Surge Analysis Program Version 2

SAP2R

Manual on Design Guidelines

K Sridharan

Department of Civil Engineering
INDIAN INSTITUTE OF SCIENCE
Bangalore – 560 012

April 2010

CONTENTS

1. BACKGROUND AND SCOPE

This manual on design guidelines for surge protection system for pumping mains is linked to the use of the surge analysis software, SAP (Surge Analysis Program) released by the Indian Institute of Science. The Institute has played a pioneering role in the country in this area over the last 25 years. This manual derives its strength from the considerable experience accumulated over these years, based on case studies for more than 200 pumping stations in all parts of the country.

The principal application area of SAP is the design of surge protection system for cross country pumping mains of water supply schemes and lift irrigation schemes. The design of surge protection system is an iterative process in which a particular protection is proposed, waterhammer analysis is made for that choice for power failure condition, the resulting surge pressures are evaluated, the protection system is modified based on the evaluation and the process is repeated until an adequate and economical protection system is arrived at. Surge or waterhammer analysis is made for each option by numerical analysis using the method of characteristics. A software is required for such an analysis, as it involves simultaneous solution of two nonlinear, first order partial differential equations. The software SAP provides the surge analysis tool and its scope covers practically all surge protection options available in the country.

Like in any other area of engineering design, design of surge protection system requires considerable engineering judgement and a skill in interpreting the results of surge analysis. As in several other engineering analysis problems, the results of analysis may appear more critical in some situations than likely in real life problems. Similarly in some other situations, the results of analysis may appear more rosy than likely in real life problems. One of the objectives of this manual is to provide an insight into how to interpret the results of surge analysis, and how to proceed in the design of surge protection system based on such interpretation.

For most pumping stations, more than one surge protection option may be a candidate for consideration. The final choice has to be made based on the twin considerations of reliability of performance and economy. Each type of protection system requires a specific approach to design. Another scope of this manual is to provide an appreciation of the specific considerations associated with the design of different types of surge protection system.

In all pumping stations, non-return valves on the delivery pipes of individual pumps is a common feature. The surge picture is very closely linked to the closure characteristics of these valves under power failure or single pump failure condition (single pump failure refers to failure of one pump when multiple pumps are in parallel operation). A distinct feature of SAP software is its ability to handle a wide range of types of non-return valves with very different closure characteristics. This manual also focuses on the implication of the choice of a particular type of non-return valve for use in the pump house.

This manual is essentially intended as a companion manual to the User Manual on SAP. However, in order to make it self contained with regard to clarity, while reading this manual as a stand alone document, some parts of the User Manual may be repeated here. As in the case of User Manual, the terms rising main and transmission main are used synonymously to represent the pipe downstream of the manifold/header.

2. PHENOMENON OF SURGES IN A PUMPING MAIN

Fig. 1 presents a schematic diagram of a pumping main in a cross country alignment. The design of the surge protection system is normally based on surge analysis for the power failure condition. Surge analysis for single pump failure condition plays a secondary role in finalising the required surge protection measures, and its importance lies particularly in relation to deciding the test pressure for the pipes and valves in the pump house.

The software SAP provides for three simulation options: a) power failure (PF); b) single pump failure (SPF); c) all pumps failure (APF). PF and APF options refer to the same physical condition, namely the simultaneous stopping of all pumps resulting from power failure. The difference between the two options lies in the approach to modelling. In PF option, the pump house pipes are not modelled, while in the APF option, the pump house pipes are modelled. In many projects, decision regarding pump house pipes and valves is taken only during detailed engineering and hence there are several situations where surge analysis has to be done before these details are available. Generally, until the final stages of the design, the design of surge protection system for the transmission main may be based on analysis with PF option. During detailed engineering, fine tuning of the design through surge analysis based on APF option may be done.

Normally, the surge picture in the transmission main will not be unduly influenced by details of pump house piping, though the type of non-return valve may have a significant effect. However, the surge picture in the pump house will significantly depend on the size of pump house piping. For this, analysis with SPF and APF options are necessary. Analysis for single pump failure with SPF option is particularly important for cases where air vessel is proposed as surge protection system and/or the number of working pumps is more than 3. However, analysis for single pump failure condition is decisive only with regard to choice of

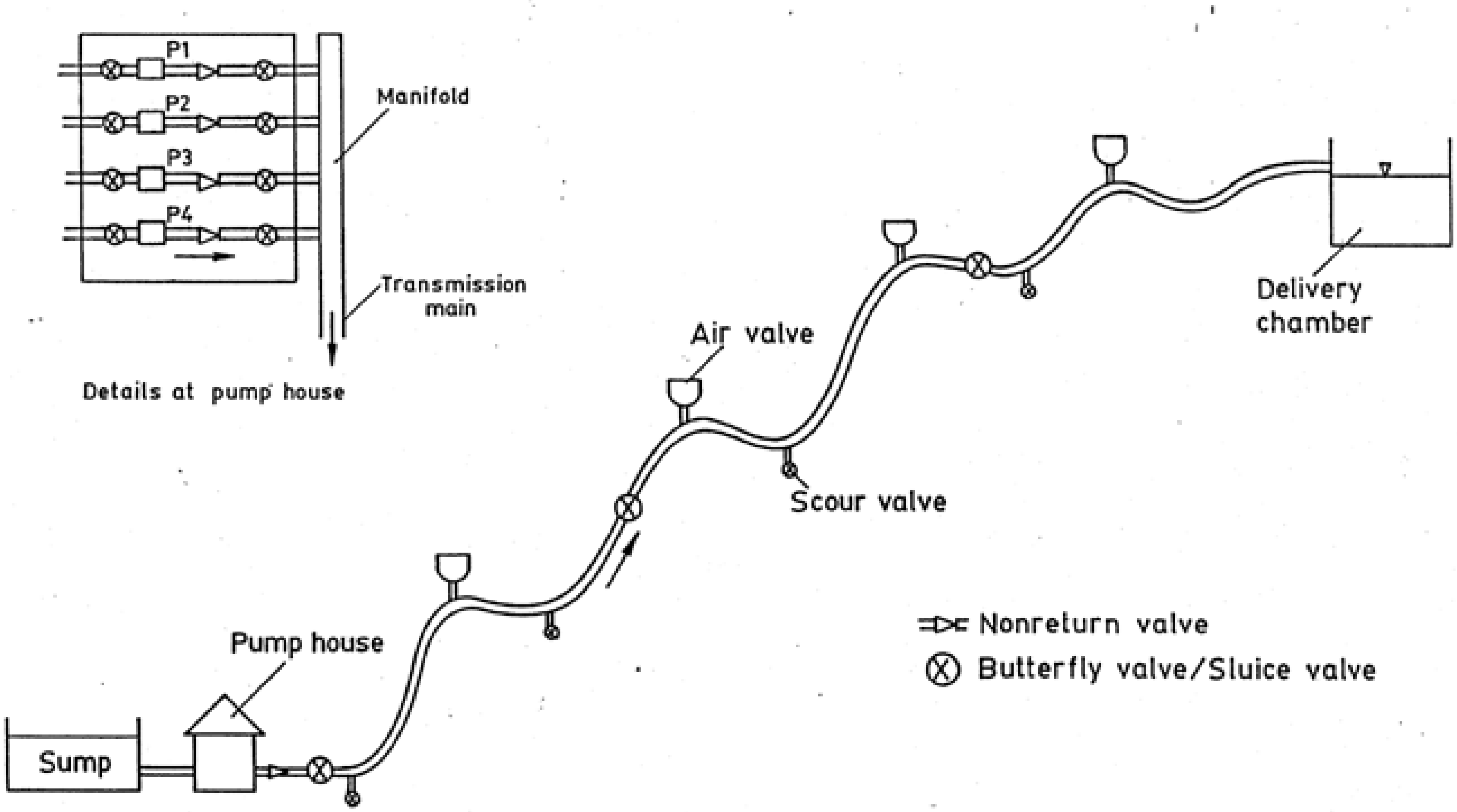


Fig.1: Schematic Diagram of a Cross Country Pumping Main

pump house pipes and valves, and not with regard to finalisation of the surge protection system for the transmission main. In all the subsequent discussions in this manual, the focus is on surge picture for the power failure/all pumps failure condition, unless otherwise specified.

