reduced.

If the pumps supplying an unprotected pipeline are stopped suddenly the flow will also stop. If the pipeline profile is relatively close to the hydraulic grade line, the sudden deceleration of the water column may cause the pressure to drop to a value less than atmospheric pressure. The lowest value to which pressure could drop is vapour pressure. Vaporization or even water column separation may thus occur at peaks along the pipeline. When the pressure wave is returned as a positive wave the water columns will rejoin giving rise to water hammer over pressures.

Unless some method of water hammer protection is installed, a pumping pipeline system will normally have to be designed for a water hammer head. This is often done with high pressure lines where water hammer heads may be small in comparison with the pumping head. For short lines this may be an economic solution. Suitable locations for various water hammer protection devices are shown in Fig.6.2.

The philosophy behind the design of most methods of protection against water hammer is similar. The objective in most cases is to reduce the down surge in the pipeline caused by stopping the pumps. The upsurge will then be correspondingly reduced, or may even be entirely eliminated. The most common method of limiting the downsurge is to feed water into the pipe as soon as the pressure tends to drop.

The sudden momentum change of the water column beyond the tank is prevented so the elastic water hammer phenomenon is converted to a slow motion surge phenomenon. Part of the original kinetic energy of the water column is converted into potential energy instead of elastic energy. The water column gradually decelerates under the effect of the difference in heads between the ends. If it is allowed to decelerate the water column would gather momentum in the reverse direction and impact against the pump to cause water hammer overpressures. If, however, the water column is arrested at its point of maximum potential energy, which coincides with the point of minimum kinetic energy, there will be no sudden change in momentum and consequently no water hammer overpressure. The reverse flow may be stopped by installing a reflux valve or throttling device at the entrance to the discharge tank or air vessel, or in the pipeline. A small orifice bypass to the reflux valve would then allow the pressures on either side to gradually equalize.

Charts are available for the design of air vessels and for investigation of the pump inertia effects, so that a water hammer analysis is not normally necessary. Rigid water column theory may be employed for the analysis of surge tank action, and in some cases, of discharge tanks.

If the pipeline system incorporates in line reflux valves or a pump by pass valve, an elastic water hammer analysis is usually necessary. The analysis may be done graphically or, if a number of solutions of similar systems are envisaged, a computer program could be developed. Normally the location, size and discharge characteristics of a protective device such as a discharge tank have to be determined by trial and error. The location and size of inline or bypass reflux valves may similarly have to be determined by trial. In these instances a computer program is usually the most economical method of solution, as a general program could be developed and by varying the design parameters methodically, an optimum solution arrived at.

