WATERHAMMER IN FLUID FLOW SYSTEMS

(1) INTRODUCTION

Fluid flow systems are systems where liquid media are circulated through pipes valves, tanks and fluid flow machinery. The range from water supply systems, pipelines, loops in power stations and chemical process plants to hydropower stations. For these systems it is not difficult at all to calculate steady state conditions. But then, a determination of design criteria such the nominal pressure of the components or type of valves can only be considered rough sizing. Besides steady state conditions, there are time varying, the so called transient operating conditions that are caused by switching cycles, operating control or even by power failure. The high energy content of liquids in motion can impose a heavy dynamic load on the components. For this reason, already when designing such plants, the transient conditions must be examined very closely in order to take effective measures to avoid unacceptable dynamic loads. The main objectives of this presentation are to offer:

1. **An understanding of the water hammer phenomena.**
2. **Cause for Waterhammer.**
3. **A quick view of governing equations of waterhammer.**
4. **A study of the types of waterhammer protection methods.**
5. **Applied cases**

(2) Definition of waterhammer

In the following lines we will deal with some aspects of hydraulic transients, the variations of flow and pressure which occur when one steady state changes to another steady state .The development of large transient pressures can occur in pipelines Whenever the velocity changes rapidly. Such transient pressures can cause major failure of the pipe and the consequent expense involved in repair can be large. It is probably true to say that the generation of pressure transients is the largest single hydraulic cause of pipeline failure. It is strange, therefore, to find that a large percentage of users are not aware of the danger to their pipelines caused by rapid velocity fluctuations, nor do they seem particularly interested in studying the considerable Volume of literature that now exists on this subject.

It may be of interest to note at this point that a velocity change of 0.3 m/s can generate a pressure head of approximately 38 m if it occurs rapidly enough, if the pipeline is long, the required rate of change is not particularly large. Some catastrophic failures have occurred and it is now clear that the cost of a pipeline that will not fail under any circumstances is too high to be contemplated. Instead, a compromise must be sought which will reduce the risk of failure to an acceptable level and yet not to be excessively expensive. The question remains of how to establish the amount of risk to which a pipeline may be exposed, and the theory that follows is the basis upon which it is assessed.

For example, when a hydroelectric turbine comes "on load" the initial steady state is zero load at static head and the final steady state is the flow and related head needed to provide the power demanded by the generator. During the time required for the water in the conduits leading to the turbine to settle down to final steady conditions, there are rapidly – moving pressure waves in the water. These waves are at the speed of sound and the phenomenon is known as waterhammer.

The term (surge) is used to cover the three main types of hydraulic transient-waterhammer, mass oscillation and open channel surge. Any alteration of the rate of flow of a fluid through a pipe causes a change of pressure. Sudden alteration of the flow rate can give rise to surge of pressure which move up and down the pipe causing it to "Knock". This effect is sometimes noticed when a bath-tap is shut quickly and the knocking noise can occasionally be heard all over the house.

Water hammer is the term applied to pressure surges set up in this way Whether actual "hammering" or knocking occurs or not.

An analogy can be drawn to develop an understanding of hydraulic transients, consider a train with loose couplings suddenly stops as in (*Fig. 1)* , the same sort of thing happens to water passing along a pipe when an outlet valve is suddenly closed.

When the fluid is a gas (i.e. the fluid is compressible) the change of pressure causes changes of density. Liquids are almost incompressible, but the compressibility, or elasticity, of a liquid has an influence on the pressure produced by a change of flow. Although the phenomenon with which we are dealing is called waterhammer it applies equally to other liquids, and although water is referred

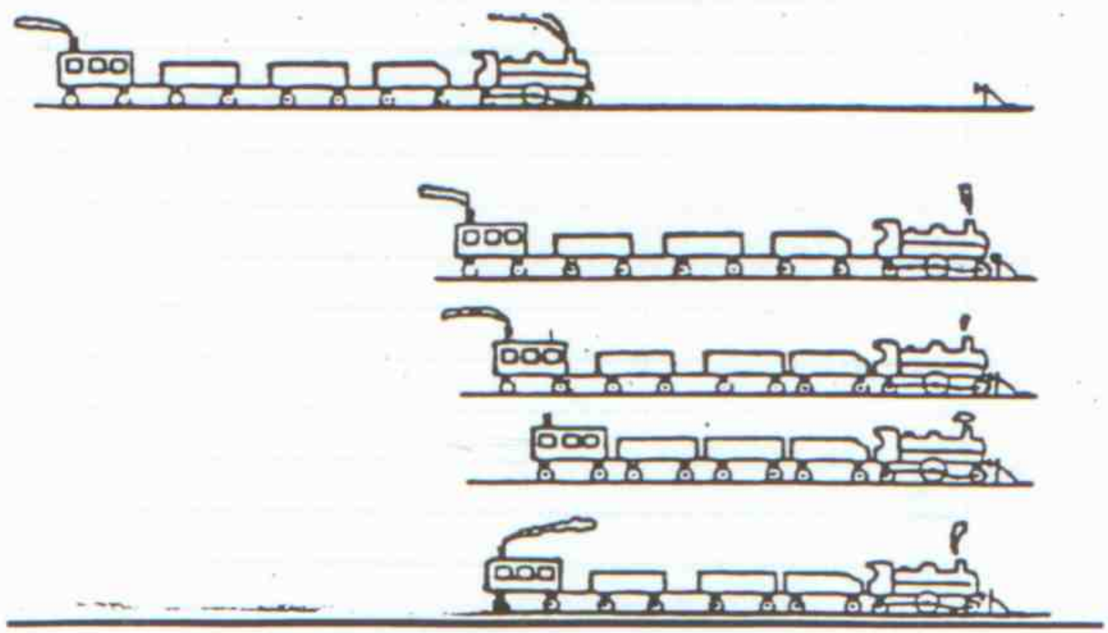


Fig. (1) Simple analogy for Waterhammer phenomena to continually in the following pages, it may be assumed that the same considerations apply to other liquids. The high pressure sometimes associated with surge in closed conduits can become dangerous, occasionally leading to fracture of pipe or pump casing. The high pressure may be due to resonance caused by the relationship under conditions of the natural frequency of the pipeline and the hydraulic transient.

Waterhammer description.

We can study a simple example to understand how is Waterhammer phenomena takes place, this is by taking a simple case such as a reservoir which discharges to a long pipeline with end gate valve.

When a valve at the end of a long pipeline is shut instantaneously, the fluid upstream of the valve will impinge upon the closed valve and its pressure will immediately rise. The fluid layer behind this is now stationary, fluid mass will in turn be brought to rest and its impact upon the first layer will cause its pressure to rise and also maintain the pressure of the first fluid layer. This process will then be repeated by the next layer and so on. Eventually all the fluid in the pipe will be brought to rest and its pressure will be raised throughout the pipe.

The increase in pressure so created will cause the fluid to be compressed and the pipe itself to be distended. This process can be pictured as shown in *Fig.3.5* .In other words, a pressure surge runs up the pipe at a wave speed of magnitude a. The wave speed a is high, approximately 1200 m/s, but it is not infinite. It will now be realized that if valve closure speeds are slow, this value of a is relatively very large and it is this that justifies the application of rigid pipe theory to slow valve closures. When the wave has reached the reservoir end of the pipe the situation is as shown in *Fig.3.6* the reservoir head is Hs but the head in the pipe is $Hs+ hi$

The fluid will now start to flow out of the pipe back in to the reservoir. By considerations of energy this reversed flow will have a velocity of-vp This can be understood by remembering that the strain energy of the distended pipe walls and the compressed fluid must have been produced by conversion of the kinetic energy of the fluid in the pipe, and when the fluid flows back into the reservoir. This strain energy must be converted back into kinetic energy. As there is very little energy lost by friction in this process. The reverse flow must have the same energy as the original flour. The fluid layer at the reservoir end of the pipe will move towards the reservoir with a velocity vp and pressure will revert to *Hs* Then the next layer will move in the upstream direction and its pressure will fall also. This process will continue, each layer moving upstream in turn, gaining velocity and losing pressure in the process. As the pressure drops back to its original value the pipe contracts back to its original diameter *(Fig.3.7)*.

This process continues and the pressure falls until eventually at a time 2L/ a the entire pipe is at a pressure Hs and the fluid is moving at a velocity vp towards the reservoir. This is illustrated in *Fig.3.8* This situation can exist only for an instant, because the fluid in the pipe will attempt to move away from the valve at velocity vp. Immediately, the pressure of the downstream layer at the valve will drop and the fluid will come to rest. The next layer will then experience the same sequence of events and each layer in turn will suffer the pressure drop and be brought to rest. The drop in pressure will cause the pipe to contract. The situation will then be as shown in *Fig 3.9* At time t=3*L*/a the situation is as shown in *Fig.3.10* Now the pipe contains fluid at a pressure less than that in the reservoir, and it is in a contracted state. As soon as this state occurs, flow at velocity vp into the pipe starts and the pressure returns to its original value Hs, the pipe returning to its original diameter *(Fig.3.11)*. At time t=4*L*/a the situation is as shown in *Fig.3.12*.