3. A SIMPLE AND SIMPLISTIC EQUATION

A very commonly referred equation for the management of waterhammer is given by

$$\Delta H = \frac{aV_o}{g} \tag{1}$$

where V_o = flow velocity, a = waterhammer wave velocity, g = gravitational acceleration and ΔH = rise in pressure head. Eq. 1 is valid when the initial velocity V_o is suddenly brought to zero by instantaneous closure of a valve. A simple derivation of the equation may be given based on momentum principle, as illustrated in Fig. 2. Ignoring frictional force and equating the rate of change of momentum in the control volume to the net force,

$$\rho A a(0 - V_o) = pA - (p + \Delta p)A$$

$$\Delta p = \rho a V_o$$

or $$\Delta H = \frac{\Delta p}{\gamma} = \frac{aV_o}{g} \tag{2}$$

where A = cross sectional area of pipe, p = pressure before the valve closure, Δp = pressure rise due to valve closure, ΔH = associated rise in piezometric head, ρ = density of water and γ = specific weight of water.

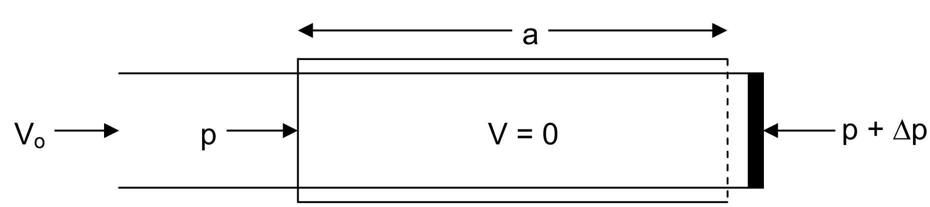


Fig.2: Momentum Principle for Suddenly Closed Valve

Eq.1 has its value and its limitations. It is perhaps not wrong to state that it has been more often misused than used. The terminologies "sudden" and "instantaneous" are not often valid under field conditions. For example, there is no way a 1000 mm valve will be closed "instantaneously". Eq.1 is a useful index of the likely intensity or severity of waterhammer. It has direct validity under some specific situations. But it should not be applied simplistically, as it may give a distorted picture. This aspect wii now be discussed further.

The simple equation presented above (Eq.1) provides a broad conceptual idea of waterhammer, rather than solution to practical real life problems. This can be illustrated by considering a simple example. There is a lift irrigation scheme involving a small lift of 20 m- and a very short length pipe. The working pressure in the system is 20 m and the velocity of flow is 2 m/sec. It appears from the low head that a PSC pipe may be suitable. Assuming that the wave velocity is 900 m/sec (typical value for a PSC pipe), the surge pressure as per Eq. 1 works out to $\Delta H = \frac{900 \times 2}{9.81} = 183 \text{ m}$

This estimate of surge pressure when added to the working pressure yields a maximum pressure in excess of 200 m, that is 10 times the working pressure! For such a maximum pressure, one may question the use of non-cylinder type PSC pipe. The question is, for this system, should the pipe be designed for 20 kgf/cm^2?

It is interesting to note that the surge pressure given by the simplistic Eq.1 is the same whether the pipe length is 10m or 10000 m, whether the motor is extra-light or ultra-heavy, and there is no consideration of longitudinal alignment either. From a physical perspective, it is obvious that all these factors (and more, such as characteristics of a non-return valve, if used) will effect the surge picture.

The above discussion is not mere academic criticism of Eq. 1. The writer has come across schemes in which field engineers face the dilemma whether they should specify test pressure for a PSC pipe, based on Eq. 1. The Manual on Water Supply and Treatment, Ministry of Urban Development, appears to recommend the use of Eq. 1, though with a rider on the time of closure (of a valve). In a pumping main, the waterhammer resulting from valve operation is generally not the critical condition.

There is another angle to the comparison picture vis-a-vis real life situation. Though Eq. 1 is valid for both pressure rise and pressure drop, the focus of the simplistic approach is generally on pressure rise. If, in the scheme referred earlier, a 2500 mm steel transmission main with slender wall thickness is used, should we not be as much concerned with pressure drop and possible occurrence of vacuum, as with pressure rise? Hence the simplistic picture may exaggerate some problems and may ignore some other problems.

The discussions so far have not considered the effect of frictional loss. If there are two pumping mains, A and B, of identical pipe size and discharge, with 100 m pump head, and if A has static lift of 90 m and B has static lift of 10 m (obviously, B is a much longer transmission main than A), will the waterhammer picture be the same in both the mains? Obviously the surge picture will be different in the two systems.

Other complexities in the system analysis may be introduced by devices and fittings in the transmission main, such as valves, break pressure tank, surge tank, air vessel (as surge protection device), etc. With regard to surge, non-return valves play a principal role and various types of non-return valves may be used. Under downsurge conditions, if pressure goes down to subatmospheric or vapour pressure, air valves also play a role.

All these discussions indicate that surge analysis if far from the simple picture projected by Eq. 1. Hence there is a need for use of software such as SAP for dealing with surge problems in a pumping main.

4. SURGE PRESSURES -INTERPRETATION OF ANALYSIS RESULTS

From engineering design view point, the, principal focus of interest in surge analysis and design of surge protection system, lies in the minimum and maximum pressures in the pipe line under surge condition. However, in order to get a proper assessment of the surge picture, it is necessary to look at the pressures in relation to the longitudinal alignment of the transmission main. In view of this, an output file giving a tabulation of minimum and maximum pressures at various chainages along the alignment is not very effective in facilitating proper design decisions, or even in deciding what should be the next case to be analysed in the iterative design process. This is best achieved by an output in terms of a graphical plot, giving a simultaneous picture of the minimum and maximum piezometric heads along with the transmission main alignment. Such a graphical plot is also in tune with the surge analysis algorithm, where the primary computational variable is the piezometric head and not pressure, though pressure can be calculated by subtracting the pipe elevation from the piezometric head.

Fig. 3 presents an example of minimum and maximum piezometric heads as obtained from a computation using SAP. The elevation in y-axis in the figure refers to piezometric heads or pipe line elevation, all in terms of reduced level (MSL or levels with respect to any other datum as may be identified for the scheme). At any location along the transmission main, the minimum and maximum pressures are obtained by subtracting the pipe elevation from the respective piezometric head, as shown in Fig. 3.

In interpreting the minimum and maximum pressures as obtained from a figure such as Fig. 3, several points are to be noted. The first one is concerned with clarity in semantics. Normally, several simple guidelines on surge provide a formula such as Eq. 1 for calculating surge pressure (The serious limitations of Eq. 1 were already discussed in Section 3). The pressure rise calculated from a formula such as Eq. 1 is referred as surge pressure, that is the pressure increase over working pressure. On the other hand, the maximum pressure