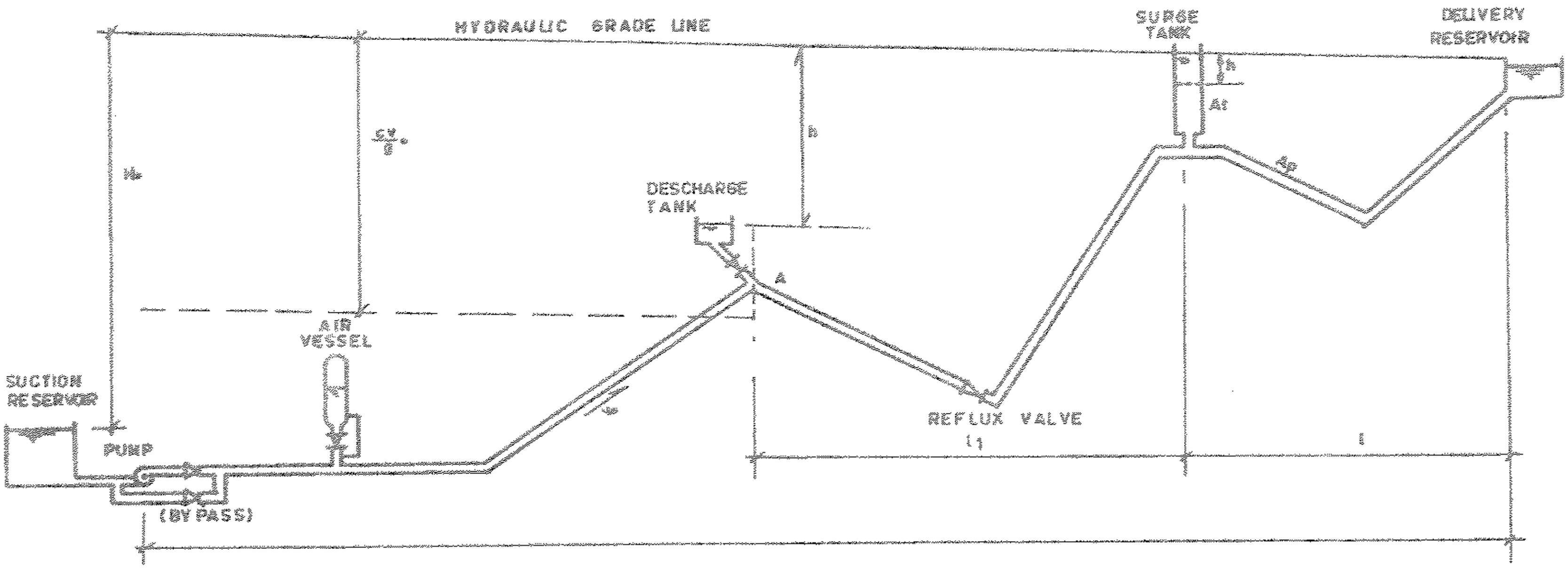

FIG.6.2 : PIPELINE PROFILE ILLUSTRATTING SUITABLE LOCATION FOR VARIOUS DEVICES FOR WATE HAMMER PROTECTION

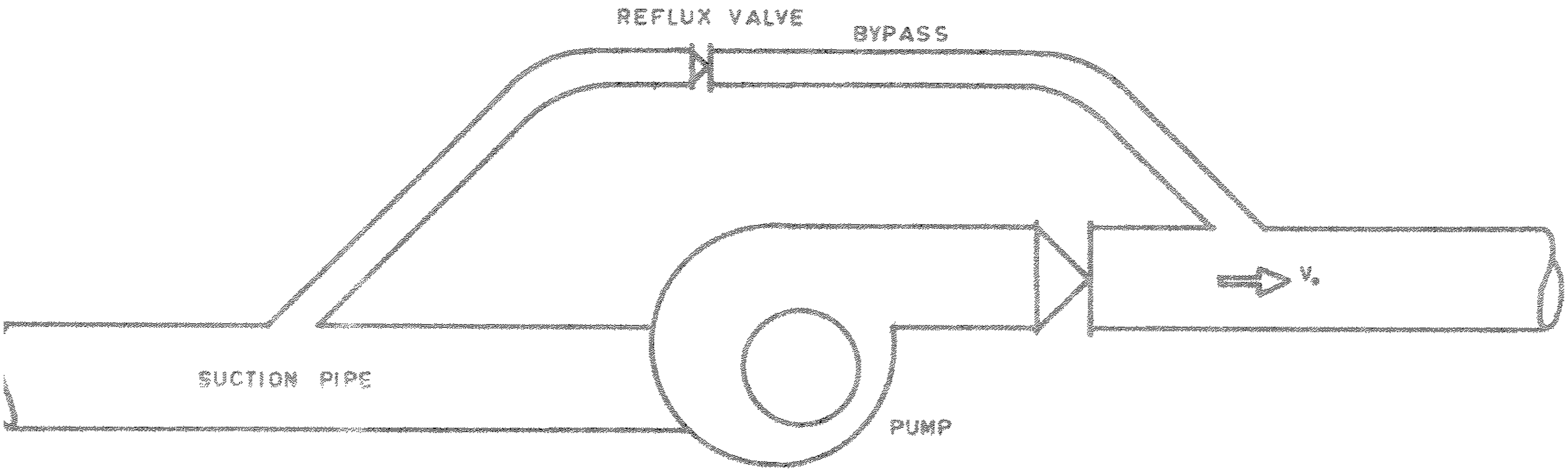

FIG.6.3: PUMP WITH BYPASS REFLUX VALUE

If the rotational inertia of a centrifugal pump and motor continue to rotate the pump for while after power failure, water hammer pressure transients may be reduced. The rotating pump, motor and entrained water will continue to feed water into the potential vacuum on the delivery side, thereby alleviating the sudden deceleration of the water column. The effect is most noticeable on low head, short pipelines.

After the power supply to the motor is cut off, the pump will gradually slow down until it can no longer deliver water against the delivery head existing at the time. It the delivery head is still higher than the suction head it will then force water through the pump in the reverse direction, with the pump still spinning in the forward direction, provided there is no reflux or control valve on the delivery side of the pump. The pump will rapidly decelerate and gather momentum in the reverse direction, and will act as a turbine under these conditions. The reverse speed of the pump will increase until it reaches runaway speed. Under these conditions there is a rapid deceleration of the reverse flow and water hammer overpressures will result.

If there is a reflux valve on the delivery side of the pump, the reverse flow will be arrested, but water hammer overpressures will still occur. The pressure changes at the pump following power failure may be calculated graphically or by computer.

The upsurge could be reduced considerably if reverse flow through the pump was permitted. If flow reversal was prevented, the maximum head-rise above operating head (H) would be approximately equal to the lowest head-drop below H_0.

A simple rule of the thumb for ascertaining whether the pump inertia will have an effect in reducing the water hammer pressures is:

If the inertia parameter $I = MN^2/WALH_0^2$ exceeds 0.01, the pump inertia may reduce the down surge by at least 10%. Here M is the moment of inertia of the pump, N is the speed in rpm and AL is the volume of water in the pipe.

Some installations have a flywheel fitted to the pump to increase the moment of inertia. In most cases the flywheel would have to be impracticably heavy, also it should be borne in mind that starting currents may thereby be increased. The effect of pump inertia can be neglected and the pumps assumed to stop instantaneously.

(i) Pump Bypass Reflux Valve

One of the simplest arrangements for protecting a pumping main against water hammer is a reflux valve installed in parallel with the pump (Fig. (6.3)). The reflux or non-return valve would discharge only in the same direction as the pumps. Under normal pumping conditions the pumping head would be higher than the suction head and the pressure difference would maintain the reflux valve in a closed position. On stopping the pumps, the head in the delivery pipe would tend to drop below the suction head, in which case water would be drawn through the bypass valve. The pressure would therefore only drop to the suction pressure less any friction loss in the bypass. The return wave over pressure would be reduced correspondingly. Fig. 6.4. gives the maximum and minimum head at pump after power failure.

This method of water hammer protection cannot be used in all cases, as the delivery pressure will often never drop blow the suction pressure. In other cases there may still be an appreciable water hammer overpressure (equal in value to the initial drop in pressure). This method is used only when the pumping head is considerably less than cv_0/g. In addition, the initial drop in pressure along the entire pipeline length should be tolerable. The suction reservoir level should also be relatively high or there may still be column separation in the delivery line.

Normally the intake pipes draw directly from a constant head reservoir. However, there may be cases where the intake pipe is fairly long and water hammer could be a problem in it too. In these cases a bypass reflux valve would, in a similar way to that described above, prevent the suction pressure exceeding the delivery pressure.

Water may also be drawn through the pump during the period that the delivery head is below the suction head, especially if the machine was designed for high specific speeds, as is the case with through flow pumps. In some cases the bypass reflux valve could even be omitted, although there is normally a fairly high head loss through a stationary pump. A constant bleeder line led off to the suction reservoir with a smaller diameter pipeline can also be connected to the pump outlet after the sluice valve to reduce the water hammer effects. This may result in wastage of energy.

(ii) Surge Tanks

The water surface in a surge tank is exposed to atmospheric pressure, while, the bottom of the tank is open to the pipeline. The tank acts as a balancing tank for the flow variations that may occur, discharging in case of a head drop in the pipe, or filling in case of a head rise. Surge tanks are used principally at the head of turbine penstocks, although there are cases where they can be applied in pumping systems. It is seldom that the hydraulic grade line of a pumping line is low enough to enable an open tank to be used. It may be possible to construct a surge tank at a peak in the pipeline profile and protect the pipeline between the pumps and the tank against water hammer by some other means. If the surge tank is relatively large, it could be treated as the discharge end of the intermediate pipeline length and this section could be treated as an independent pipeline shorter in length than the original pipeline.

The fluctuations of the water surface level in a surge tank following power failure may be studied analytically. The fluctuations in tank level may be dampened with a throttling orifice. In this case the pressure variations in the line may be more extreme than for the unrestricted orifice. The maximum heads at pump after power failure is presented in Fig. 6.4. A differential surge tank includes a small diameter riser in the middle of the tank. The tank may have a varying cross section or multiple shafts. Such variations are more applicable to hydropower plant than pumping systems as they are useful for dampening the surges in cases of rapid load variation on turbines.