This last state is exactly the same as the state just before valve closure occurred Therefore the cycle will start again: a positive pressure wave running up the pipe causing a pressure $Hs + hi$ then reflecting with equal magnitude but opposite sign, causing a negative pressure Wave to run back to the valve and producing a pressure head of H_s This negative wave then reflects at the closed valve with the same magnitude and the same sign. so a negative wave runs back up the pipe again, causing a pressure head $H_s - h_i$. This reflects at the reservoir with the same magnitude and opposite sign, so causing a positive wave to return to the valve end, giving a pressure head H_s

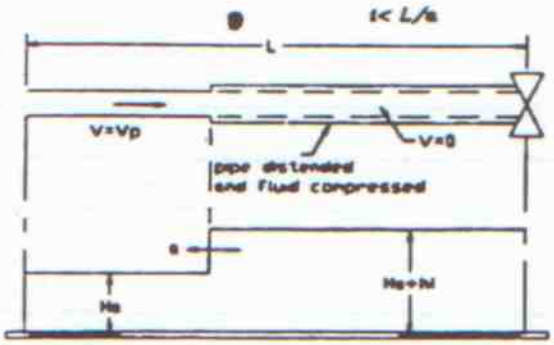


Fig.3.5

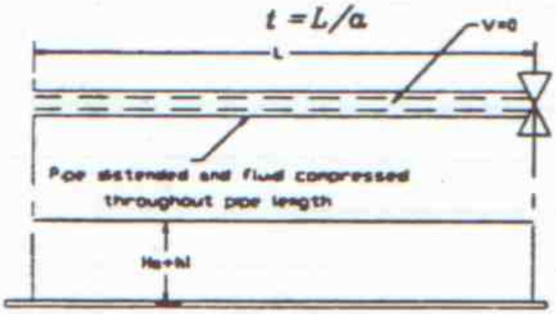


Fig.3.6

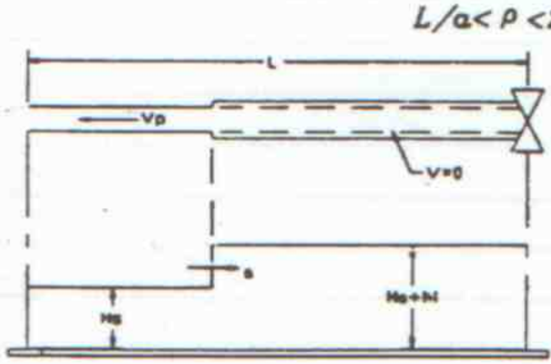


Fig.3.7

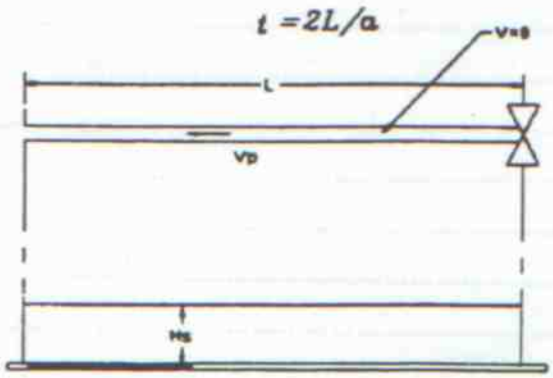


Fig.3.8

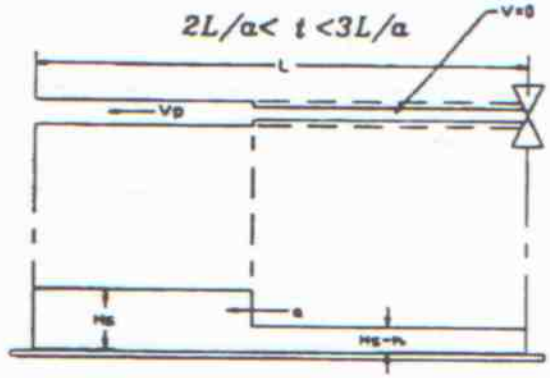


Fig.3.9

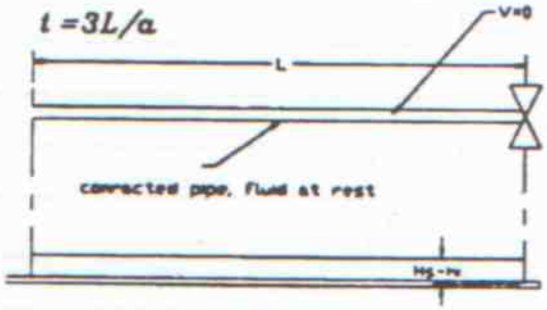


Fig.3.10

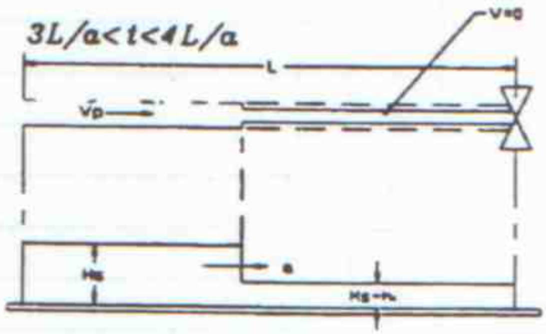


Fig.3.11

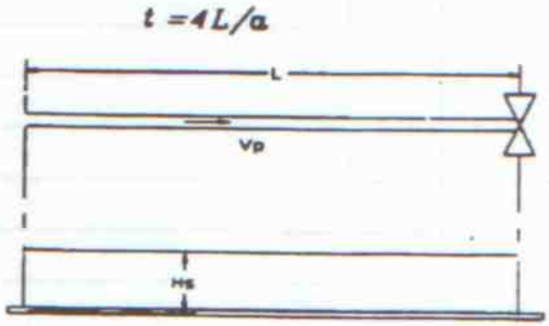


Fig.3.12

Fig 2 Waterhammer description.

(3) Causes of Waterhammer

In pipeline systems any change in the operating state leads to dynamic pressure changes which must be taken into account in the planning and operation of installations. They are capable of causing serious damage. Water conveyance and supply systems are often extremely varied in nature, so that it is impossible to find by approximation procedures a solution that will reliably preclude overstressing of components in any system.

In steady operation, the flow velocity is constant in time and place. By contrast, in transient flow, the velocity varies in time and place. Transient flows occur at every change from an existing steady operating state to a new one. Pressure surges result from transient flows.

(3-1) 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.

(3-2) Check Valves

Check valves can cause large transient pressure differences if the flow backwards through them can occur before the valve closure is complete, in which check-valve slam was caused by an air chamber at the pump discharge, documents such a case. 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.

(3-3) 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.3* shows, e.g., a partially-closed valve or an open air-vacuum valve, then a serious water hammer situation can occur.

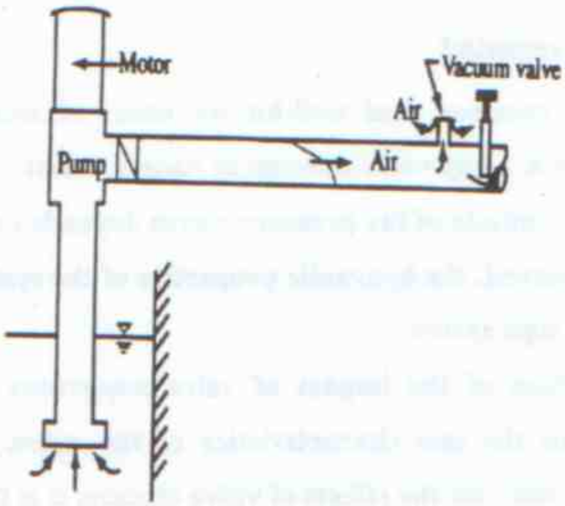


Fig 3 filling an initially empty pump discharge line.

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.

Another situation wherein air exhaustion can cause significant pressures is depicted in *Fig.4*. Here the pump discharge column is initially empty, having been vented to the atmosphere by an air-vacuum valve. A check valve restrains the water in the pipeline. 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 waterhammer pressures can develop.

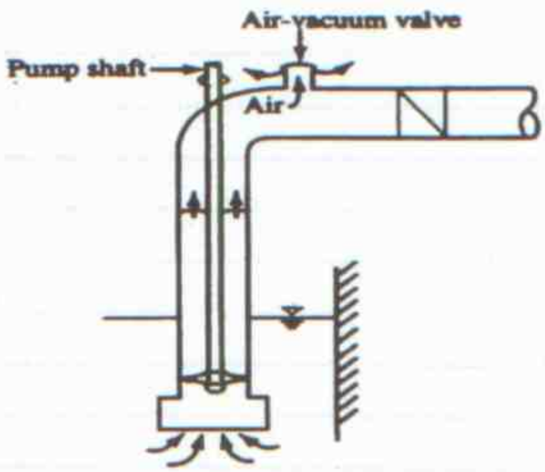


Fig 4 filling a pump discharge column behind a closed check valve.

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.

(3-4) 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.

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 those head increases greater than ten times the original head can be generated under certain circumstances.

(3-5) 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, or this pressure drop propagates downstream at the wave speed *(see Fig.5)*. 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 n he ystem, enerally n he icinity f he 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 reservoirs may then cause unanticipated high or low pressures on either side of thee pumps. These situations are the most common causes of the transient problems in pipe systems. Other situations are often combinations of these basic ones.