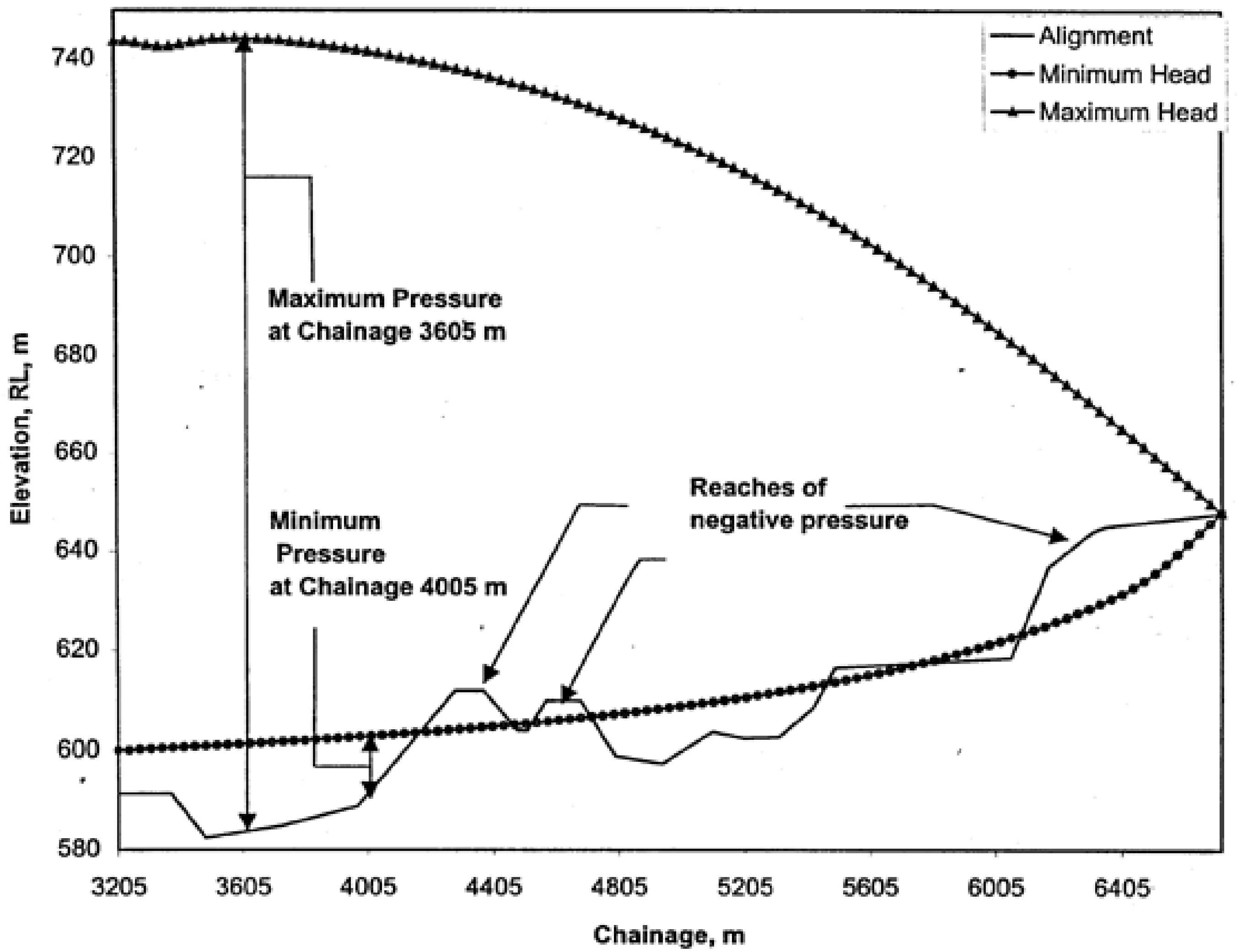


Fig.3: Minimum and Maximum Piezometric Heads – An Example

obtained from Fig. 3 at any location is the maximum pressure that occurs in the pipe under surge condition of power failure, and should be viewed holistically rather than dividing it into working pressure + surge pressure. However, to facilitate practical decision in the design, the maximum pressure may be interpreted as K times working pressure (or pump head), where K > 1.

The second point to be noted with respect to Fig. 3 also concerns with semantics. The terminologies upsurge and downsurge are commonly used in interpreting the surge picture. Downsurge is concerned with pressure drop or minimum pressure, while upsurge is concerned with pressure rise or maximum pressure. In power failure situation, the primary surge is downsurge, which occurs immediately following power failure. The upsurge is a secondary surge occurring as a result of pressure wave reflection from the delivery reservoir, or due to reverse flow and non-return valve closure. Normally the focus is on pressure rise or upsurge, but depending on the type, size and strength of the pipe and joints, one has to review the effects of both upsurge and downsurge before finalising the surge protection system. Besides, control of the primary downsurge very often leads to control of upsurge also.

The third point to be noted with respect to Fig. 3 is with regard to the exact value of minimum or maximum pressure as inferred from the figure. The elevation of the transmission main alignment in the figure may refer to ground level or pipe invert level. Based on this, the minimum pressure should be calculated with respect to pipe top level and the maximum pressure should be calculated with respect to pipe invert level. This refinement may be of importance, particularly, for minimum pressure for large size pipes.

The fourth point to be noted with respect to Fig.3 is regarding interpretation of the results. There is no ambiguity in interpreting the results for maximum pressure, as the difference in elevation between the maximum piezometric head and the pipe elevation. However, the same can not be said for minimum pressure. In Fig. 3, where the minimum piezometric head profile is below the pipe alignment level, pressure becomes negative or subatmospheric under minimum pressure condition. But unlike maximum pressure for which there is no theoretical upper limit, physically there is a lower limit for minimum pressure as governed by the vapour pressure (approx. -9 m for water, under normal conditions). If the vapour pressure occurrence is limited to one or two isolated locations along the alignment, the system can be analyzed reliably by imposing a constraint on lower limit at vapour pressure at these locations. When occurrence of vapour pressure is extensive over the alignment, analysis becomes uncertain as explained in Sections 14.1 and 14.2 of the User Manual.

In SAP, constraint on lower limit of pressure at vapour pressure may be imposed at one location, or may not be imposed at all. The minimum piezometric head profile is also plotted without placing any lower limit, except at one location if vapour pressure condition is imposed. Hence spurious minimum pressures with negative values in excess of -10 m may be indicated in the surge picture such as Fig. 3. These values in excess of -10 m should be interpreted only qualitatively and not quantitatively. When computations are done without placing any lower limit on minimum pressure, the magnitude of the "spurious" negative pressure values gives a very good indication of the severity of the downsurge problem, the likely impact of water column separation, and an indication of the type of protection system required. When the minimum pressure profile is limited to -10 m in the pressure plot, as in some software, the indications with regard to above aspects are relatively less effective.

5. SEVERITY OF SURGE - UPSURGE AND DOWNSURGE EFFECTS

The safety of the pipe may be endangered due to upsurge or downsurge depending on the type of pipe (pipe material), size of the pipe and its strength. There are essentially three possible problems: a) direct effect of downsurge due to occurrence of vacuum, causing buckling of the pipe or dislocation of the joints in the case of flexible joints; b) effect of direct upsurge resulting in undue pressure rise causing failure of the pipe; c) effect of secondary upsurge resulting from water column separation (occurrence of vapour pressure) and associated shock pressure rise due to the rejoining of the separated water columns. Out of these three types of problems, (a) and (c) are associated with downsurge and (b) is associated with upsurge.

Large size pipes are generally more vulnerable to the effect of vacuum occurring due to downsurge. This is particularly true for large size thin walled steel pipes (D/t ratio greater than 150, where D = diameter of the pipe, t = wall thickness). The problem is further compounded by the fact that large size steel pipe may have some ovality due to inadequate quality control in fabrication, or due to handling and transportation, or due to deflection resulting from soil over burden. Even a small ovality significantly reduces the strength of the pipe to withstand buckling.

PSC pipes, particularly the non-cylinder pipes, may be generally more vulnerable to upsurge effect, compared to downsurge. However, in this regard, upsurge due to water column separation effect should also be considered.

In all pipes with flexible joints, the possibility of dislocation of the rubber gasket due to occurrence of rapid vacuum in the downsurge phase, should be kept in view.

6. WATER COLUMN SEPARATION EFFECT

In many pumping mains where there is no surge protection or there is no protection device for the contro1 of downsurge, extensive occurrence of vapour pressure along the alignment is likely. In such situations, SAP can be used for analysis. To consider water column separation effect at one location only in each analysis. The following practical approach is proposed to deal with this problem. A few critical locations (usually pronounced local peaks along the alignment) for consideration of water column separation effect may be identified. This can be done based on the minimum piezometric head profile for the case where no water column separation effect is considered. For example, in Fig. 3, Ch. 4280 m and Ch. 6350 m may be identified for the analysis of water column separation effect. Analysis may be repeated considering water column separation effect at each of these locations, and the locus of maximum piezometric head from all these computations may be considered in the design. In general, when water column separation effect is considered at one location under conditions of extensive vapour pressure occurrence, the minimum piezometric head profile obtained from such analysis has not much value and hence the minimum piezometric head profile may even be deleted from the figure. To sum up, where there is indication of extensive occurrence of vapour pressure: a) review the severity of down surge based on minimum piezometric head profile without considering water column separation effect; b) review the severity of upsurge based on the maximum piezometric head profiles considering water column separation effect at a number of identified critical locations.

It must be noted that where extensive occurrence of vapour pressure is indicated, the results of analysis are to be treated as approximate, as there are no well established analysis procedures to handle the problem.

7. PUMP HOUSE NON-RETURN VALVES AND PRESSURES IN THE PUMP HOUSE

One of the features of the software SAP is the wide range of choice allowed for the pump house non-return valves. The term pump house non-return valves refer to the non-return valves located inside the pump house on the delivery pipes from individual pumps. These non-return valves should be distinguished from the non-return valves that may be located in the transmission main after the manifold/header or at an intermediate location along the alignment.

The six options allowed for the pump house non-return valves are as follows:

1. Code 1 type closure - swing check valve closing instantaneously with/without delay, following flow reversal.

2. Code 2 type closure - swing check valve closing with uniform speed, with closure starting on flow reversal with or without delay.
3. Code 3 type closure - non-return valve closing in two speed (90% rapid +10% slow), with closure starting on flow reversal, with or without delay.
4. Code 4 type closure - non-return valve closing with uniform speed, with closure starting from the instant of pump trip.
5. Code 5 type closure - non-return valve closing in two speed (90% rapid + 10% slow), with closure starting from the instant of pump trip.
6. Dual place check valve.