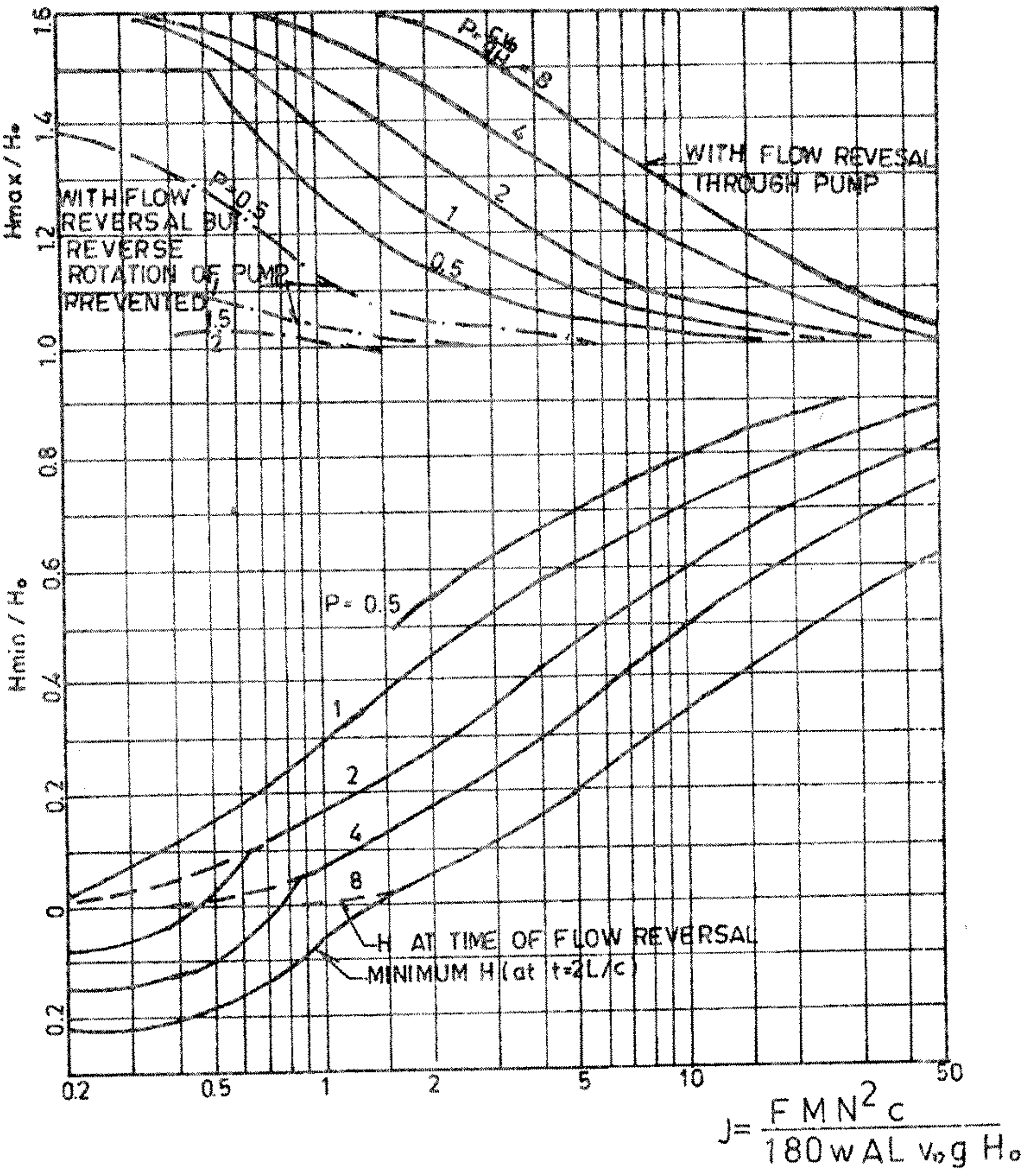

FIG. : 6.4 MAXIMUM AND MINIMUM HEADS AT PUMPS AFTER POWER FAILURE

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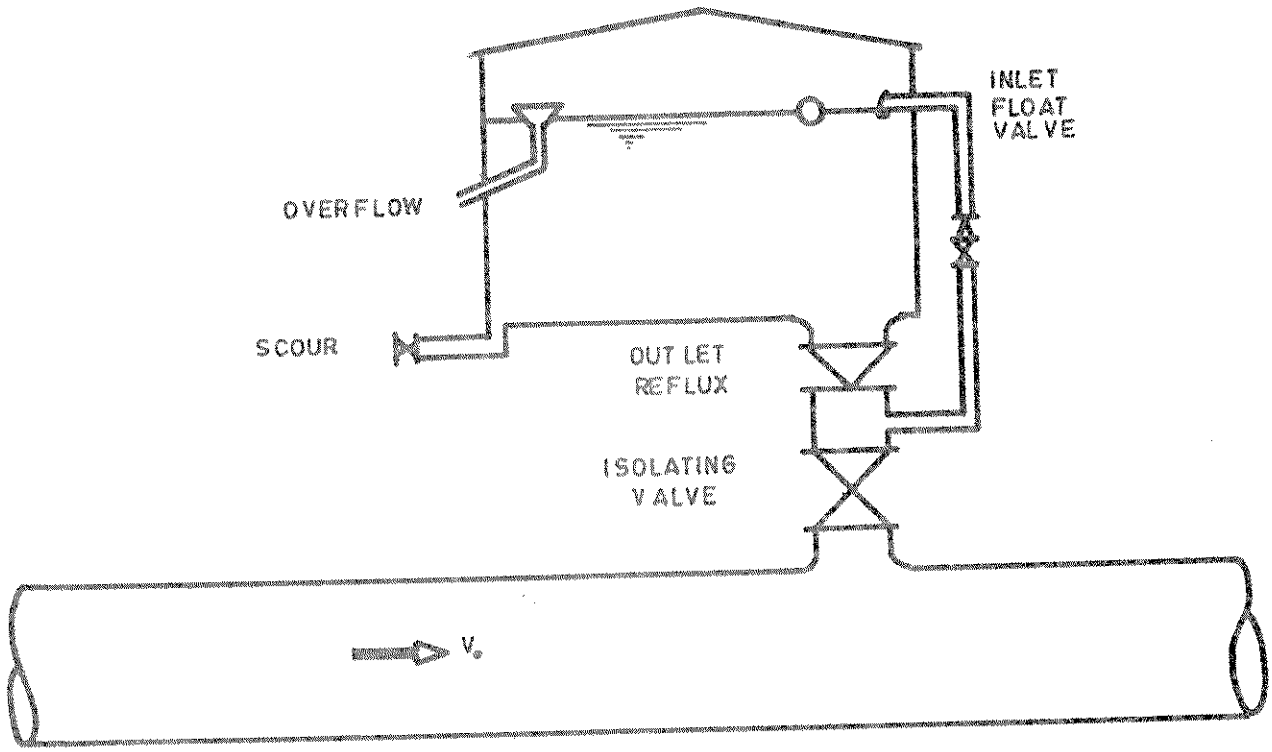

FIG. 6.5 : DISCHARGE TANK

(iii) Discharge Tanks

In situations where the pipeline profile is considerably lower than the hydraulic grade line it may still be possible to use a tank, but one which under normal operating conditions is isolated from the pipeline. The tank water surface would be subjected to atmospheric pressure but would be below the hydraulic grade line, as opposed to that of a surge tank.

A discharge tank would normally be situated on the first rise along the pipeline and possibly on subsequent and successively higher rises. The tank will be more efficient in reducing pressure variations, the nearer the level in the tanks is to the hydraulic grade line. It should be connected to the pipeline via a reflux valve installed to discharge from the tank into the pipeline if the pipeline head drops below the water surface elevation in the tank. Normally the reflux valve would be held shut by the pressure in the pumping line. A small bore bypass to the reflux valve, connected to a float valve in the tank, should be installed to fill the tank slowly after it has discharged. Fig. 6.5 depicts a typical discharge tank arrangement.

The function of a discharge tank is to fill any low pressure zone caused by pump stoppage, thus preventing water column separation. The water column between the tank and the discharge end of the pipeline (or a subsequent tank) will gradually decelerate under the action of the head differences between the two ends. It may be necessary to prevent reverse motion of the water column which could cause water hammer over pressures by installing a reflux valve in the line.

A discharge tank will only operate if the water surface is above the lowest level to which the head in the pipeline would otherwise drop following pump stoppage. For very long pipelines with a number of successively higher peaks, more than one discharge tank may be installed along the line. The tanks should be installed at the peaks where water column separation is most likely. The lowest head which will occur at any point beyond a tank as the down surge travels along the line is that of the water surface elevation of the preceding tank.

