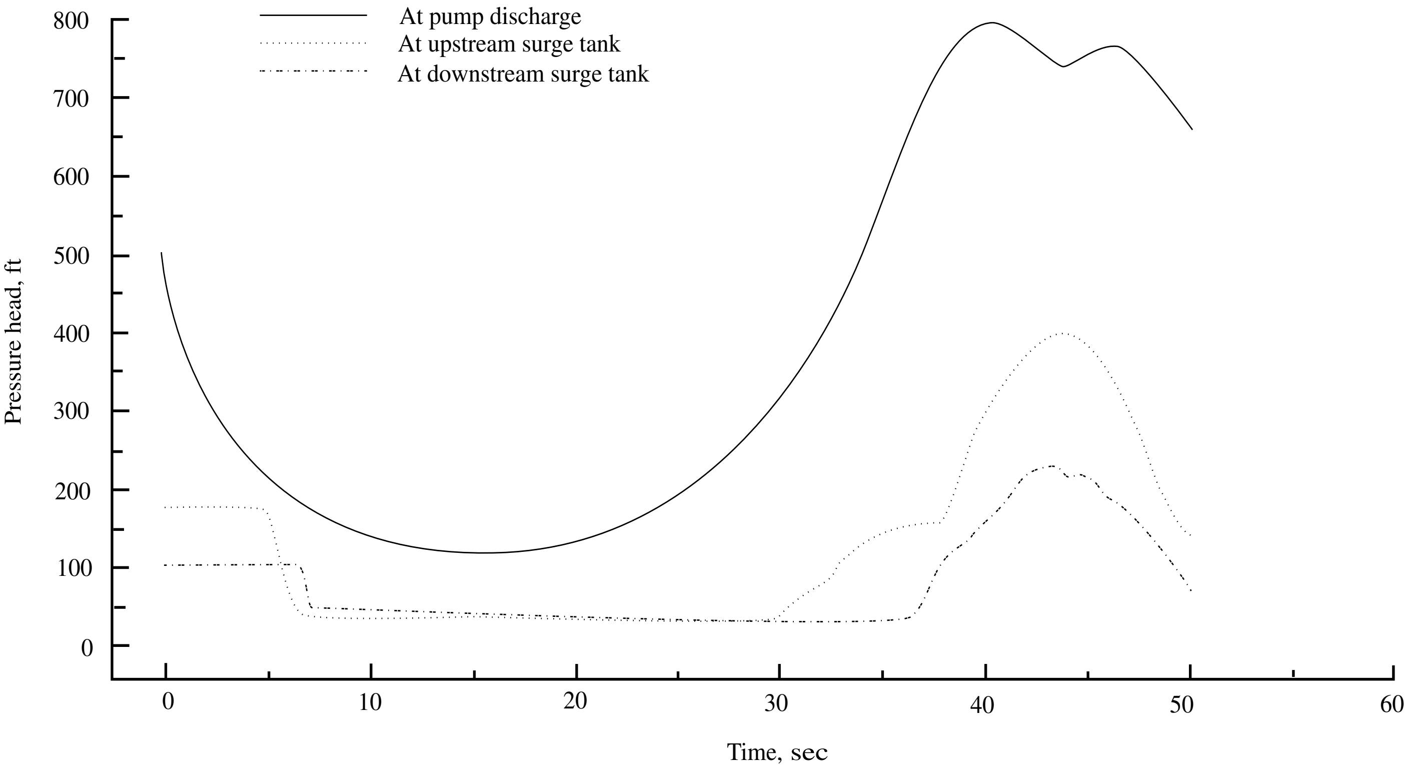
In the analysis of alternative (c) the maximum air volume reached approximately 730 ft^3. We can now proceed to the design decisions about the number and size of the air chamber units.

By using two one-way surge tanks, it is possible to reduce the air chamber volume significantly. The practicality of this alternative depends on the economics of the design and on aesthetic considerations at the site. Two one-way surge tanks, 40 ft and 50 ft high, respectively, may be more expensive and unsightly than a larger air chamber. This alternative is presented mainly to show that combinations of surge control devices may be more effective than any one device. In fact, if there were a local summit in the pipeline, it is likely that a one-way surge tank would be needed to prevent column separation downstream of the summit, and an air chamber would be needed at the pump to prevent the same problem upstream of the summit.