The choice of the type of non-return valve in the pump house may have a significant global effect on the surge pressures over the entire length of the transmission main, or it may strongly affect only the surge pressures within the pump house, the pressures in the transmission main remaining largely unaffected. This will depend on the hydraulic parameters of the system and the type of surge protection system proposed. For example, if the rising main length is relatively short, a rapid closure of swing check valve with delay in closure may deteriorate the surge pressures not only in the pump house, but also over the entire rising main. On the other hand, if the pumping system is friction dominated with long pipe length and low static lift, the effect of change in the closure characteristics of the pump house non-return valves will essentially influence the surge pressures within the pump house only. If an air vessel is used as a surge protection system and a slow closing non-return valve is used in the pump house, on power failure, some water from the air vessel may flow back to the sump thus reducing the effectiveness of the air vessel to an extent which may influence the surge pressure over the entire rising main for a given size of the air vessel.

Depending on the type of non-return valves in the pump house, there will be several cases where the surge pressures (minimum and maximum) will be significantly worse in the pump house, compared to the pressures after the delivery manifold. In such surge pictures, it is possible that minimum pressure at the pump house may be shown (spuriously) as below -10 m, with associated higher maximum pressures. Such situations commonly occur in single pump failure analysis with air vessel used as the surge protection system. Fig. 4 gives such an example with pronounced severity of surge pressures with the pump house, but completely acceptable pressure profiles in the rising main after the pump house. Even for power failure condition, such a trend of worse surge pressures in the pump house compared to rising main, may occur, though in a much weaker form than shown in Fig. 4.

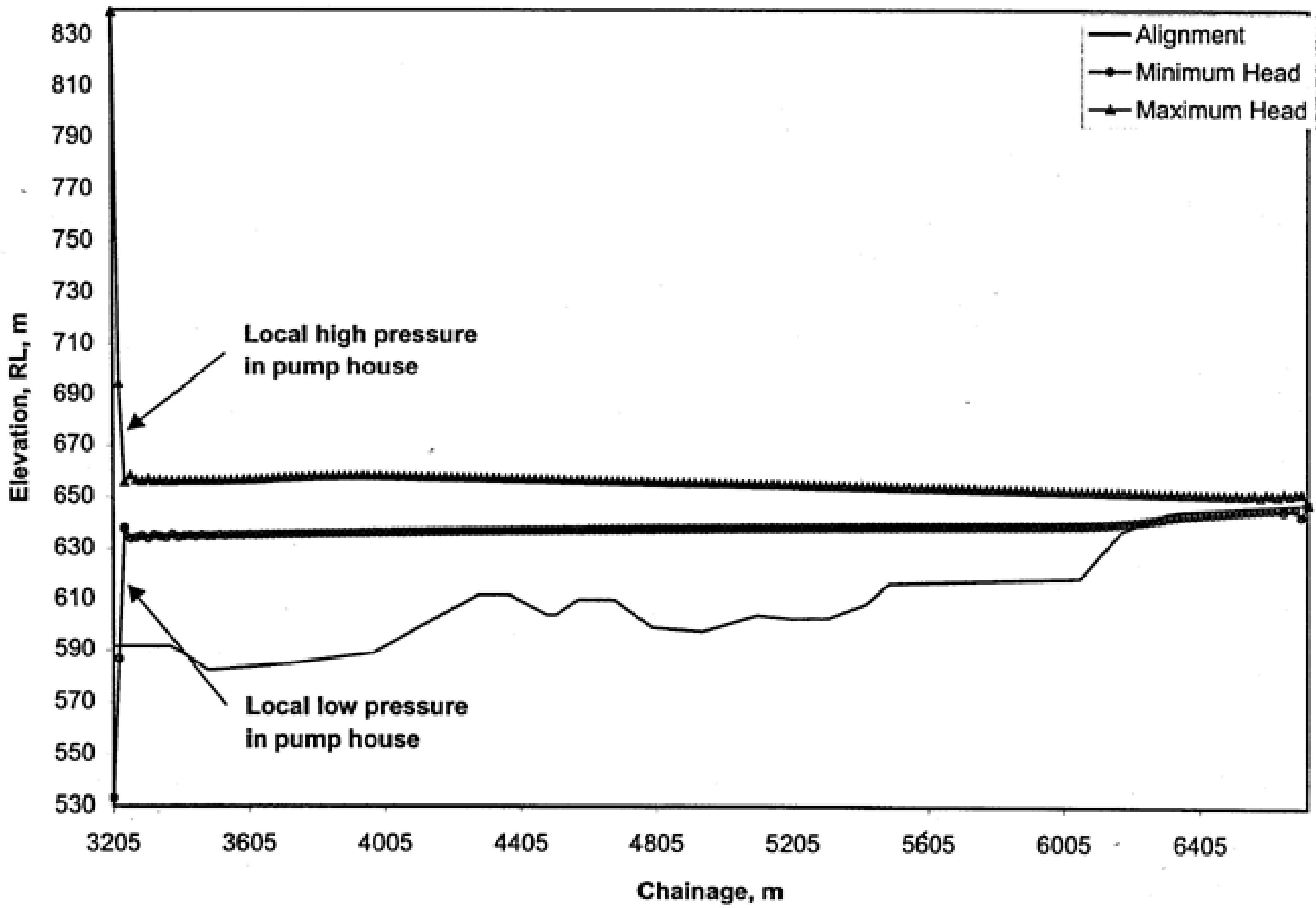


Fig.4: Minimum and Maximum Piezometric Heads for Air Vessel – Example of Single Pump Failure

Due to the trend discussed above, it is possible that occurrence of vapour pressure may be indicated at the pump house, but not outside the pump house (as shown in Fig. 4). In interpreting these results, it must be noted that the length of the pipe between the pump non-return valve and the manifold is generally not even 10m, and the time required for a pressure wave to travel this length is of the order of 0.01 sec. Hence, no undue significance may be attached to the indication of minimum pressure less than - 10m inside the pump house, but not outside. In such cases, the focus may only be on the local maximum pressure within the pump house, in order to decide on the required pressure rating of the pump house pipes and valves. For example, the results in Fig. 4 may be used to conclude that the valves (non-return valves and butterfly valves) in the pump house should have a body test pressure not less than 25 kgf/cm^2, as the maximum head is (840-591) = 249 m. Besides such a conclusion, there need be no undue worry about the spurious low value of minimum pressures where it occurs inside the pump house only.

Besides the nuances of interpretation of surge pressures in the pump house as discussed above, one general observation with regard to closure characteristics of pump house non-return valves must be noted. Valves which close rapidly on flow reversal may cause pressure rise associated with flow reversal, but there will be no reverse rotation of the pump in such cases. Valves with slow closure with external damping arrangement may not cause much pressure rise, but they may allow significant reverse flow and associated reverse rotation of the pump. This trade-off has to be kept in view in deciding on the type of pump house non-return valves.

8. PUMP CHARACTERISTICS IN SURGE ANALYSIS

In surge analysis, pump characteristics in different zones of pump operation are generally required. Fig. 5 shows in the flow-speed (Q - N) four quadrant diagram, the three zones of operation where pump characteristics may be relevant for surge analysis. The first quadrant domain Q > 0, N > 0 refers to the normal zone of pump characteristics.

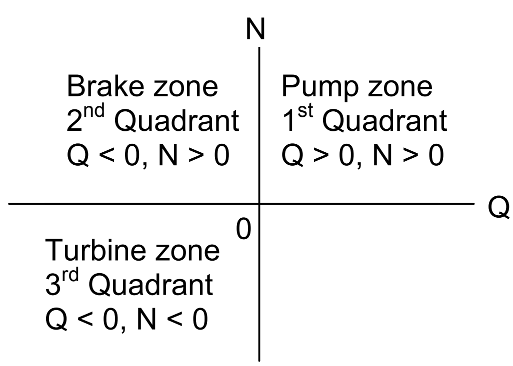


Fig.5: Schematic Diagram of Four Quadrant Pump Operation

The characteristics curve provided by the pump manufacturer corresponds to this zone of operation. Following power failure, the flow and pump speed reduce. Generally, the flow reduces at a more rapid rate than pump speed, and hence when the flow starts reversing ($Q < 0$), the speed N is still greater than zero. The pump operation is now in the brake or energy dissipation zone (second quadrant). If the non-return valve closure is delayed or very gradual, the reverse flow increases and soon reverse rotation may start. This corresponds to turbine zone of operation with $Q < 0$, $N < 0$ (third quadrant). The pump characteristics given by the manufacturer for the pump zone of operation are to be extended to the brake and turbine zones of operation. For this purpose, SAP uses the three types of standard four quadrant characteristics available in literature for radial, mixed and axial flow pumps (Stepanoff, A.J., Centrifugal and Axial Flow Pumps, John Wiley and Sons, 1948; Wylie, E.B. and Streeter, V.L., Fluid Transients, McGraw Hill Book Co., 1978). Based on the head discharge characteristics of the pump in the normal pump zone of operation, the type of standard characteristics which is closest is identified. The actual characteristics in the pump zone of operation is now extended by extrapolation into brake and turbine zones of operation based on the identified standard pump characteristics. In situations where pump characteristics are not available as the pumps are not yet finalised, SAP provides an option for using an identified type of standard characteristics.