The best position for discharge tanks and inline reflux valves is selected by trial and error and experience. In a case with many peaks or major pipelines with large friction heads, a complete analysis should be carried out, either graphically or by computer. In particular, a final check should be done for flows less than the maximum design capacity of the pipeline.

Even though a number of tanks may be installed along a pipeline, vaporization is always possible along rising sections between the tanks. Provided there are no local peaks, and the line rises fairly steeply between tanks, this limited vaporization should not lead to water hammer overpressures.

6.17.4 AIR VESSELS

If the profile of a pipeline is not high enough to use a surge tank or discharge tank to protect the line, it may be possible to force water into the pipe behind the low-pressure wave by means of compressed air in a vessel. The pressure in the vessel will gradually decrease as water is released until the pressure in the vessel equals that in the adjacent line. At this stage the decelerating water column will tend to reverse. However, whereas the outlet of the air vessel should be unrestricted, the inlet should be throttled. A suitable arrangement is to have the water discharge out through a reflux valve that shuts when the water column reverses. A small orifice open bypass would allow the vessel to refill slowly. (Fig 6.6)

A rational design of air vessel involves calculation of the dimensionless parameters, as follows:

$$\text{Pipeline parameter} = \rho = CV_0/\ 2gH_0 \quad (6.22)$$

$$\text{Air vessel parameter} = \rho\frac{2C_0\ C}{Q_0\ L} \quad (6.23)$$

Kc = Coefficient of Head Loss such that $K_c\ H_0$ is the total head loss for a flow of Q_0 into air vessel. (Ref. to Fig. 6.7 to 6. 10) C is water hammer wave velocity, V_0 is initial velocity and Ho is absolute head (including atmospheric head), Co is the volume of Air, L is the length of pipeline.

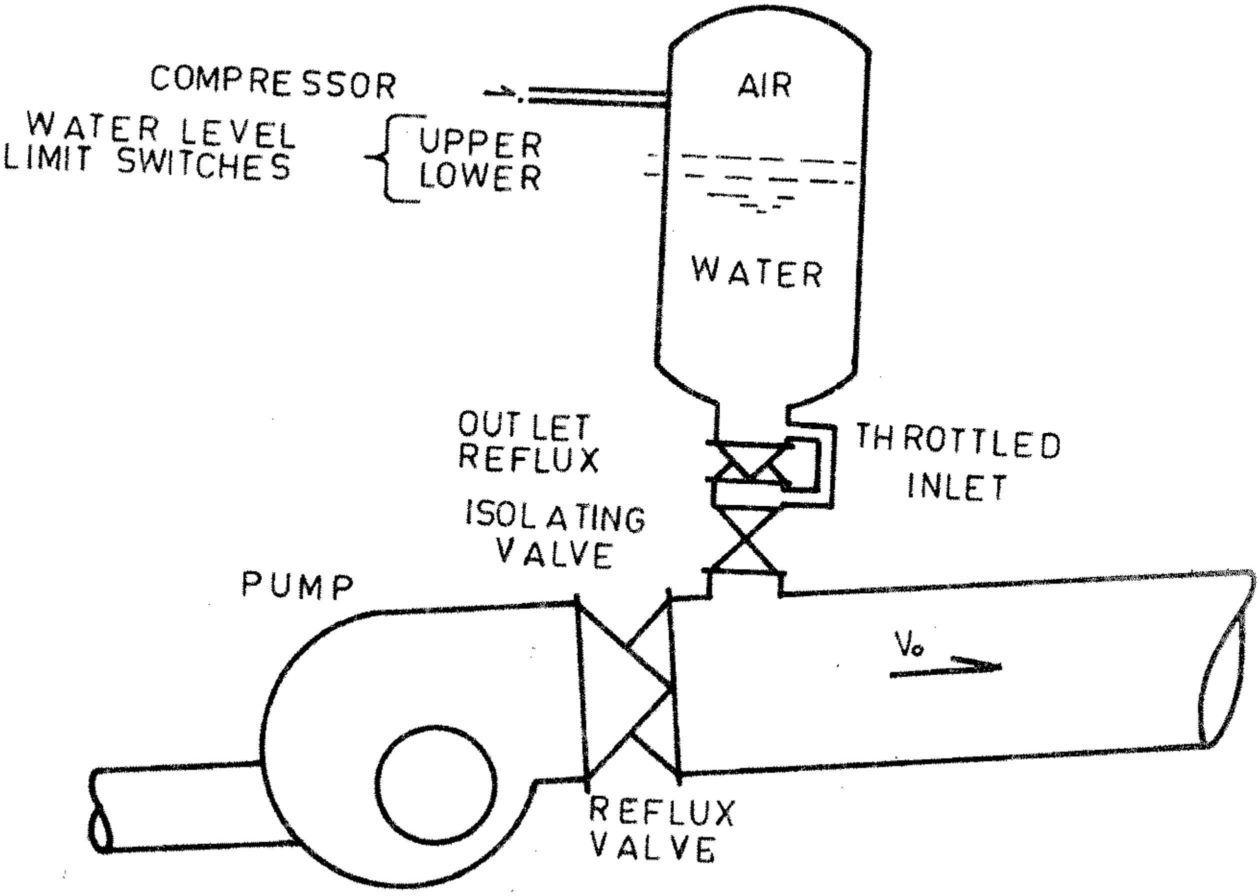

FIGURE 6.6 : AIR VESSEL

6.17.4.1 Design Of Air Vessel

The pipeline parameter, C is calculated from the maximum likely line velocity and pumping head, and the corresponding chart selected from Figs. 6.7 to 6. 10 for an assumed K_C value i. e. 0.0, 0.3, 0.5 or 0.7. The value of Air Vessel parameter corresponding to the selected line is used to read off the maximum head envelope along the pipeline from the same chart.

The volume of air, Co, is calculated once the air vessel parameter is known. The vessel capacity should be sufficient to ensure no air Where escapes into the pipeline, and should exceed the maximum air volume. This is the volume during minimum pressure conditions and is $S(H_0/H_{mm})^{1/1.12}$.

The outlet diameter is usually designed to be about one-half the main pipe diameter. The outlet should be designed with a bellmouth to suppress vortices and entertainment. The air in the vessel will dissolve in the water to some extent and will have to be replenished by means of a compressor.