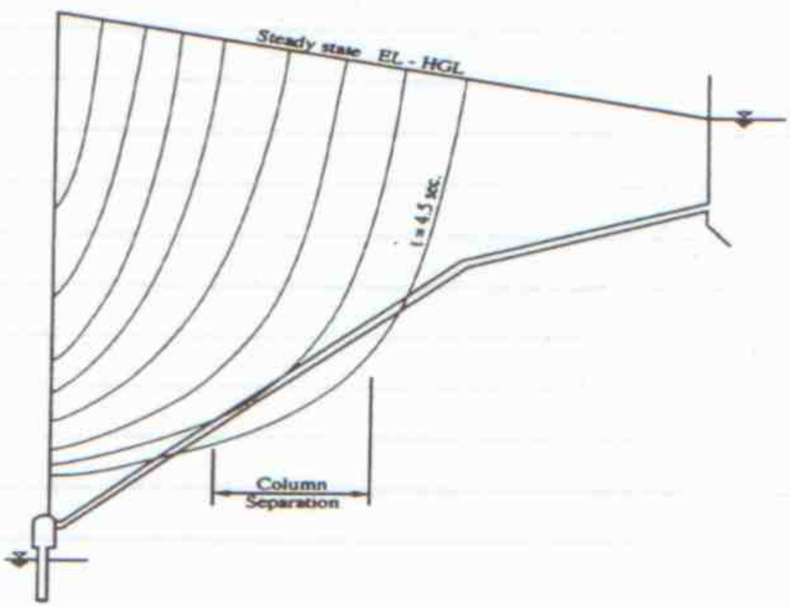


Fig 5 Propagation of a negative wave resulting from pump power failure.

(3-6) Others

- **Vibration of the impeller or quid vanes in the pump.**
- **Sudden change elevation of the reservoir.**
- **Wave on the reservoir.**
- **Unstable pump characteristics.**
- **Vibration on deformable apparatuses such as valves.**

(4)Harmful effect of waterhammer:

(4-1) Increase in maximum pressure,

Where the valve at downstream is Suddenly closed this will cause pressure rise in piping system, which may be higher than the max. Permissible pressure that the pipe material can withstand. This will cause damage in joints or explosion of the pipe that is very dangerous.

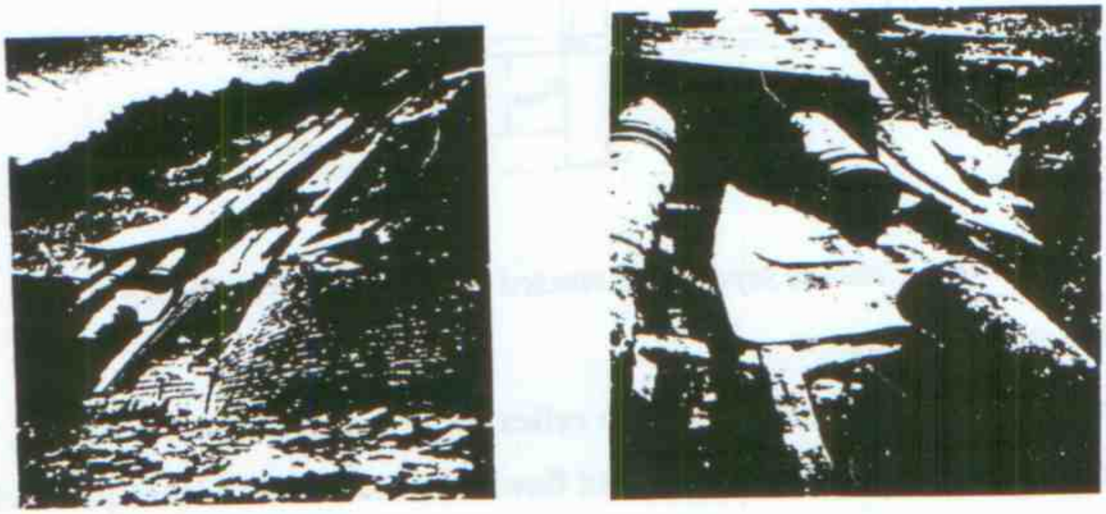


Fig 6 View of burst penstock of Oigawa power station, Japan, due to excessive transient pressure caused by operating errors and malfunctioning of equipment

(4-2) Separation of water columns,

If the absolute pressure in a pipe drops below hvp equal to the vapor pressure of the water plus the partial pressure of the released gases, a "vacuous space" is formed. What happens of courser, is that as the pressure drops from Ho to hvp the water near the pump or valve "stretches" to allow the continued discharge Q downstream. When the head becomes hvp the water can stretch no more; at the reservoir end of the pipeline the flow is still as steady state and a gap or 'vacuous space' is formed near the pump or valve. When the gap closes a high pressure results. Waterhammer and separation can also be caused by cavitation in a high-speed pump.

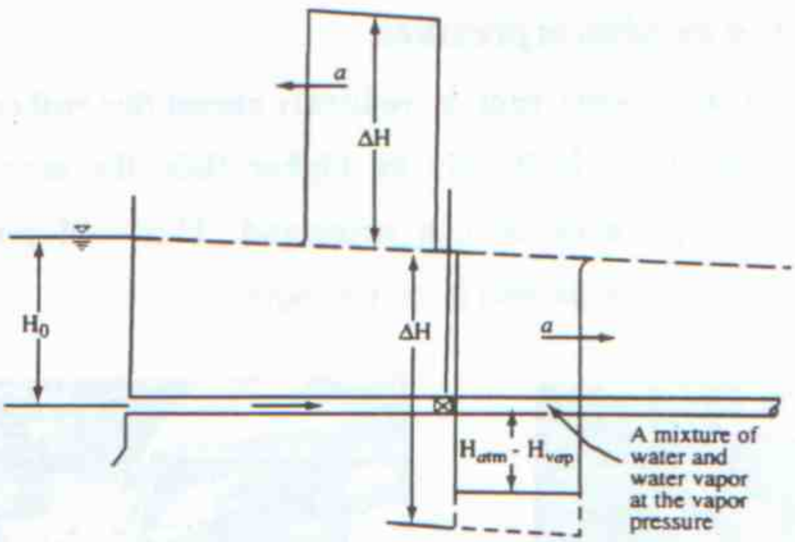


Fig 7 Column separation caused by sudden valve closure

(4-3) Reverse flows.

When a pump with inertia has no reflex valve and the power is cut-off, the water in the pipeline slows down and flows back towards the pump, which is still rotating in the normal forward direction. The reverse flow at first acts as a water brake, bringing the pump to rest and then the rotation of the pump is reversed. The pump now behaves as a badly designed turbine.

As we see in the above lines the harmful effect of Waterhammer, these effects can cause some of the following dangerous in the hydraulic systems:

Ruptured Piping	**Damaged Water Meters**
Leaking Connections	**Damaged Pressure Regulators and Gauges**
Weakened Connections	**Damaged Recording Apparatus**
Pipe Vibration and Noise	**Loosened Pipe Hangers and Supports**
Damaged Valves	**Ruptured Tanks and Water Heaters**
Damaged Check Valves	**Premature Failure of other Equipment and Device**
Damaged for civil works	

(4-4) Waterhammer noise,

Although noise is generally associated with the occurrence of Waterhammer, it is a known fact that Waterhammer can occur without audible sound or noise. Quick closure always creates some degree of shock - with or without noise. Therefore, the absence of noise does not indicate that water hammer or shock is non-existent in a water distribution system.

Waterhammer arrests prolong the life and service and piping, valves, fittings, trim, equipment, apparatus and other devices, which are part of a water distribution system.

(5) Mathematical formulation of Waterhammer :

The analysis of Waterhammer in liquid pipe system is based on the transient mass and momentum equations,

***Momentum equation*:**

$$\frac{1}{\rho}\frac{\partial P}{\partial x}+\frac{\partial V}{\partial t}+g\sin(\alpha)+\frac{fV|V|}{2D}=0$$

where

P	= pressure
V	= velocity
ρ	= density
x	= distance along pipe
t	= time
g	= acceleration due to gravity
D	= diameter
f	= friction factor
α	= angle of pipe slope

Mass contimuity equation ;

$$\frac{a^2}{g}\frac{\partial V}{\partial x}+\frac{\partial P}{\partial t}=0$$

where

a = wavespeed

(6) Modeling of Waterhammer equations :

(6-1) Graphical Solution:

In order to describe some basic aspects of transient propagation and to introduce the graphical method of solution, it s necessary to rewrite the equations of continuity and dynamic in the simplified form below

$$\frac{\partial v}{\partial x} + \frac{g}{a^2}\,\frac{\partial h}{\partial t} = 0$$

$$\frac{\partial h}{\partial x} + \frac{1}{g}\,\frac{\partial v}{\partial t} = 0$$

The graphical method of solution of the transient equations has two major limitations:

***First*: The inability to represent friction losses accurately without greatly increasing the complexity of the construction.**

***Second*: The difficulty in representing graphically transients in any complex pipe system.**

(6-2) The method of characteristics:

In recent years graphical methods does not satisfy our requirements because of the mentioned limitations, and after the great development in computers, we are able to use numerical methods in solution of pressure transient problems.

The characteristic method converts the two partial differential equations of motion and continuity into four total differential equations. These equations are then expressed in finite difference form, using the method of specified time intervals, and solutions are carried out with use of the digital computer.

The characteristics method has many advantages: (1) stability criteria are firmly established; (2) boundary Conditions are easily programmed; (3)

minor terms may be retained if desired; (4) very complex systems may be handled; (5) it has the best accuracy of any of the finite difference methods; (6) programs are easy to debug because steady state satisfies all conditions, and an error in programming shows up as a change from steady state; (7) it is a detailed method Which allows complete tabular results to be printed out. If the calculation is to supply meaningful results, the system data used as inputs must also be defined precisely. If calculations are carried out in the project planning stage the following variables must be known as minimum:

Pumping station data:

1. Type of pump, number, and maximum number in parallel operation.
2. Moment of inertia of pump & motor.

*3. Pump and system characteristics.