9. PARAMETERS GOVERNING SURGE IN A PUMPING MAIN

The following parameters play a principal role with regard to the severity of surge in a pumping main:

(a) Pipe line constant, $B = \dfrac{aV_o}{gH_o}$

(b) Pump-motor inertia constant, $K_p = \dfrac{450 g\gamma Q_p H_p L}{\pi^2 \left(\dfrac{GD^2}{4}\right) \eta_o N_o^2 a}$

(c) Friction loss parameter, HF_o

(d) Nature of longitudinal alignment

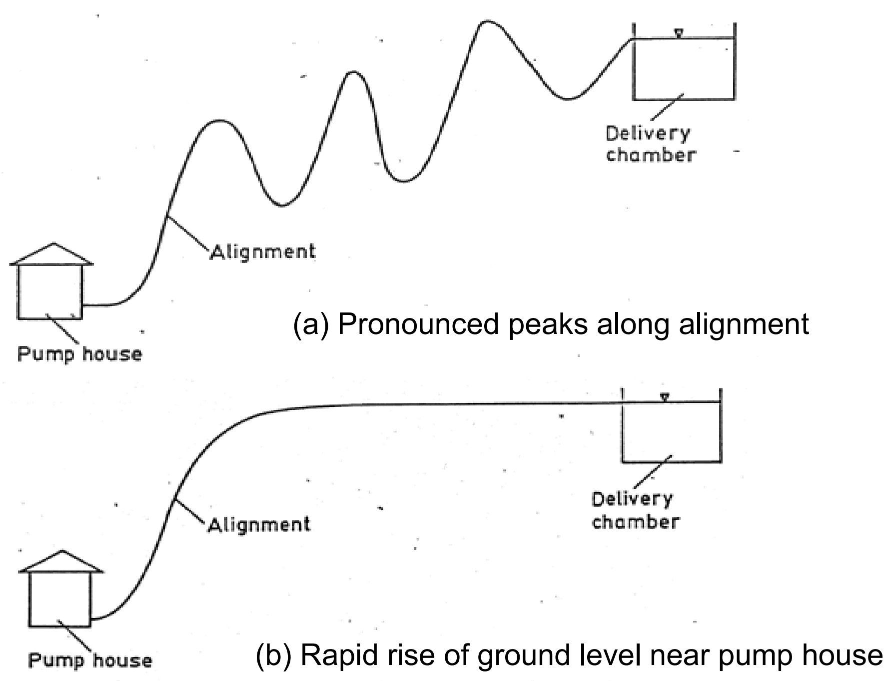
Here, V_o = flow velocity, H_p = pump head, Q_p = discharge of each pump, N_o = rated speed of the pump, η_o = rated efficiency of the pump, GD^2 = combined inertia of pump and motor, L = length of the transmission main, a = pressure wave velocity, γ = specific weight of water and g = gravitational acceleration; HF_o refers to the ratio of head loss due to friction and other losses to the pump head.

Larger the B value, the surge intensity will be more. The magnitude of surge, for this purpose, has to be viewed in terms of working pressure. B value less than 0.5 is unlikely to require any large scale surge protection system. As B increases beyond 1.5, the possibility of extensive occurrence of vapour pressure is almost certain.

As K_p increases, surge pressure increases. As motors are becoming lighter and lighter, and as pumping main lengths are increasing, K_p is almost invariably relatively high. A value of K_p less than 0.1 may mean relatively less surge pressures, but K_p values are often more than 1.0, which is a high value.

The parameter, HF_o refers to the proportion of friction loss in the pump head. As HF_o increases, that is, as friction effect dominates, downsurge deteriorates while upsurge improves. For $HF_o < 0.05$, upsurge is likely to be the critical factor in the design of surge pressure system. For $HF_o > 0.30$, downsurge is likely to be the critical factor. In between these values, both upsurge and downsurge may have to be controlled in a balanced way.

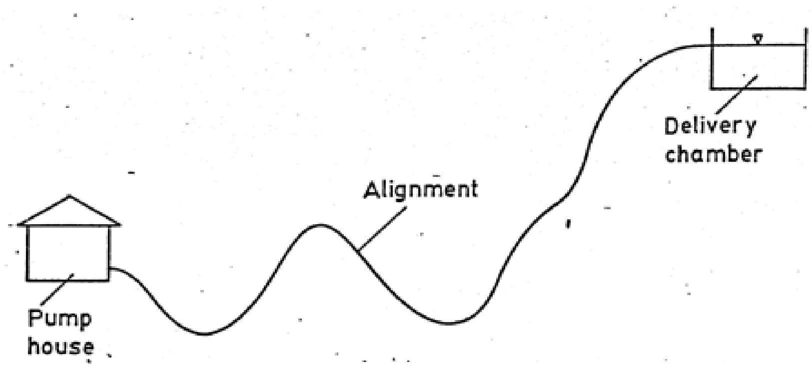
The surge picture is very closely related to the longitudinal alignment of the pumping main. Pronounced peaks along the alignment make such locations very vulnerable to downsurge. Presence of deep valleys, particularly near the pump house, means a significant impact of upsurge. Fig. 6 presents alignment types which are vulnerable to downsurge, and Fig. 7 presents alignment types which are vulnerable to upsurge.



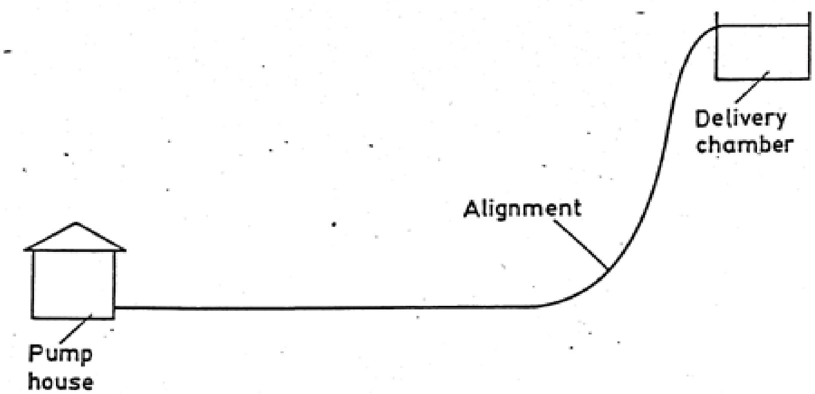
(a) Pronounced peaks along alignment

(b) Rapid rise of ground level near pump house

Fig. 6 Alignments Vulnerable to Downsurge



(a) Alignment with pronounced valleys



(b) Alignment with very rapid rise of ground level near delivery chamber

Fig. 7 Alignments Vulnerable to Upsurge

10. DESIGN CONSIDERATIONS AND METHODOLOGY

The design of surge protection system is an iterative process in which a particular protection is proposed, waterhammer analysis is made for that choice for power failure condition, the resulting surge pressures are evaluated, the protection system is modified based on the evaluation and the process is repeated until an adequate and economical protection system is arrived at. Surge or waterhammer analysis is made for each option by numerical analysis in SAP using the method of characteristics. The analysis involves the solution of a system of two nonlinear, first order partial differential equations in two unknowns - piezometric head and flow velocity in two independent variables - distance along the pipe and time. The solution requires specification of initial condition at time t = 0 before the surge condition, and boundary conditions at external boundaries such as pumps and reservoir and internal boundaries such as air vessel and one way surge tank. The theory and computational methodology for solution by the method of characteristics are available in standard references (Wylie, E.B. and Streeter, V.L., Fluid Transients, McGraw Hill Intl. Book Co., 1978).