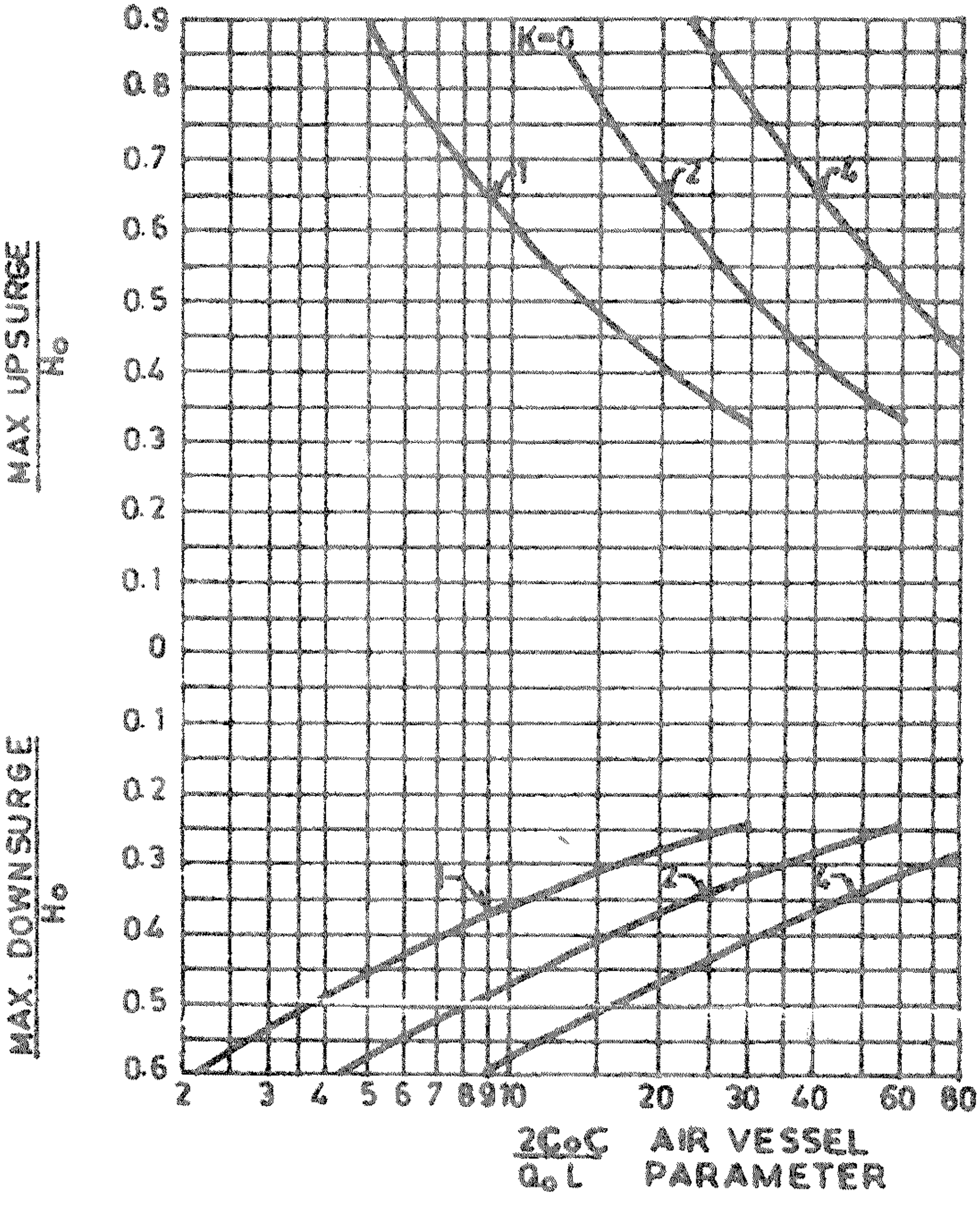

FIGURE 6.7 SURGES IN PUMP DISCHARGE LINE, $K_C = 0$

The requisite effective capacity of the vessel is also calculated from the expression.

$$V_0 = 1200 \text{ to } 1500\ Q/Z_P \qquad (6.24)$$

Where,

V_0 = effective volume in litres.

Q = discharge of pumps in lps and

Zp = permissible number of switching operation per hour for three-phase motors:

(10-15 for squirrel-cage motors direct in line,

6-10 for squirrel-cage motors with star delta starter,

6-10 for motors with rotor starter,

Permissible number of starts for motors as per IS 325 is 3.

A worked out example is at Appendix 6.7)

6.17.4.2 In-Line Reflux Valves

Inline reflux valves would normally be used in conjunction with surge tanks, discharge tanks or Air vessels. Following pumps shutdown, the tank or vessel would discharge water into the pipe either side of the reflux valve. This would alleviate the violent pressure drop and convert the phenomenon into a slow motion effect. The reflux valve would then arrest the water column at the time of reversal, which coincides, with the point of minimum kinetic energy and maximum potential energy of the water column. There would therefore be little momentum change in the water column when the reflux valve is shut and consequently negligible water hammer pressure rise.

There are situations where water column separation and the formation of vapour pockets in the pipeline following pump stoppage would be tolerable, provided the vapour pockets did not collapse resulting in water hammer pressures. Reversal of the water column beyond the vapour pocket could in fact be prevented with an in-line reflux valve at the downstream extremity of the vapour pocket. The water column would be arrested at its point of minimum momentum, so there would be little head rise.

Vaporization would occur at peaks in the pipeline where the water hammer pressure drops to the vapour pressure of the water. If the first rise along the pipeline was higher than subsequent peaks, the vaporization would be confined to the first peak.

In locating the reflux valve, allowance should be made for some lateral dispersion of the vapour pocket. The valve should be installed at a suitable dip in the pipeline in order to trap the vapour pocket and to ensure proper functioning of the valve doors when the water column returns.