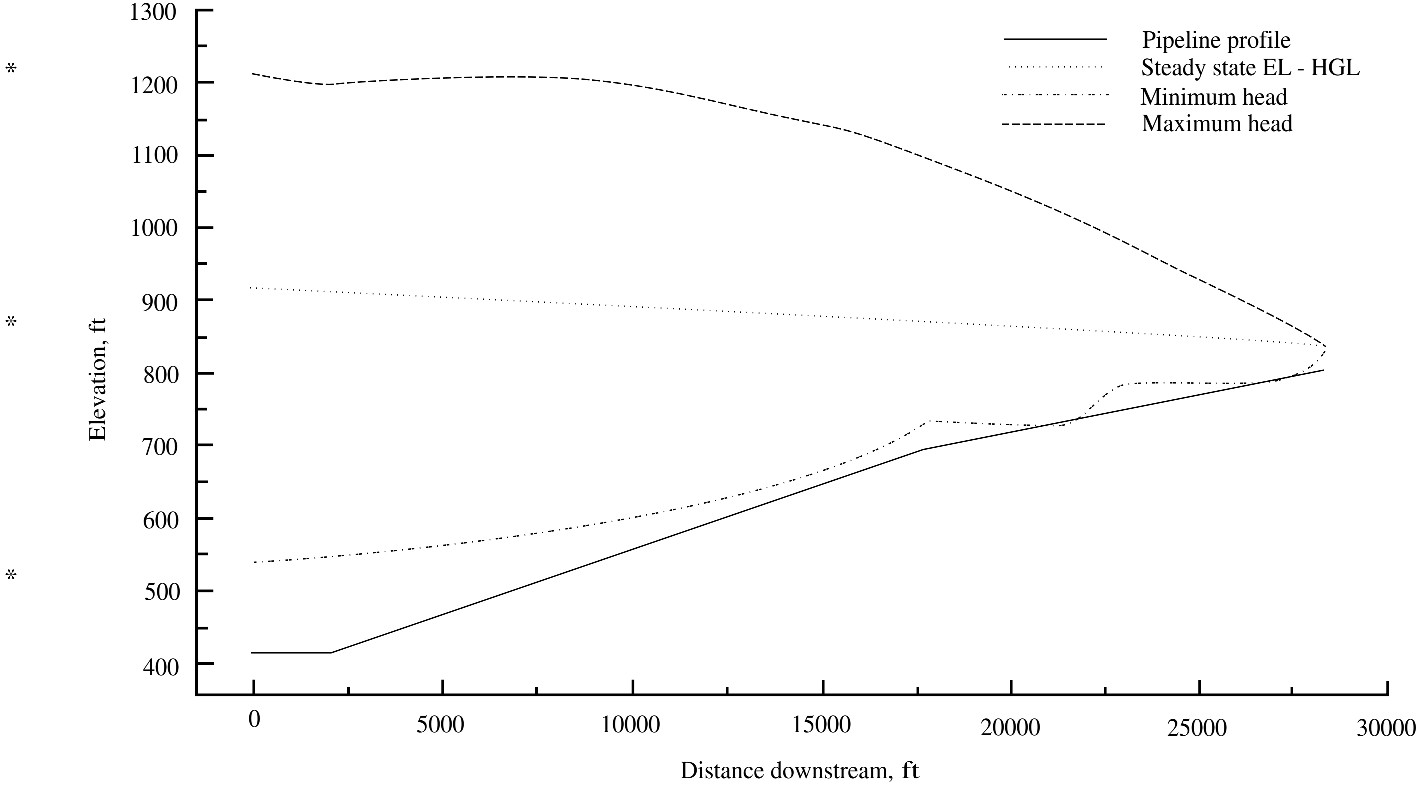
Design of the physical configuration of the pump station and pipeline, into which the various control devices are incorporated, is outside the subject matter of this book. For more information consult Sanks et al. (1981) for a comprehensive treatment of pumping station design.

The following two pages present a plot of head vs. time for three locations along the pipeline and a plot of the maximum and minimum heads along the pipeline.

Example Problem 13.3
Pump power failure with air chamber and one-way surge tanks



Example Problem 13.3
Pump power failure with air chamber and one-way surge tanks



Vented surge tanks

A variant of the one-way surge tank is the vented surge tank. This device is conceptually a one-way surge tank for downsurge and an air chamber for upsurge. The tank is sealed and equipped with a vacuum valve (actually a spring-loaded check valve exposed to the atmosphere) to permit air to enter the tank during downsurge but not exhaust air when the flow reverses (see Fig. 13.9). It also has an air release valve to bleed the ingested air out slowly. The tank is connected to the pipeline through an open line so that the line pressure is continually communicated to the tank, i.e. the tank is continually "on line." When the EL-HGL drops to the level of the liquid in the tank during a downsurge, the vacuum valve opens, permitting air to enter the tank to replace the liquid flowing into the line; this behavior mimics the behavior of a one-way surge tank. With an upsurge the liquid flows into the tank, but the air is prevented from exhausting rapidly by the vacuum (check) valve, so it is compressed much like the air in an air chamber on upsurge. The compressed air acts as a shock absorber in the system. The size of the air release valve is sufficiently small that it does not materially affect the compression process. After a short time the air release valve has bled all of the air from the tank, and it is once again full of liquid and ready to function.