The design criteria for the surge protection system for a pumping main are stated in terms of limits on allowable downsurge and upsurge for the critical design condition of power failure. In a system with multiple pumps in parallel operation, the surge pressure following single pump tripping, can be locally high in the pump delivery pipe from the non-return valve upto the delivery manifold. However, surge protection system for the transmission main can not take care of the single pump tripping condition. The strength of the pipe and valves in the pump house should be adequate to withstand these local pressures.

The limits on allowable downsurge and upsurge in the transmission main may vary from system to system. Generally, if conservative design criterion is used, subatmospheric pressures are not allowed and the maximum pressure may be restricted to 1.25 to 1.5 times the pump head or working pressure. Alternately, one may allow subatmospheric pressures, but not vapour pressures. In some designs, vapour pressure may also be allowed, but limitations may be placed on the pressure rise following the rejoining of separated water columns. There are situations when the design of surge protection system is reduced to the art of selecting a feasible alternative, taking into consideration the pipe strength and different alternative design criteria. For example, the pipe line alignment and other hydraulic parameters may be such that complete elimination of subatmospheric pressures may be impossible or too costly. Hence specification of uniform design criteria for all projects may not be a desirable practice. It is necessary to consider the type of pipe, the pipe strength, the values of relevant hydraulic parameters, the possible operating conditions and the nature of the pipe line alignment, while deciding on the design criteria.

11. OPTIONS OF SURGE PROTECTION DEVICES

The software SAP provides options for choosing one or more of the following.
protection devices:

- Air vessel
- One way surge tank
- Zero velocity valve
- Dual plate check valve
- Intermediate non-return valve
- Air valve
- Air cushion valve
- Stand pipe
- Surge relief valve

These options cover practically all surge protection options available in the country at present. Where multiple number of the same device can be used, the software provides option for it. One limitation is deliberately included, namely, restriction of the total number of air valves and Air cushion valves to three only. This restriction is imposed as design of a surge protection system relying extensively on air valves for control of downsurge is not a desirable practice. Such a design may be permitted only in special circumstances based on a careful review of the pipe strength, pressure drop rates, nature of alignment and other hydraulic parameters. It is not desirable to permit such a design based on software intended for general use.

Another restriction imposed on the choice of protection devices is with regard to certain combination of protection devices. There are two such restrictions: a) A combination of air vessel and surge relief valve is not allowed as provision of surge relief valve with air vessel will significantly affect the efficacy of the air vessel. b) For upsurge control through spring loaded non-return valves located along the raising main, either Zero velocity valve or dual plate check valve may be used, but not a combination of both. This restriction is placed from practical considerations including cost factor, as there is no advantage in mixing both the types of valves in the same scheme. However, this restriction does not apply to the use of dual plate check valve within the pump house.

12. USE OF SAP OUTPUT FILES FOR DESIGN

The software SAP provides output files in text form as well as graphical plots. These output files are specifically planned to help in the design process, keeping in view the twin objectives of any engineering design, namely reliability and economy.

The basic output file is SAP.RES. Here, the system data is provided along with summary of results relating to the pumps, and minimum and maximum piezometric heads at the locations specified by the user. Instead of the exact chainage, results are available at the nearest nodal chainage as per the discretisation of the pipe. The difference between these two chainages are very small and not of significance. In addition to these basic results, SAP.RES provides specific results concerning the following details where relevant: a) details at water column separation location (b) details at an air vessel (c) details at a one way surge tank (d) details at a surge relief valve. In planning the details to be printed, their utility in design is kept in view. For example, for air vessel, the maximum expanded air volume in the air vessel which is necessary for deciding the size of the air vessel is made available. For one way surge tank, the extent of draining of the tank or in case of full draining, the time of draining, are made available to decide the size of the tank. As the cost of a one way surge tank depends critically on the connecting pipe size, the maximum velocity through the connecting pipe is made available to facilitate the design of the pipe size. Similarly, in regard to surge relief valve, the output is intended to help in setting the low and high pressure pilots and the closure time besides the choice of valve size.

The second output file in text form is TABLE.RES. In this file, a summary of results for minimum and maximum flows, minimum and maximum heads and associated times of occurrence is provided in a non-dimensional form. These results are intended for users interested in understanding the details of the surge process and some experience is required to use these results as a learning tool.

SAP provides results through several graphical output plots, each obtained through a single short cut key, as explained in Section 11 of the User Manual. Among these graphical plots, the basic one is the plot of minimum and maximum piezometric heads along with longitudinal alignment of the pipeline and HGL (as in Fig. 3). These basic plot files form the locomotive driving the design process.

Another important graphical plot is the plot of pressure with time for the first several seconds following power failure, at three identified locations along the rising main. By repeating the analysis varying these three locations in data input, the pressure drop rate may be reviewed at all desired locations. These pressure drop rate plots are particularly useful in determining the reliability of air valves and Air cushion valves as vacuum breaker at the proposed locations.

A graphical plot is also available for the variation of pump speed with time until the pump house non-return valve is fully closed and the pump gets isolated from the transmission main. This plot is essentially intended to review the acceptability of the magnitude of reverse rotation for cases where the non-return valve closure is made gradual with external damping.

Besides the above plots for all cases of analysis, supplementary graphical plots are available for the design of air vessel or one way surge tank. These are plots of variation of velocity in the connecting pipe between the air vessel or one way surge tank and the transmission main. These plots help in deciding the size of the connecting pipe. They are particularly useful for the design of one way surge tank, as the cost of a one way surge tank protection system is significantly influenced by the decision on the size of the connecting pipe and associated valves in the connecting pipe.

13. GUIDELINES FOR AIR VESSEL DESIGN

13.1 Description of air vessel

Air vessel (or air chamber as it is sometimes referred) is a pressure vessel fabricated of steel, containing water in the lower part of the vessel and compressed air at working pressure in the upper part of the vessel. The relative proportion of water and compressed air is a design variable. The air vessel as a surge protection device is invariably located very near the pump house, and the vessel is connected to the transmission main by a connecting pipe downstream of the manifold at a convenient location.

There are two types of connecting pipe system possible for the air vessel and based on this, the designs are catagorised as Type 1 or Type 2 design as shown in Fig.8 (It is desirable to install the air vessel at a slight inclination of 2^o to 3^o, instead of horizontal as shown in Fig.8). In Type 1 design, a rounded orifice is installed in the connecting pipe, in such a way that the head loss for inflow into the air vessel is much larger than for outflow from the air vessel. This is intended to achieve some control on the upsurge without significant deterioration in the downsurge. In the Type 2 design, a non-return valve is provided in the connecting pipe, with a bypass of smaller size for allowing inflow into the air vessel. This design provides for an independent two-way control for inflow and outflow, but at the additional cost of a non-return valve. The software SAP handles both the design options.

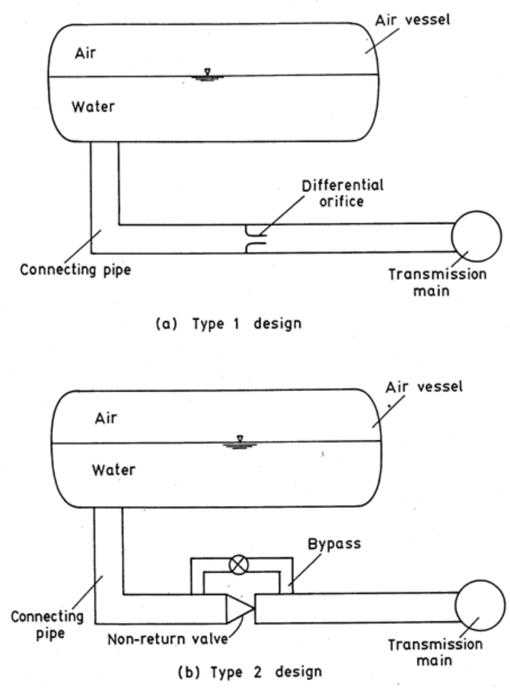


Fig. 8 Schematic Diagram of Alternate Types of Design for Air Vessel

The function of the air vessel is as follows. When power fails, the pump head reduces rapidly, while the pressure in the air vessel reduces much more gradually, accompanied by expansion of air. As a result, the non-return valve located just upstream of the air vessel or on the delivery pipes of pumps closes. Now water is supplied to the transmission main from the air vessel, at a gradually diminishing rate, as the air expands. Essentially, the compressed air functions as a stored energy, cushioning the rate of velocity reduction in the transmission main, and hence controlling the surge pressures. As the air expands, the forward flow velocity reduces, and soon flow reversal takes place. Now water enters the air vessel, compressing the air. This process wherein the variation in pressure is related to the expansion and compression of air in the air vessel, cushions the surge pressures in the transmission main very significantly.