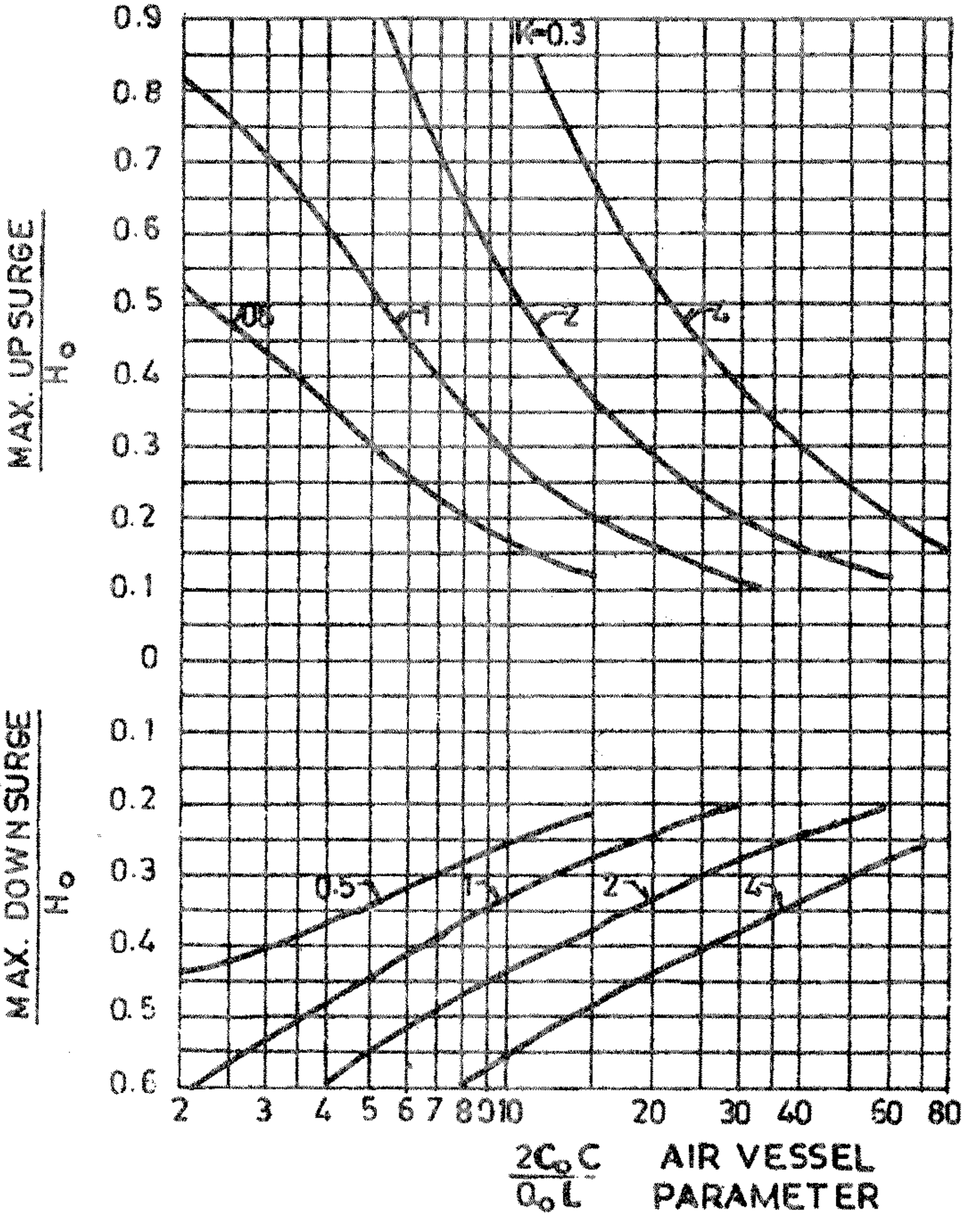

FIGURE 6.8 : SURGES IN PUMP DISCHARGE LINE, K_C = 0.3

A small diameter bypass to the reflux valve should be installed to permit slow refilling of the vapour pocket otherwise over pressures may occur on restarting the pumps. The diameter of the bypass should be of the order of one-tenth of the pipeline diameter. An air release valve should be installed in the pipeline at the peak to release air which would come out of solution during the period of low pressure.

It is common practice to install reflux valves immediately downstream of the pumps. Such reflux valves would not prevent water hammer pressures in the pipeline. They merely prevent return flow through the pump and prevent water hammer pressure reaching the pumps.

Normally a reflux valve installed on its own in pipe-line will not reduce water hammer pressures, although it may limit the lateral extent of the shock. In fact, in some situations indiscriminate positioning of reflux valves in a line could be detrimental to water hammer pressures. For instance if a pressure relief valve was installed upstream of the reflux valve the reflux valve would counteract the effect of the other valve. It may also amplify reflections from branch pipes or collapse of vapour pockets.

In some pumps installations, automatically closing control valves, instead of reflux valves, are installed on the pump delivery side.

6.17.4.3 Release Valves

There are a number of sophisticated water hammer release valves (often referred to as surge relief valve or surger suppressors) available commercially. These valves have hydraulic actuators which automatically open, then gradually close after pumps tripping. The valves are normally the needle type, which discharge into a pipe leading to the suction reservoir, or else sleeve valves, mounted in the suction reservoir. The valves must have a gradual throttling effect over the complete range of closure. Needle and sleeve valves are suitably designed to minimize cavitation and corrosion associated with the high discharge velocities which occur during the throttling process.

The valves are usually installed on the delivery side of the pump reflux valves and discharge directly to the suction reservoir. They should not discharge into the suction pipe as they invariably draw air through the throat, and this could reach the pumps.

The valves may be actuated by an electrical fault or by a pressure sensor. The valve should open fully before the negative pressure wave returns to the pumps as a positive pressure wave. As the pressure on the top of the piston increases again the valve gradually closes, maintaining the pressure within desired limits. The closing rate may be adjusted by a pilot valve in the hydraulic circuit.

If no over pressure higher than the operating head is tolerable, the valve would be sized to discharge the full flow at a head equal to the operating head, where reliability is of importance, and if water hammer is likely to be a problem during a partial shutdown of the pumps, two or more release valves may be installed in parallel. They could be set to operate at successively lower delivery heads.