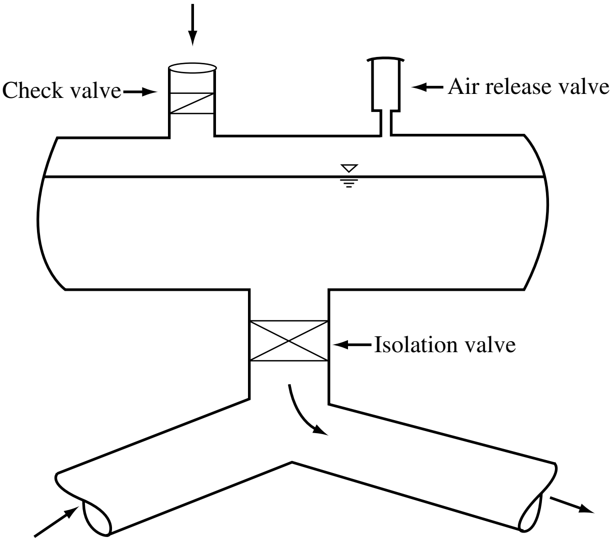


Figure 13.9 Schematic diagram of a vented surge tank.

The additional versatility of the vented surge tank in comparison with the one-way surge tank can be useful if reverse flow problems are anticipated. However, the tank must be designed to withstand the line pressure. Unless it is as tall as the one-way surge tank, it loses some of its effectiveness in preventing column separation. It is most effective at a well-defined summit of a pipeline.

Computationally, the vented surge tank is modeled as a one-way surge tank on downsurge (keeping track of the accumulating air volume). When flow begins to enter the tank, it is then treated like an air chamber. Computer code from the previous two sections can be utilized to accomplish such an analysis.

13.2.7. OTHER TECHNIQUES FOR SURGE CONTROL

Air-vacuum valves

Air-vacuum valves are a potential source of surge control. By opening when the pressure in the line drops below atmospheric pressure, they expose the pipeline to the atmosphere, which permits the liquid to decelerate more slowly. This does not prevent the occurrence of column separation at points in the pipeline that are remote from the location of the air-vacuum valves, but it may reduce the intensity of a cavity closure shock by keeping the velocities lower. However, a problem may develop when (1) a pump restart or (2) a reversed flow driven simply by gravity causes the air to exhaust from the pipe and slam the air-vacuum valve shut. To determine whether air-vacuum valves are an asset or a liability in a pumped pipeline system, one can use PROG8 to analyze the system. For a pumped pipeline this analysis will permit one to develop an operational strategy which will minimize transient pressures.

Surge anticipation valves

In some cases the low pressures associated with column separation are not a problem. Rather the problem to avoid is the creation of potentially high shock pressures from the closure of a cavity. The surge anticipation valve provides this service. Although it does not prevent column separation, it minimizes the impact of cavity closure. It is most effective in pumping systems which run uphill with no major intermediate summits in the pipeline profile. Because the pressure could drop below atmospheric for some time over a large fraction of the pipeline, air may be ingested into the pipeline through air-vacuum valves. This may or may not be a positive occurrence for surge control, as it depends on the amount of air ingested and a host of other considerations. We are also then faced with the removal of the air in the system as a part of the pump restart procedure. Finally, the pipeline should be designed to withstand vacuum pressures because they are likely to occur somewhere along the pipeline.

The surge anticipation valve is a specially-operated surge relief valve placed at the upstream end of a pipeline. It is adjusted so that the valve opens after pump power failure when the pressure at the valve drops below a set value. As a consequence, the pressure at the valve quickly drops nearly to atmospheric pressure, causing the pressure in the line downstream to drop sharply. The liquid in the line decelerates rapidly with extensive column separation likely to occur. When the flow reverses, the surge valve is already open so the reverse flow is routed out of the system without a sudden decrease in velocity which would cause cavities to close and lead to high shock pressures. That is, the nearby cavities may be washed out of the system through the open surge anticipation valve. The valve then closes slowly to bring the reverse flow gently to rest.

Pump inertia control

Because column separation in pumped pipelines is normally the direct result of the low rotational inertia of the pumping system, increasing the inertia is another means of mitigating column separation. The impact of increasing the moment of inertia of the pump and motor unit was demonstrated by Streeter and Wylie (1967); for a long pipeline where most of the pumping head is used to overcome pipe friction, they show that a quadrupling of the rotational inertia would prevent column separation. This can be accomplished by incorporating a flywheel into the linkage between the pump and motor. It is easiest to manage this for pumps driven by diesel or gasoline engines. This alternative is attractive because it is simple, low maintenance, and relatively inexpensive. However, owing to the practical limits on how much inertia can be added, the method has not found wide application.