*4. Maximum flow rate.

5. Maximum flywheel admissible for motor (weight, J).
6. Normal starting and stopping (against closed valve or check valve only) .

***System data*:**

1.pipe profile of inflow and delivery lines to length scale 1:100000 or 1:20000, situation plan.

*2. Pipe diameter, material and wall thickness.

3. Boundary conditions
   - Where does the water come from (reservoir, ring main . . .)
   - Where does the delivery line lead to (reservoir, ring main, mains . . .).
4. Maximum pipe pressure admissible.
5. Minimum pipe pressure admissible.
6. Type and closing law of the valves provided ..
7. Throttling characteristic of stop valve (pressure loss as a function of opening .

Note: * minimum data at project planning stage .

(7) 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.

(7-1) Controlled Valve Movement

In Section (3-1) we demonstrated how a valve closure schedule could affect the maximum ransient ressure. or ate alve e aw hat he ast -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

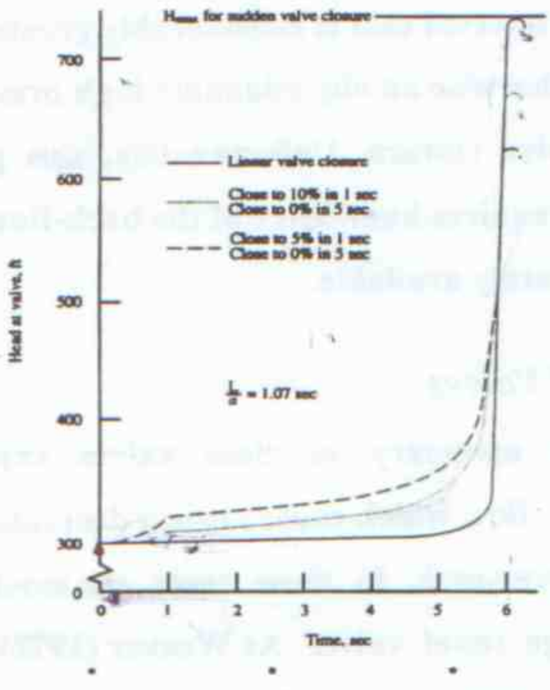


Fig 8 Effect of valve closure on Waterhammer pressure

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 tworate losure chedules re ot elevant o he study.

(7-2) 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 knowledge of the back-flow loss characteristics of the valve, which is rarely available.

(7-3) 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.

(7-4) Air Venting Procedures

(7-4-1) 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 those severe transients do not occur.

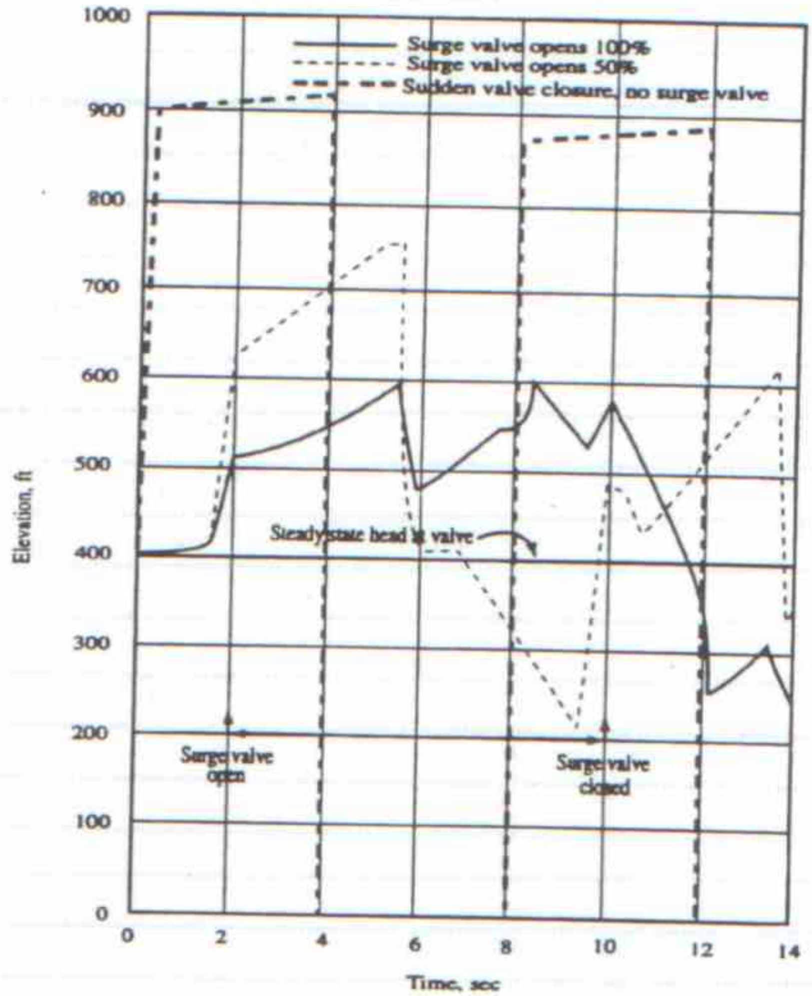


Fig 9 Effect of surge valve closure on Waterhammer pressure

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 the pump itself. This feature is almost always required for axial-flow pumps.

(7-4-2) Removing Air from Lines

Proper location and sizing of air-release and air-vacuum valves is an important consideration in pipeline design. 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.

(7-5) SURGE TANKS

Surge tanks can be used to mitigate both high and low pressures. They may act as temporary storage devices for excess liquid that 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.

(7-5-1) 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 surface f he iquid n he ank. 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.

(7-5-2) 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. *Fig.10* 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. *Fig 11* 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.

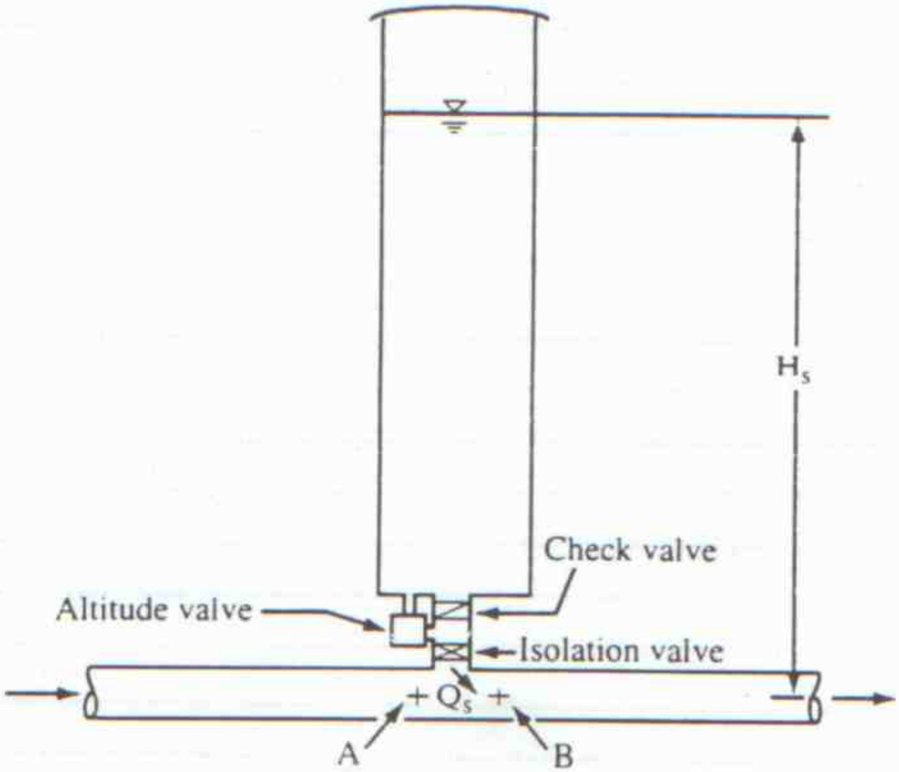


Figure 10 Diagram of a one-way surge tank.

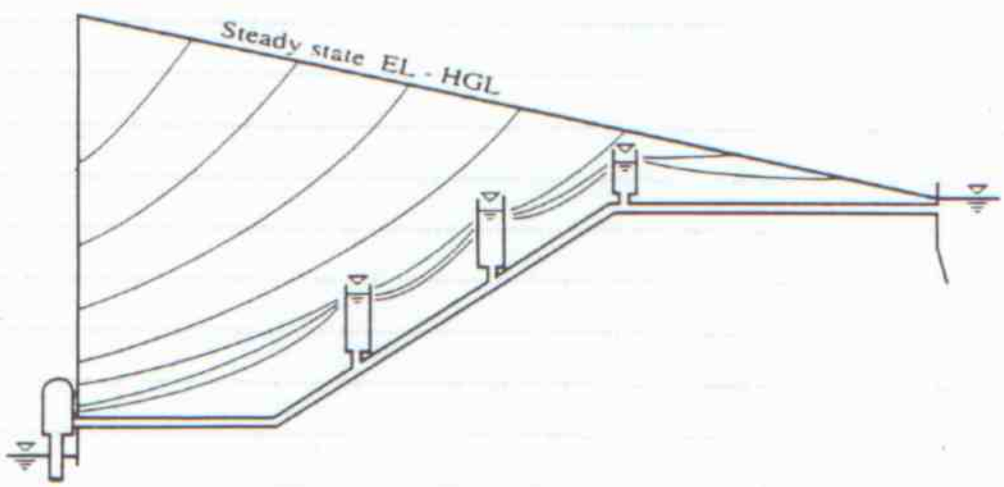


Fig 11 One-way surge tanks in a pumped pipeline

To include one-way surge tanks in a transient analysis, it is necessary to model them with a particular set of boundary conditions. Input data to a computer program must specify the locations of the tanks, their geometry, and their hydraulic performance.