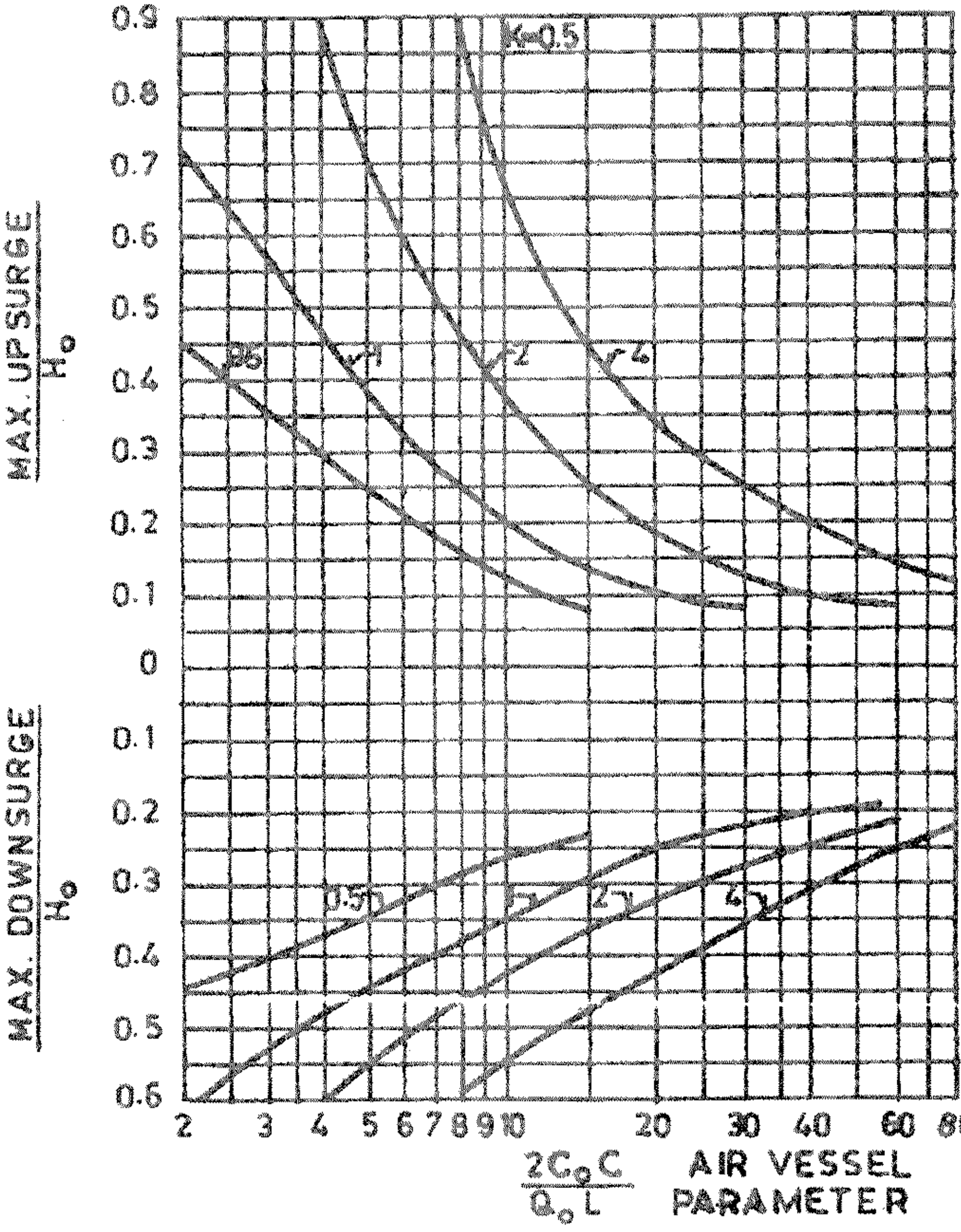

FIGURE 6.9 : SURGES IN PUMP DISCHARGE LINE, $K_C = 0.5$

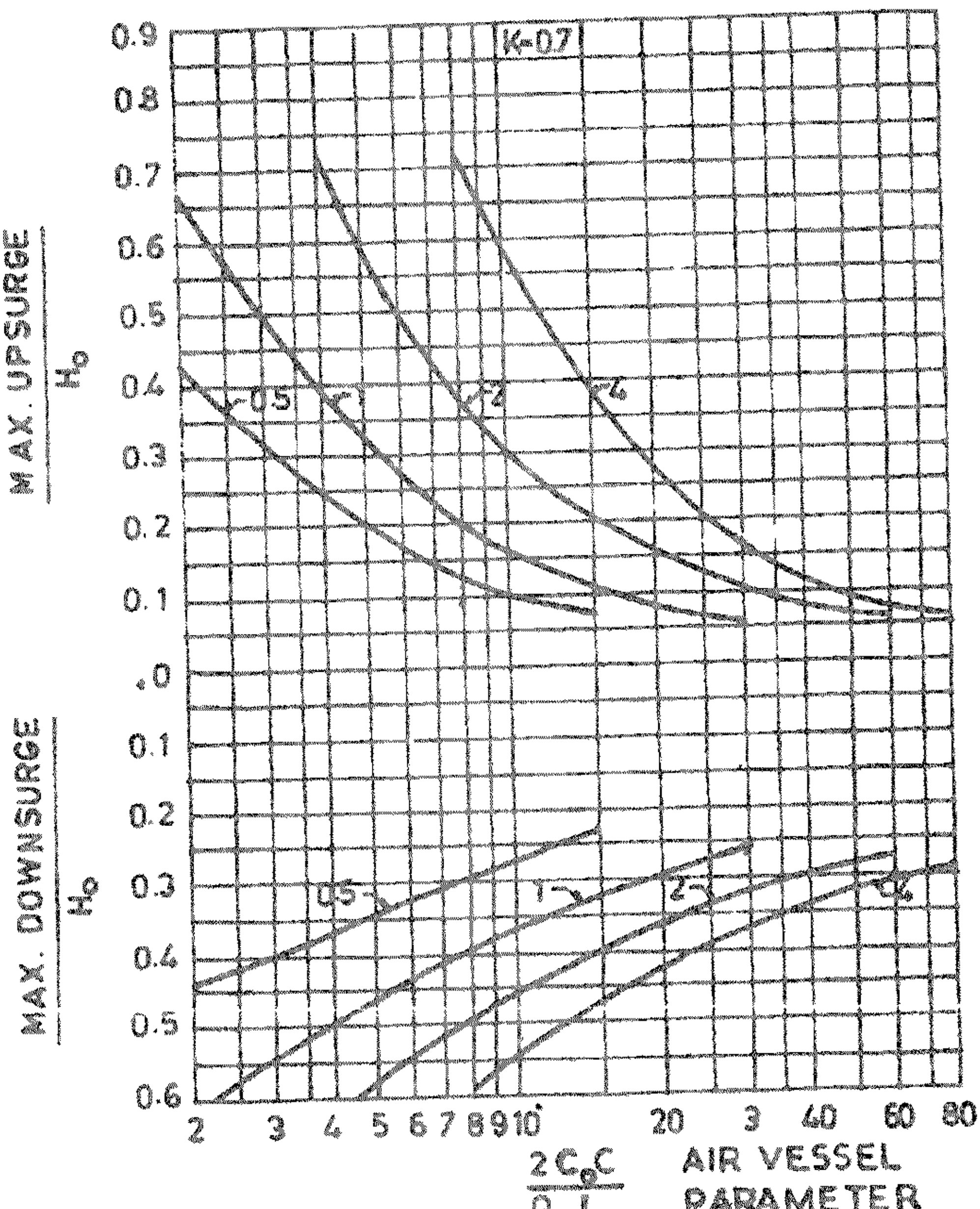

FIGURE 6.10 : SURGES IN PUMP DISCHARGE LINE, K_C = 0.7

could be disengaged to prevent their operation.

The types of control valves available as release valves for pumping lines normally cannot open in less than about five seconds. Their use is therefore limited to pipelines over two kilometers in length. This method of water hammer protection is normally most economical for cases when the pumping head greatly exceeds cv_0/g, since the larger the pumping head, the smaller the valve needed.

A less sophisticated valve than the control valves described above, which has been used on small pumps installation, is the spring-loaded release valve. The valve is set to open when the pressure reaches a prefixed maximum. Some over pressure is necessary to open the valve and to force water out.

Where a relief valve is power operated and actuated by a relay so as to open before reversal of flow takes place, over pressures can be held down so as not to rise more than 10 to 20% above normal operating pressure, although there may be an initial drop in pressure at the pump down to atmosphere or below. With the surge relief valve open, however, all succeeding reversals are dissipated through the open valve. The pipeline then assumes a penstock condition and the surge relief valve must be closed very slowly to prevent penstock surge. With large diameter lines for low pressure water service the economic justification for rather elaborate protective devices is obvious since without them the lines would have to be designed for shock pressures considerably in excess of the normal working pressure. This is particularly true in the case of concrete pipes, or of thin-walled steel pipes. With thin-walled steel pipes where the pressure may fall below atmospheric under shock conditions, it may be necessary to provide vacuum breakers to prevent collapsing of the pipe.

6.17.4.4. Shut-Off Effects On Suction Line

The effect of power interruption on the pump suction line depends on the arrangement of the suction piping. Nothing of much consequence will occur where the suction line is short and considerable suction lift has to be developed by the pump in order to get water flow to it. In the case of a booster pump, however, where water flows to the pumps suction through a long line under pressure, the result of a power interruption is much like what takes place in a discharge line and the measures taken to cushion shock are similar. To be most effective, a suppressor in such a booster pump suction should be placed close to the pumps. The booster pumps problem is frequently encountered in connection with the intermittent filling of standpipes such as overhead sprinkler tanks, pressure tanks in tall buildings and locomotive filling tanks in railroad yards. In cases where frequent fillings are required, the shock-pressure problem may be most annoying and corrective measures are clearly called for, especially if the pumps suction is taken from a branch line off a distribution network which may be adversely affected for large distances back from the pump. As an alternative to installing suppressors in such cases, consideration should be given to providing automatic means for slowly closing a valve in the pump discharge before power is cut off.