13.2 Suitability as surge protection

Air vessel is a comprehensive surge protection device which can control both downsurge and upsurge. In theory, air vessel can be designed to control surge pressures within specified limits in any pumping main. But, in practice, the vessel size may turn out to be too large in some cases, and alternate protection systems may prove to be more economical.

The control of downsurge is essentially achieved by providing the required size of the air vessel with associated compressed air volume under working conditions. The control of upsurge can be done, to an extent, by providing a differential orifice as in Type 1 vessel (Fig. 8a), or by providing a small size bypass as in Type 2 vessel (Fig. 8b). In systems where air vessel design involves balancing the requirements of upsurge and downsurge control, consideration of both Type 1 and Type 2 vessels may be appropriate. If control of downsurge requires a size of air vessel for which upsurge gets automatically controlled, or if the upsurge is not severe due to the relatively large frictional loss in the system, the design may consider only Type 1 air vessel. Where Type 2 air vessel is considered, before making the final design decision, it must be verified whether the saving due to the reduction in air vessel size (compared to Type 1 design), is nullified by the additional cost of the non-return valve on the connecting pipe.

In practice, if the pumping main is heavily friction dominated system ($HF_o > 0.5$), air vessel is likely to turn out to be a costly protection system, and alternative protections may be more suitable. In fact, cost is the single major limiting factor in deciding an air vessel protection. Air vessel may not also be a convenient protection where the operating conditions may vary widely (ex: a network).

13.3 Design Variables

It was stated in Section 10 that design of surge protection system is an iterative process, where a protection system is assumed, surge analysis done, and based on a review of the surge picture, the protection system is modified in the next iteration for further analysis. This procedure suggests that if an air vessel is to be designed, first a size of air vessel may be assumed, surge analysis done and based on a review of the results, the vessel size may be increased or decreased for the next analysis. This procedure is not strictly correct for air vessel design. What is first assumed is the value of a non-dimensional size parameter for the air vessel, instead of the actual size of the air vessel. Repeated analysis is done with different values of the size parameter and when the design is satisfactory, the volume of the vessel is determined based on the results of surge analysis. The size parameter of the air vessel, KAV is defined by,

$$KAV = \frac{2C_o a}{Q_o L} \tag{3}$$

where C_o = air volume under working condition, Q_o = design discharge, L = length of the transmission main, and a = pressure wave velocity.

The design variables for the air vessel are as follows:

a) Type of air vessel (Type 1 or Type 2)

b) Size parameter of the air vessel, KAV

c) Connecting pipe size

d) For Type 1 vessel, orifice size

For Type 2 vessel, bypass size

e) Whether a non-return valve is provided on the transmission main.

The last item is taken up first for discussion. The software SAP provides for analysis with air vessel, with/without a non-return valve located on the transmission main just upstream of the air vessel. This non-return valve is a transmission main non-return valve, as distinct from the non-return valves in the delivery pipes from individual pumps inside the pump house. This is an optional valve (Fig. 9) to be provided or not as per the designer's choice. If this main line non-return valve is not provided, the air vessel function depends on

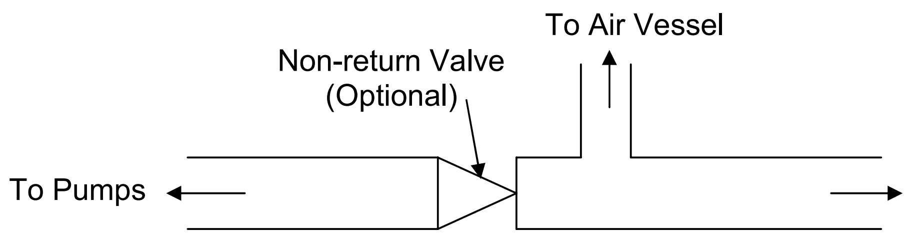


Fig. 9 Schematic Diagram of Pipeline System at Air Vessel

the proper closure of all the non-return valves in the pump house on individual pump delivery pipes. If the number of working pumps is large, the air vessel function becomes dependent on proper function of several non-return valves. On the other hand, if there are only two working pumps, a main line non-return valve upstream of the air vessel may not be necessary. Another factor which may be relevant in the decision to provide (or not to provide) main line non-return valve is the type of non-return valves used inside the pump house. If they are slow closing type with external dash pot arrangement, some water from the air vessel may flow back to the sump following power failure, reducing the efficiency of the air vessel to some extent. A third and important factor in the decision to provide transmission main non-return valve, is the size of the non-return valve and its cost. If it is decided to provide transmission main non-return valve upstream of the air vessel, multi door swing check valve and dual plate check valve are suitable types, as they close rapidly minimising reverse flow from the air vessel to the pump.

The factors governing the choice between Type 1 and Type 2 air vessels was discussed in Section 13.2. In the writer's experience, for most schemes as prevalent in India, Type 1 air vessel is found to be the appropriate choice. In Type 1 air vessel, the utility of the orifice is in controlling the upsurge. If the size of the orifice is reduced, downsurge may deteriorate, particularly in the downstream half of the alignment. If upsurge is not a problem (due to dominant friction effects in the pumping main), the orifice need not be provided (In SAP data, for the case of no orifice, orifice size is to be given the same as the connecting pipe size). In deciding the orifice size, the maximum velocity through the orifice is to be considered. The SAP output file provides this value. The allowable maximum velocity will depend on the pump head, with the allowable velocity being less for smaller pump head and more for larger pump head. The normal range of maximum allowable orifice velocity is 12 to 20 m/sec. It is clearly desirable not to allow the maximum velocity through the orifice to exceed 20 m/sec in any case.

The size of the connecting pipe between the air vessel and transmission main is essentially based on cost consideration, along with maximum velocity through the pipe. The output file of SAP provides the maximum velocity through the connecting pipe. A graphical plot option is also available which gives the variation of velocity through the connecting pipe with time for the first cycle of outflow from and inflow into the air vessel. If Type 2 air vessel is used, the negative or reverse flow velocity corresponds to the velocity through the bypass pipe. The bypass pipe for Type 2 vessel is based on upsurge consideration. As the bypass size is reduced, upsurge will improve. The normal velocity through the connecting pipe may be in the range of 3 to 5 m/sec. If the maximum velocity exceeds 5 m/sec, it may still be accepted if the plot of velocity with time in the connecting pipe shows that such high velocity occurs for a very short duration (about 1 sec).

The last, but the most important design variable to be considered is the air vessel size parameter, KAV (Eq.3). The usual range of KAV is 1 to 10. An air vessel with KAV value of 1 to 2 refers to a relatively small size air vessel. An air vessel with KAV value of 2 to 4 refers to a relatively moderate size air vessel. An air vessel with KAV value in excess of 4 refers to a relatively large size air vessel. The key word in the above statements, is "relative". The absolute size of the air vessel can not be compared from project to project, as it will vary widely depending on the scale of the project. If the design works out such that KAV < 1, the implied conclusion is air vessel is not necessary. If the required value of KAV is found to be more than 10, the implied conclusion is that air vessel protection is too costly and unsuitable. The most suitable range of KAV for good designs is 1.25 to 4.0.

13.4 Design procedure

The design procedure is explained for Type 1 air vessel, but the approach is similar for Type 2 air vessel. The connecting pipe size is decided based on velocity considerations as discussed in Section 13.3, with maximum velocity in the range of 3 to 5 m/sec. Now, the parameters to be varied are the air vessel size parameter, KAV and the size of the orifice in the connecting pipe. First, the orifice size may be either fixed based on nominal velocity considerations (say, for a velocity of 10 m/sec through the orifice), or the orifice may even be eliminated (In SAP, this is done by specifying orifice size the same as connecting pipe size). The value of KAV may be varied and the surge picture reviewed for several cases, with focus on the downsurge picture (In SAP, the graphical plots, ctrl+g or ctrl+h provide the suitable plots for the review). Based on a review for a number of KAV values, the suitable value of KAV from downsurge angle may be decided. Now the focus is shifted to upsurge also. If the maximum pressure is found to be more than specified limit, the orifice size may be decreased, keeping the maximum velocity within the limits specified in Section 13.3. As the orifice size is decreased, the upsurge picture will improve, but the downsurge picture may deteriorate. By keeping a watch on both upsurge and downsurge, the KAV value and orifice size are both find tuned. Once KAV value and orifice size are decided, one may proceed to determine the size of the air vessel, as explained in the following sections.