(7-6) 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 that 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. 12* 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 initial air volume, the rate at which liquid is drawn from the chamber, and the thermodynamic rocess 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. *Fig 13* illustrates how the air chamber affects the pressure profile during a transient incident. Compare this behavior with the scenario shown in *Fig. 5*.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.

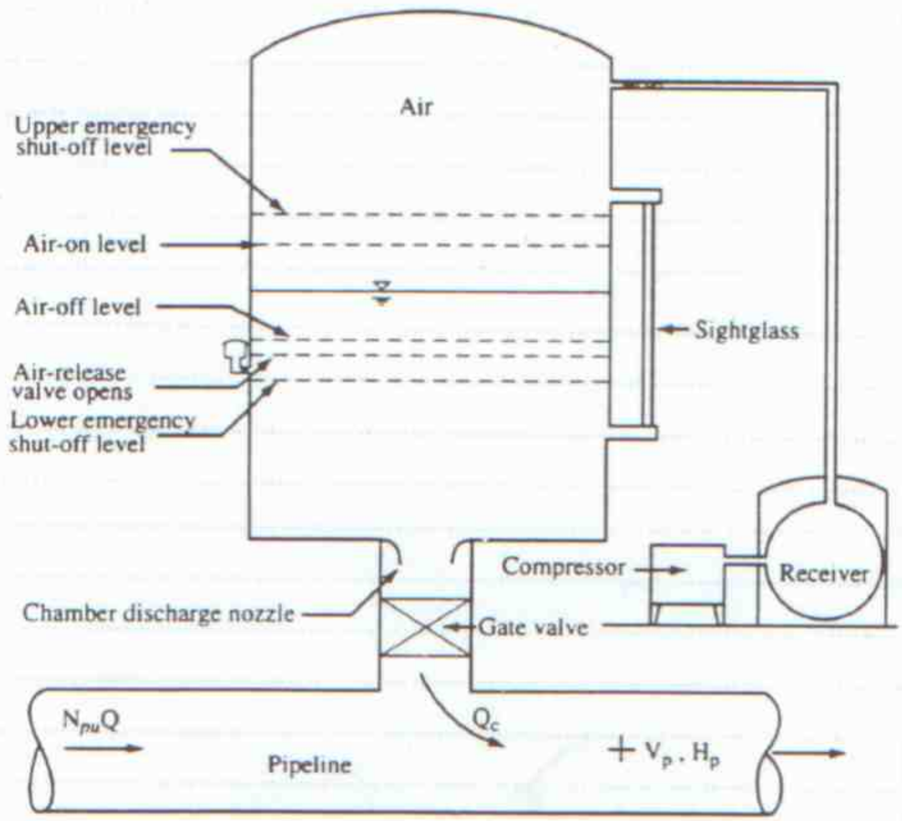


Fig.12 Diagram of an air chamber and its appurtenances

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. 12* 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. *Fig. 14* illustrates this technique.

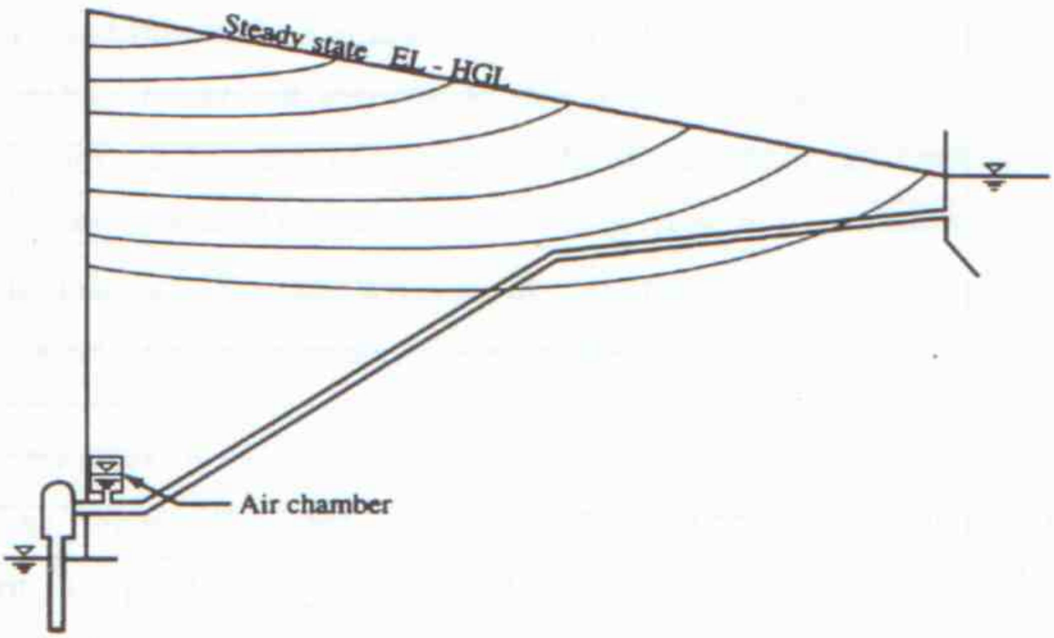
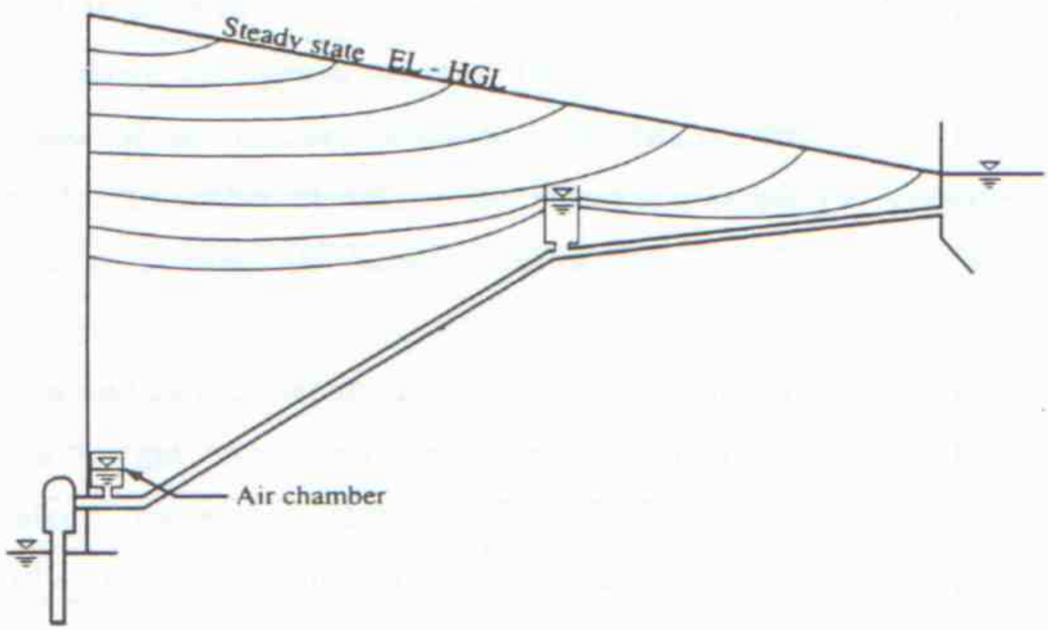


Fig 13 Propagation of a negative wave after pump power failure with an air chamber at the pump



Figs 14 propagation of negative wave after pump power failure with an Air chamber and a One-way surge tank.

(7-7) Flywheel,

Attaching a flywheel to the pump may reduce the danger of column separation. This increases the value of inertia and therefore the slowing down of the pump takes longer.

The flywheels have the disadvantage that more power is required to start the pump, and this method of controlling waterhammer is therefore not suitable for motors connected directly to the electricity supply. There are other restrictions on the use of flywheels, The actual size of the flywheel itself is a disadvantage, and the additional bearings that are necessary increase the length of the set. Windage losses in the rotating flywheel and additional losses of extra bearing decrease the offer all efficiency.

(7-8) By pass

Various forms of bypass valving are also possible. Two alternatives are shown in *(Fig.14-1)* for protection of a pumping station. To prevent backflow through the pump a check valve is installed in *(Fig. 14-1a),* With a control valve in a smaller bypass line. The control valve is opened after pump failure and then is allowed to close slowly. Care must be exercised to be sure the control valve is not opened too soon. In some installations this could Increase the danger of the column separation In long pipelines where there is little concern for excessive backflow the pump can be isolated from the pipeline transient by a pump discharge -control valve as shown in *(Fig. 14.1b)*. A check valve in a bypass line allows free flow to the pipeline to prevent low pressures and column separation. In long lines with a small gravity load, long duration surges may exist in such a system. Although these are not particularly dangerous they persist for some time since the losses are generally low. A small-diameter bypass of the check valve shown schematically with the dotted lines in *(Fig.14.1b)* may help alleviate this problem.