Another pump-suction problem involving surge on a large scale is encountered in water works intakes where the pumps may be fed through a conduit extending for several kilometers from some lake or reservoir in the mountains. In order to look after surge in the case of a sudden power interruption, it may be necessary to provide ample relief valves of gravity overflow, discharging to a receiving basin of generous proportions.

6.17.4.5 Reciprocating Pumps Or Hydraulic Rams

Reciprocating pumps cause pulsation problem not encountered with the continuous action of centrifugal pumps. Owing to the irregularity of flow through a reciprocating pump, more or less water hammer develops in the suction and discharge lines and cannot be suppressed entirely with vacuum or air chambers. For this reason it is advisable to design the suction and discharge lines of reciprocating pumps for something like 50% in excess of the normal working pressure and to provide ample air chambers at the pumps. Shock conditions obtaining with hydraulic rams are decidedly worse than with reciprocating pumps and generous provision should be made in the design of their piping. An allowance of at least 21 kg/cm^2 extra beyond the working pressure is called for with rams.

6.18 SPECIAL DEVICES FOR CONTROL OF WATER HAMMER

The philosophy is (i) to minimize the length of the returning water column causing water hammer (ii) to dissipate energy of the water column length by air cushion valve and (iii) to provide a quick opening pressure relief valve to relieve any rise in pressures in critical zones. These objectives are achieved by the following three valves.

6.18.1 Zero Velocity Valve

The principle behind the design of this valve is to arrest the forward moving water column at zero momentum i.e. when its velocity is zero and before any return velocity is established.

The valve fitted in the pipeline consists of an outer shell and an inner fixed dome leaving a streamlined annular passage for water. A closing disc is mounted on central and peripheral guide rods and is held in the closed position by one or more springs when there is no flow of water. A bypass connects the upstream and downstream sides of the disc. The springs are so designed that the disc remains in fully open position for velocity of water equal to 25% of the designed maximum velocity in the pipeline.

With sudden stoppage of pumps the forward velocity of water column goes on decreasing due to friction and gravity. When the forward velocity becomes less than 25% of the maximum, the flap starts closing at the same rate as the velocity of water. The flap comes to the fully closed position when forward velocity approaches zero magnitude, water column on the upstream side of the valve is thus prevented from acquiring a reversed velocity and taking part in creating surge pressures. The bypass valve maintains balanced pressures on the disc and also avoids vacuum on the downstream side of valve if that column experiences certain reversal.

The main advantages of zero velocity valves are :

(i) Controlled closing characteristics, and

(ii) Low loss of head due to streamlined design.

6.18.2 Air Cushion Valve

The principle of this valve is to allow large quantities of air in the pumping main during separation, entrap the air, compress it with the returning air column and expel the air under controlled pressure so as to dissipate the energy of the returning water column. An effective air cushion is thus provided.

The valve is mounted on TEE-joint on the rising main at locations where water column separation is likely. The valve has a spring loaded air inlet port, an outlet normally closed by a float, a spring loaded outlet poppet valve and an adjustable needle valve control orifice.

When there is sudden stoppage of pump due to power failure, partial vacuum is created in the main. With differential pressure, the spring loaded port opens and admits outside air into the main. When the pressure in the main becomes near atmospheric, the inlet valve closes under spring pressure. The entrapped air is then compressed by the returning water column till the poppet valve opens. With float in dropped position, the air is expelled through poppet valve and controlled orifice under predetermined pressure thus dissipating the energy of the returning water column.

6.18.3 Opposed Poppet Valve

As the name implies, the valve has two poppets of slightly different areas mounted on the same stem. The actual load on the stem is thus the difference in loads on the two poppets and is thus light. A weak spring is therefore, able to keep the valve closed under normal working pressure. If pressure in the water main increases beyond a certain limit, the increase in differential pressure overcomes the holding pressure of the spring, opens the valve and allows water to discharge through both the poppets.

On account of the light spring, the valve is able to open quickly and thus reduce the peak surge pressure to the desired limit.

6.19 WORKING OF THE SPECIAL DEVICES AS A SYSTEM

Every valve has a different function to perform for limiting water surge after power failure. Locations of the valves have therefore to be based on the results of the analysis of water column separation. Air cushion valves are located where separation of water column is indicated. Zero velocity valves are so placed that the entire length of water column is suitably divided in spite of differing gradients and undulations. More than one valve may be required in such cases.

Opposed Poppet pressure relief valves are generally placed near the air cushion valves or on the upstream side of the Zero Velocity Valves, if further limiting of peak surge pressure is required for the safety of the pipeline.

6.19.1 Choice Of Protective Device

The best method of water hammer protection for a pumping line will depend on the hydraulic and physical characteristics of the system. The accompanying Table 6.8 summarizes the ranges over which various devices are suitable. The most influential parameter in selecting the method of protection is the pipeline parameter $\rho = cv_0/gH_0$. When the pipeline parameter is much greater than 1, a reflux valve by passing the pumps may suffice. For successively smaller values of ρ it becomes necessary to use a surge tank, a discharge tank in combination with an inline reflux valve, an air vessel, or a release valve. The protective devices listed in Table 6.8 are arranged in approximate order of increasing cost. Thus, to select the most suitable device, one checks down the Table until the variables are within the required range.

It may be possible to use two or more protective devices on the same line. This possibility should not be ignored as the most economical arrangement often involves more than one method of protection. In particular the rotational inertia of the pump often has a slight effect in reducing the required capacity of a tank or air vessel. A comprehensive water hammer analysis would be necessary if a series of protection devices in combination is envisaged.

TABLE 6.8

SUMMURY OF METHODS OF WATER HAMMER PROTECTION

Method of protection (In approximate order of increasing cost)	Required range of Variables	Remarks
Inertia of pump	$(MN^2 / WALH_0)2 > 0.01$	Approximate
Pump bypass reflux valve	$(cv_0 / gH_0)2 >> 1$	Some water may also be drawn through pump
In-line reflux valve	$(cv_0 / gH_0)2 > 1$	Normally used in conjunction with some other method of protection. Water column separation possible

Method of protection (In approximate order of increasing cost)	**Required range of Variables**		**Remarks**
Surge tank	H small		Pipeline should be near hydraulic grade line so height of tank is practical
Automatic release valve	$(Cv_0 / gH_0)2$ $(L/C)2$	$<< 1$ $>$ 5secs	Pipeline profile should be convex downwards. Water column separation likely.
Discharge tanks	$(Cv_0 /gh)2$	> 1	h = pressure head at tank./ Pipeline profile should be convex upwards
Air vessel	$(Cv_0 /gH_0)2$	< 1	Pipeline profile preferably convex downwards.

The example in App. 6.7 gives the methods of analysis and calculations for water column separation and computation of Air Vessel size.

- M = Moment of Inertia of rotating parts of pump, motor and entrained water (mass x radius of gyration^2)
- N = Pump speed in rpm
- W = Wt. of water per unit volume
- A = Pipe cross section Area
- L = Pipeline length
- H_0 = Pumping head
- h = Pressure head
- c = Water hammer wave velocity
- v_0 = Initial velocity
- J = Pump parameter,
- f = Pump rated efficiency (expressed as a fraction).