13.3 PROBLEMS

13.1 For Problem 11.1 use PROG7 to determine the appropriate size for an air chamber which will prevent any negative pressures from occurring in the pipeline.

13.2 For Problem 11.4 what is the size of the air chamber which will prevent any negative pressures from occurring in the pipeline? Use PROG7.

Complete another design which employs both an air chamber and one-way surge tanks to accomplish the same purpose.

13.3 For Problem 11.5 use PROG7 to determine the size of an air chamber which will prevent any negative pressures from occurring in the pipeline.

Investigate the feasibility of a design using only one-way surge tanks.

Complete a third design using an air chamber and one-way surge tanks.

13.4 For Problem 11.3 use PROG7 to determine the size of an air chamber which will prevent negative pressures from occurring over any significant portion of the pipeline.

13.5 A preliminary design is being prepared for a pumped pipeline which lifts water from a reservoir at elevation 5760 ft to a canal at elevation 6220 ft. The steel pipe is 72 in in diameter with a friction factor of 0.020 and a wave speed of 3100 ft/s. The pipeline profile is described in the following table:

Station, ft	**Elevation, ft**
0	5765
350	5875
1100	5905
2100	6165
3150	6095
6400	6115
7700	6185
13,400	6055
14,000	6200

The pumping station employs ten six-stage pumps operating at 1170 rev/min. Each pump and motor unit has $Wr^2 = 1500$ lb-ft^2. The pump characteristics are given in the following table:

Discharge, gal/min	**Head/stage, ft**	**BHP/stage, hp**
0	145	180
2500	124	180
5000	104	180
6500	87	180
8500	62	180
10,500	10	180

Use PROG7 to devise an air chamber and one-way surge tank configuration which will prevent negative pressures from occurring in the pipeline. Consider reducing the number of series pipes by approximating the pipeline profile. This approach will allow more freedom in choosing Δt and save both computational time and machine storage.

13.6 A ten-stage pump lifts water through an 8-inch steel pipeline (7.85 in inside diameter) from a reservoir at elevation 4700 ft to a reservoir at elevation 5120 ft. The steel pipe is 14 ga ($e = 0.075$ in) with a friction factor of 0.023. The pump characteristics are for a speed of 1770 rev/min. For the pump and motor unit $Wr^2 = 70$ lb-ft^2.

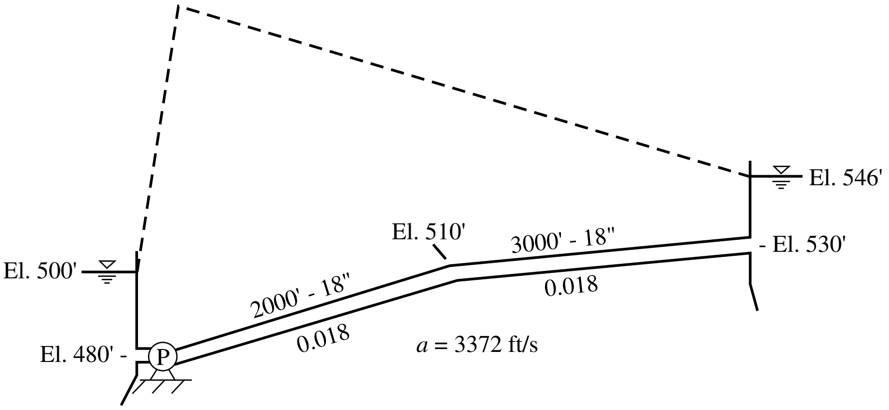
Discharge, gal/min	**Head/stage, ft**	**BHP/stage, hp**
0	80	8
300	71	9
600	65	10
900	60	13
1200	48.5	15
1500	32	14

The pipeline profile is as follows:

Station, ft	**Elevation, ft**
0	4700
2210	4950
4780	5040
5120	5040
5600	5100
6400	5115

Use PROG3 to analyze the system for pump power failure. If column separation occurs, use PROG7 to find the air chamber size which will prevent negative pressures from occurring over a significant portion of the pipeline.

13.7 In the pipeline system shown below, two two-stage Ingersoll-Dresser 20KKH pumps are placed in parallel to pump water into the upper reservoir (For pump characteristic diagrams see Appendix B). Driven by diesel engines, the pumps use 15-in impellers and have $Wr^2 = 330$ lb-ft^2 for the pump and motor combination.



The design engineer suspects that a power failure will cause column separation in the pipeline. Use PROG3 to determine whether this suspicion is correct.

If so, the decision has been made to add flywheels to the pump shafts to slow the pump deceleration and prevent column separation. Apply PROG3 again to determine the value of the moment of inertia for each of the proposed flywheels that will be required to prevent column separation.

How large must each value of the moment of inertia be to prevent any negative pressures from occurring?