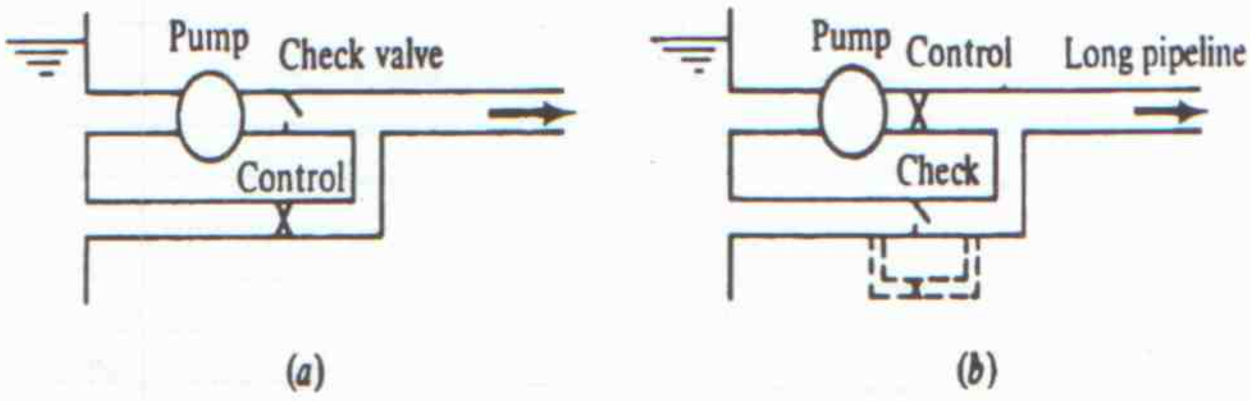


Fig14.1 pumping station with by-pass pipeline

(8) Practical cases

The effects of various protective measures can be made by two cases,

Case 1:

***Fig (15)* and *(16)* show calculation results for a system with 8000 m pipe line length and 90 m geodetic head. A total capacity of 1.11 m^3/s is provided by 3 pumps. The minimum pressures are plotted against the pipeline profile in *Fig (15)* for the following states:**

1. **Without additional protection**
2. **With the biggest flywheel possible (maximum size governed by motor acceleration).**
3. **With an air chamber.**

From the minimum pressure curve it is evident that only the air vessel prevents unacceptably low values being reaches. *Fig. (16)* plots the pressure and flow rate at the beginning of the line against time. Without protection and with flywheel, the flow curve is very steep, causing an extremely steep pressure drop. Only with the air vessel is a slow, steady change of flow rate possible, resulting in sufficiently flat pressure curve.

Case 2:

This example shows the results of measurements on a system with 2670mlinelength, 515m geodetic head and 0.080 m3/s capacity operating with one pump *Fig (17), (18), (19) and (20). Fig. (17)* shows the pipeline profile and the extreme pressures. Without additional protection the admissible line pressure of 600 m is serious exceeded. *Fig. (18)* owing to the water column operation between 1600 and 2550 m line length .An attempt was made to prevent column own in the critical part of the line by means of air admission valves. As *Fig. (19)* shows, however, this did not cure the problem. Only the provision of an air vessel brought success *Fig. (20)*. At the beginning of the line maximum line pressure is now only 585 m.

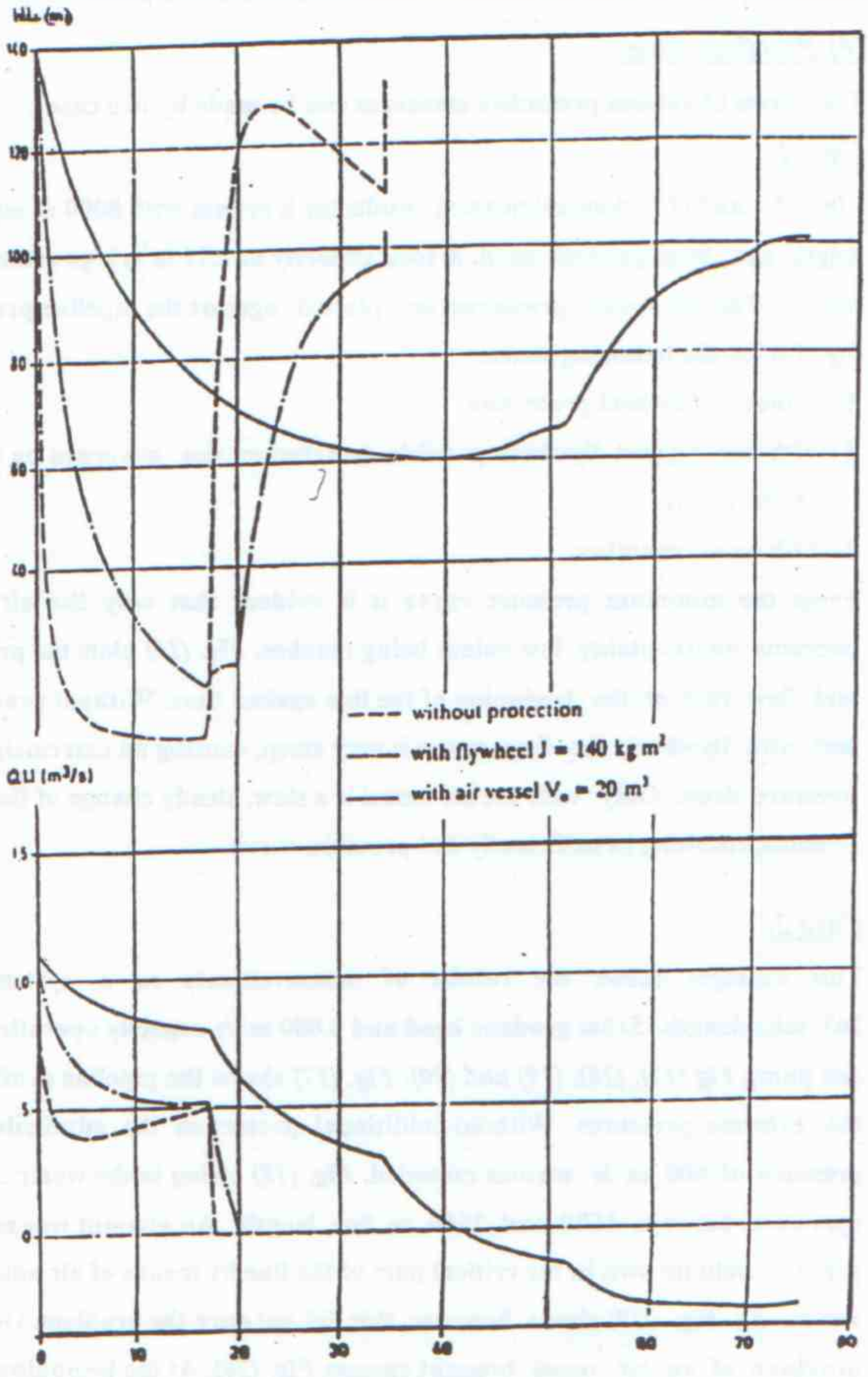


Fig 15 Show the minimum pressure along the pipeline after power failure using flywheel or air chamber

(Case 1)

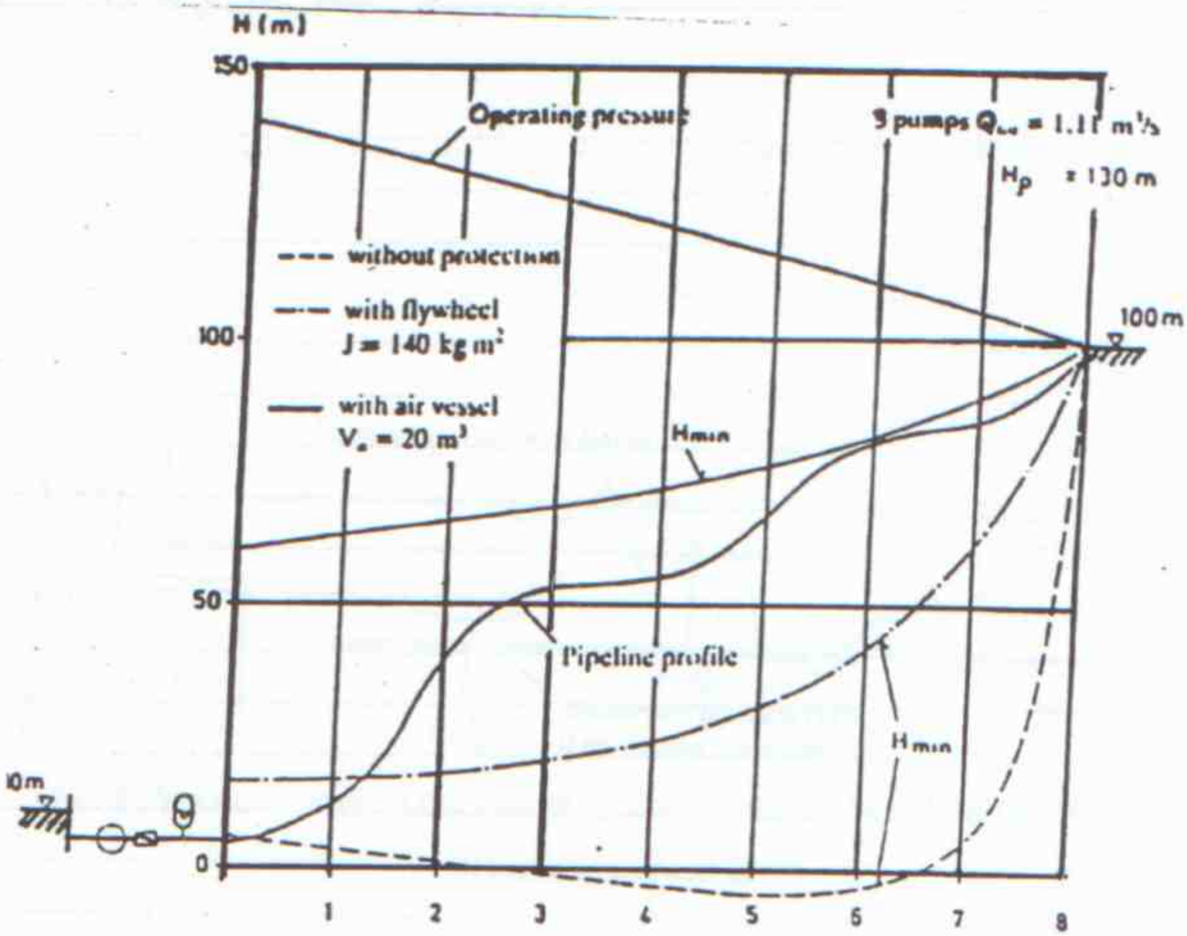


Fig 16 Pressure and flow rate at the beginning of the line against time (case 1)

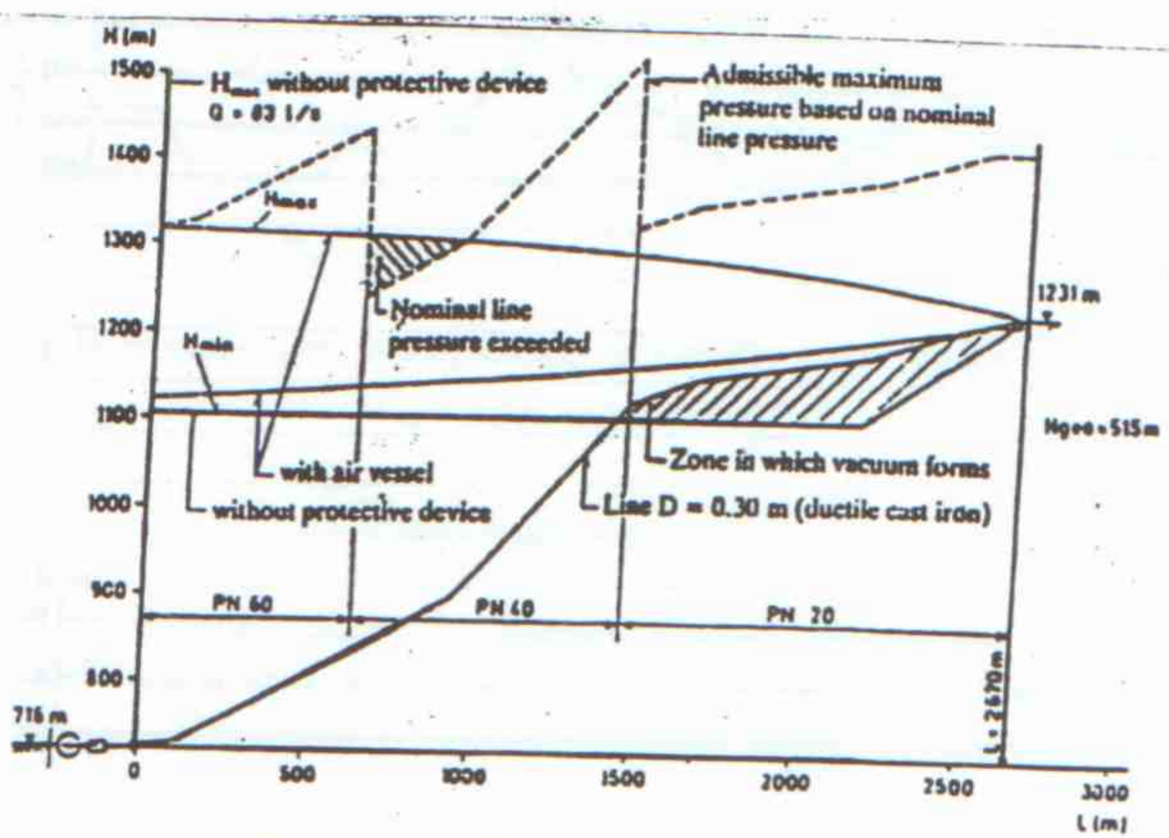


Fig 17 pipeline profile and extreme pressure (case2)

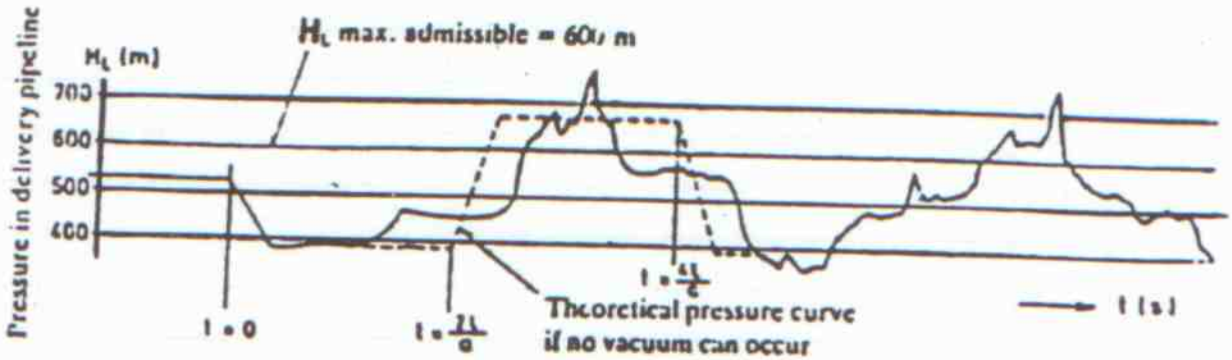


Fig 18 Pressure curve in the pumping station after power failure, without protection (case 2)

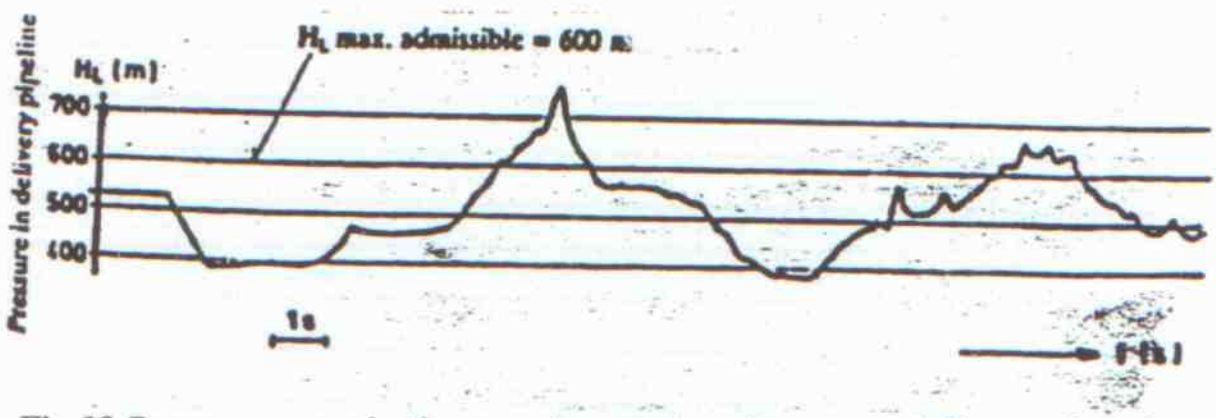


Fig 19 Pressure curve in the pumping station after power failure, using air admission valve (case 2)

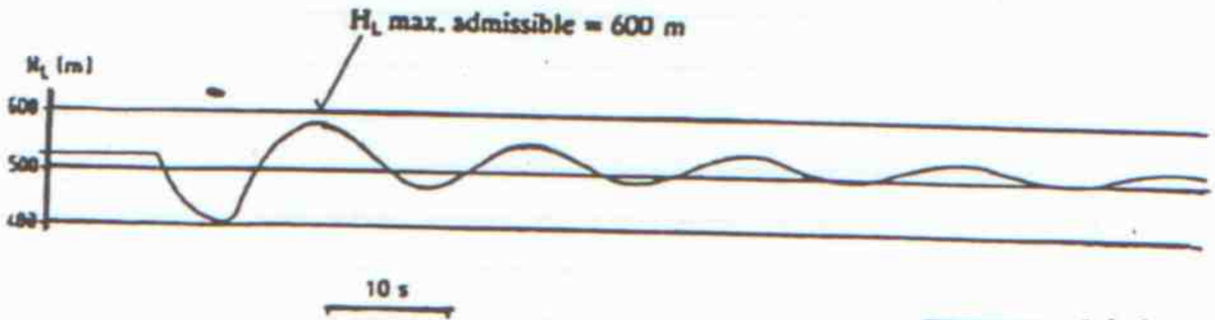


Fig 20 Pressure curve in the pumping station after power failure, with Air chamber (case 2)

Appendix A

Waterhammer Solution Method

The analysis of waterhammer in liquid pipe systems is based on the transient mass and momentum equations.

Momentum Equation

. the momentum equation can be expressed as

$$(1) \qquad \frac{1}{\rho}.\frac{\delta \mathrm{p}}{\delta \mathrm{x}}+\frac{\delta \mathrm{V}}{\delta \mathrm{t}}+\mathrm{g}\sin(\alpha)+\frac{FV|V|}{2D}=0$$

where

P	= pressure
V	= velocity
ρ	= density
x	= distance along pipe
t	= time
g	= acceleration due to gravity
D	= diameter
f	= friction factor
α	= angle of pipe slope

Mass Continuity Equation

the continuity equation can be expressed as

$$(2) \qquad \frac{\mathrm{a}^2}{g}.\frac{\delta \mathrm{V}}{\delta \mathrm{X}}+\frac{\delta \mathrm{P}}{\delta \mathrm{T}}=0$$

where

a = wavespeed

Equations 1 and 2 are two partial differential equations with the two unknowns *P* and *V* with the two independent variables *x* and *t*. Application of the characteristics method will convert these two partial differential equations to four ordinary differential equations as follows. To maintain flexibility with g-level, the development will leave the parameter *P* in the equations rather than convert to head, *H*, as in Reference 1.

The equations are identified as L1 and L2

$$\frac{1}{\rho}.\frac{\delta \mathrm{p}}{\delta \mathrm{x}}+\frac{\delta \mathrm{V}}{\delta \mathrm{t}}+\mathrm{g}\sin(\alpha)+\frac{FV|V|}{2D}=L_1$$

$$\frac{\mathrm{a}_2}{g}.\frac{\delta \mathrm{V}}{\delta \mathrm{X}}+\frac{\delta \mathrm{P}}{\delta \mathrm{T}}=\mathrm{L}_2$$

Combine these two equation linearly using a parameter, λ

$$L_1 + \lambda L_2 = 0$$

(3) $$\lambda\left[\frac{1}{\lambda}\frac{\delta p}{\delta x}+\frac{\delta p}{\delta t}\right]+\left[\rho\frac{\delta V}{\delta t}+\lambda\rho a^2\frac{\delta V}{\delta x}\right]+\rho g\sin(\alpha)+\frac{\rho f V|V|}{2D}=o$$

If

(4) $$\frac{dx}{dt}=\frac{1}{\lambda}=\lambda \ a^2$$

then

$$\lambda=\pm\frac{1}{a}$$

and

(5) $$\frac{dx}{dt}=\pm a$$

From calculus

(6) $$\frac{dp}{dt}=\frac{\delta p}{\delta x}\cdot\frac{dx}{dt}+\frac{\delta p}{\delta t}$$

(7) $$\frac{dv}{dt}=\frac{\delta v}{\delta x}\cdot\frac{dx}{dt}+\frac{\delta v}{\delta t}$$

Substituting Equation 4 into 3

(8) $$\lambda\left[\frac{\delta p}{\delta x}\cdot\frac{dx}{dt}+\frac{\delta p}{\delta t}\right]+\left[\rho\frac{\delta v}{\delta t}+\lambda-\frac{\delta v}{\delta x}\frac{dx}{dt}\right]+\rho g\sin(\alpha)+\frac{\rho f v|v|}{2D}=o$$

and substituting Equations 6 and 7 into 8

$$\lambda\left(\frac{dp}{dt}\right)+\left[\rho\frac{dV}{dt}\right]+\rho g\sin(\alpha)+\frac{\rho f|V|V|}{2D}=o$$

(9) $$\pm\frac{1}{a}\cdot\frac{dp}{dt}+\rho\frac{dv}{dt}+\rho g\sin(\alpha)+\frac{\rho f V|V|}{2D}dX=o$$

Now multiply Equation 9 by ($a\,dt$), which also equals dx

(10) $$\pm dp+\rho\,a dv+\rho g\sin(\alpha)dx+\frac{\rho f V|V|}{2D}dX=o$$

The gravity term contains the term α, and the term can be converted as follows

(11) $$\rho g\sin(\alpha)dX=\rho g\left(\frac{dz}{dx}\right)dx=\rho\ g\,dz$$

$$C = \sqrt{\frac{K/\rho}{\left(1 + a \frac{D}{t} \frac{K}{E}\right)}}$$

$a = 0$ pipe is free with expansion joint everywhere

$a = \frac{5}{4}\mu$ anchord upstream only

$a = 1 - \mu^2$ anchord both upstream and downstream

where K : Bulk modulus of Elasticity of fluid

E Young " " " for pipe material

t pipe thickness

D " Diam

μ Poisson ratio

$\Delta p = \rho V C$ for sudden closure

$t_{closure} < \frac{2L}{C}$

if $t_{closure} > \frac{2L}{C}$

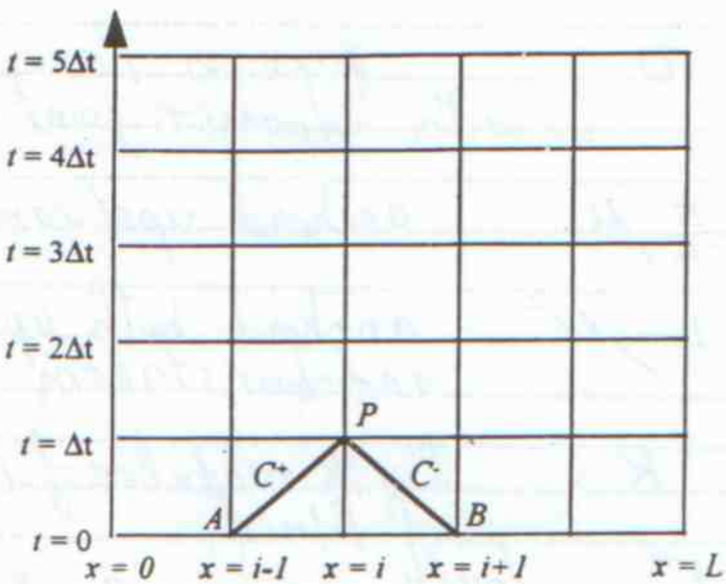
$$\Delta p = \rho V \left(\frac{2L}{t_{closure}}\right)$$

Where dz is the vertical change in pipe elevation. Therefore, substituting 11 into 10

$$\pm dp + \frac{\rho a}{A} dQ + \rho g \, dz + \frac{\rho f}{2 D A^2} dx Q|Q| = 0$$

Further substitution of the volumetric flow rate for velocity yields

(12)
$$\pm dp + \frac{\rho a}{A} dQ + \rho g \, dz + \frac{\rho f}{2 D A^2} dx Q|Q| = 0$$



Integrating Equation 12 with the positive sign along the $C+$ characteristic from point A to P yields

(13)
$$\int_{pA}^{pp} dp + \frac{\rho a}{A} \int_{QA}^{QP} dQ + \rho g \int_{zA}^{zp} dz + \frac{\rho f}{2 D A^2} \int_{xA}^{xP} Q|Q| \, dx = 0$$

where the subscript P denotes the current solution point at $x = i$ at time $t = \Delta t$, and subscript A denote the values at point $x = i$-1 at the previous time step, $t = 0$. A similar equation can be written for the C- characteristic from point B to P.

The term on the right before the equal sign in Equation 13 can be integrated assuming a second order accurate representation of Q to obtain

(14)
$$(p_P - p_A) + \frac{\rho a}{A}(Q_P - Q_A) + \rho g (Z_P - Z_A) + \frac{\rho f \Delta x}{2DA^2} Q_P|Q_A| = 0$$

similarly

(15)
$$-(p_p - p_B) + \frac{\rho a}{A}(Q_p - Q_B) + \rho g (Z_p - Z_B) + \frac{\rho f \Delta x}{2DA^2} Q_A|Q_A| = 0$$

Introducing two convenient parameters

Impedance

$$B = \frac{\rho a}{A}$$

Resistance

$$R = \frac{f\rho\ \Delta x}{2 D A^2}$$

The effects of flow resistance tends to be less important than the impedance.

Equations 14 and 15 then become

$$(p_p - p_A) + B(Q_p - Q_A) + \rho g(zp - zA) + r Q p|Q_A| = o$$

$$-(p_p - p_B) + B(Q_p - Q_B) + \rho g(z_p - z_B) + r Q_p|Q_p| = o$$

Substituting more general variables for *A*, *B* and *P*, and simplifying the equations yields

(16)
$$p_{i,new} = c_p - B_p Q_{i,new}$$

(17)
$$p_{i,new} = cM + B_M Q_{i,new}$$

where

$$C_p = p_{i-1,old} + BQ_{i-1,old} - \rho g(z_i - z_{i-1})$$
$$C_M = P_{i+1,old} - BQ_{i+1,old} - \rho g(z_i - z_{i+1})$$
$$B_p = B + R|Q_{i-1,old}|$$
$$B_M = B + R|Q_{i+1,old}|$$

Equations 16 and 17 are referred to as the *compatibility* equations. Since all the parameters in *CP*, *CM*, *BP*, and *BM* are known, the only unknowns in 16 and 17 are *Pi,new* and *Qi,new*. We thus have two equations and two unknowns.

For example, to solve for the pressure at an interior pipe point, we can eliminate the flow rate and solve for the pressure directly

(18)
$$P_{i,new} = \frac{C_P . B_M - C_M . B_P}{B_P + B_M}$$

We can use this value for pressure to substitute back into equation 16 or 17 to solve for flow rate, or we can similarly solve for flow rate directly

(19)
$$Q_{i,new} = \frac{C_P - C_M}{B_P + B_M}$$

The compatibility equations allow a solution of all interior points in a pipe. However, the pipe endpoints are solved by applying specific boundary conditions. The boundary condition relationships build on the previous methods, and offer the final needed information to generate a complete solution.