13.4.1 Water level control band in air vessel

The water level in the air vessel decides the relative volume of compressed air and water in the air vessel. From practical considerations, it is clear that the water level can not be maintained at a single unique level, but may vary over a small range. This range is to be decided in the design, with the upper most level in the range referred as upper emergency level (UEL), and the lower most level in the range referred as lower emergency level (LEL), vide Fig. 10. Within this band, there may be intermediate control levels. Depending on the scale of the project and size of the air vessel, there may be, in all, three or five control levels. Further discussion is restricted to the case where there are five control levels, that is four small bands between UEL and LEL. The provision of volume for these bands is a matter of judgement by the designer. For horizontal orientation of the air vessel, a volume corresponding to 20 to 30 mm band may be allowed between two control levels. For vertical orientation of the air vessel, a volume corresponding to 60 to 90 mm band may be allowed between two control levels.

13.4.2 Size of the air vessel

The KAV value finalised as discussed in Section 13.4 can be used to calculate the C_o value (that is, compressed air volume) from Eq. 3. In fact, the output file of SAP gives this volume under "Details regarding air vessel". This value of C_o (air volume under working condition) corresponds to the UEL, as this is the minimum value of compressed air required for surge protection as per the design. The maximum expanded air volume in the output, multiplied by a suitable factor (1.2 to 1.25), gives the approximate size of the air vessel. Based on this approximate size, the total control band volume is fixed, using the criteria for the height of the bands as given in Section 13.4.1. By adding the control band volume to C_o (UEL) value, C_o (LEL) value is obtained. From Eq. 3, the KAV value corresponding to LEL can now be calculated. Surge analysis is now done with this KAV value. The maximum air volume under surge obtained from this analysis is used to finalise the volume of the air vessel.

The maximum air volume under surge obtained from analysis for KAV at LEL is the absolute minimum volume of the air vessel, to avoid the loss of compressed air. However, some margin over this volume is to be provided, to ensure trouble-free performance. This margin may vary from 10% to 20%. Hence, if C_{max} is the maximum air volume under surge for KAV value corresponding to LEL, the air vessel volume is fixed as,

$$\text{Air vessel volume} = K \times C_{max}$$

where K = 1.1 to 1.2. The choice of K in this range is a matter of judgement by the designer. In general, K may be chosen larger if the air vessel design is such that (C_{max}/C_o) is large. If (C_{max}/C_o) is 4.0 or more, K = 1.2 is desirable. For $(C_{max}/C_o) < 2$, K value towards the lower limit of 1.1 may be considered.

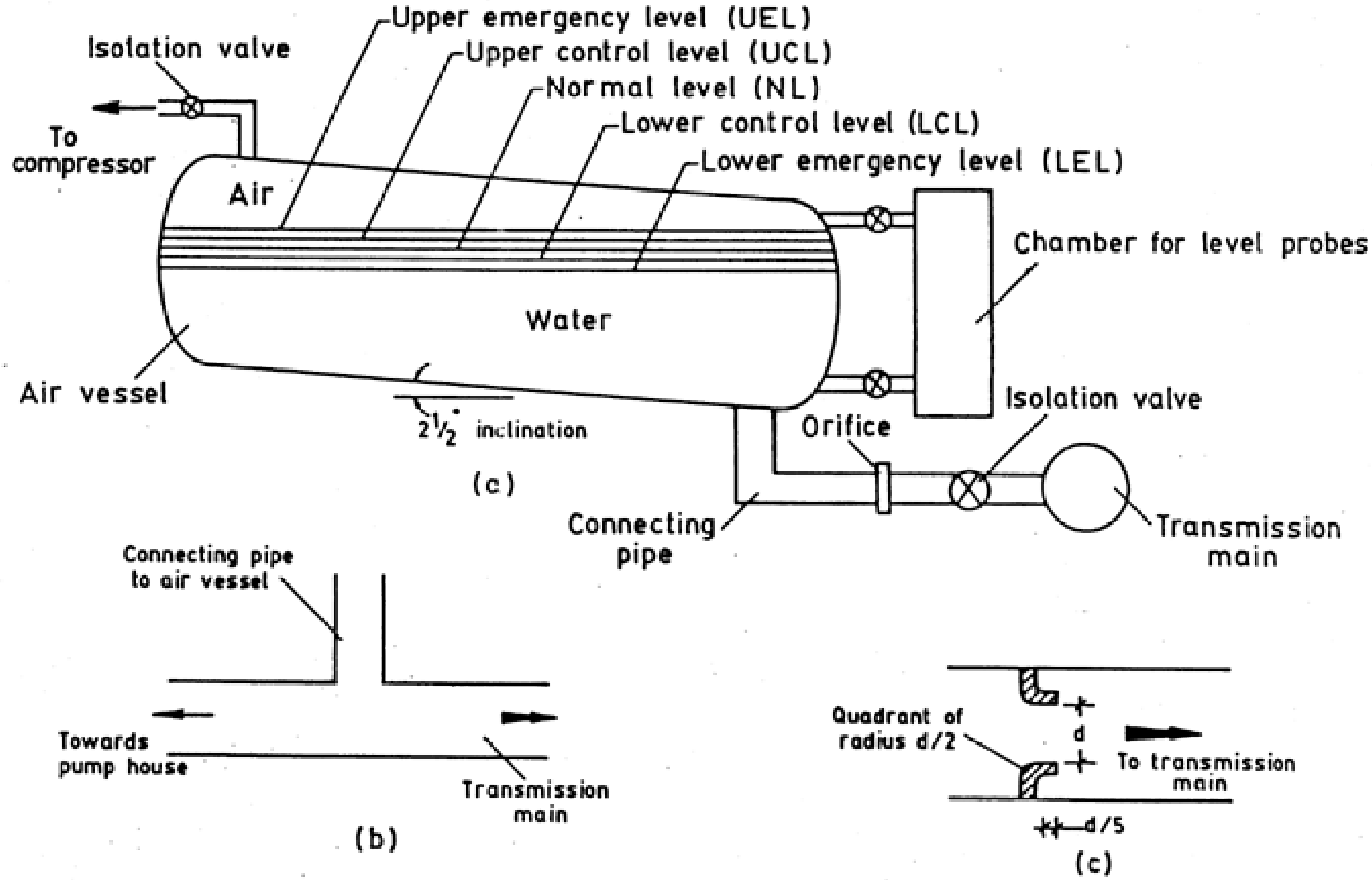


Fig. 10 Schematic Diagram of Air Vessel Installation

The air vessel volume decided based on the above procedure ensures: a) There is adequate compressed air volume in the air vessel to control the surge pressures within specified limits; b) There is adequate water in the air vessel so as to prevent the break of water seal in the air vessel at the instant of maximum expansion of air during surge following power failure. This ensures that when the pumps are restarted, the water level in the air vessel comes to the normal level, without any replenishment of compressed air.

13.4.3 Number of air vessels

The volume of air vessel calculated based on the procedure explained in Section 13.4.2 can be provided in one or more vessels. Obviously, provision of the total volume in one vessel is the most economical option. However, if the volume of air vessel calculated is very large, one vessel may turn out to be impractical. The difficulties arise from transportation of the vessel (long length and large diameter of the vessel) and the need for the use of very thick steel plate for fabrication (large diameter of the vessel). Normally, for a vessel diameter of 3 m, a maximum vessel volume of 90 to 100 m^3 may be acceptable, while for a vessel diameter of 4 m, a maximum vessel volume of 160 to 170 m^3 may be acceptable. If the required volume cannot be provided with one vessel, multiple number of vessels may be used.

13.5 Installation of air vessel

The air vessel is to be installed at a convenient location near the pump house, connecting it downstream of the manifold. The air vessel may be installed vertically or near horizontally. Instead of strict horizontal orientation, a slight inclination of 2° to 3° is preferable. Fig. 10 presents a schematic diagram showing three options for air vessel orientation. In option (a) where the air vessel is located directly over the pumping main, it must be ensured that the load of the air vessel is not transmitted to the pumping main. Normally vertical orientation may be preferred only for small size air vessels. If the air vessel size is moderate to large, near horizontal orientation is preferable.

The non-return valve on the transmission main upstream of the air vessel, shown in Figs. 9 and 11a, is an optional valve as decided by the designer. The pros and cons of providing or not providing this valve are discussed in Section 13.3.

Fig. 10 presents a schematic diagram of an air vessel oriented near horizontally. The figure also shows the five level control scheme and the shape of the differential orifice.

13.6 Accessories for air vessel

As mentioned in Section 13.4.1, the water level in the air vessel is to be maintained between the two extreme levels - UEL and LEL in Fig. 10. The water level variation in the air vessel may occur due to small leakages of compressed air from the vessel and pneumatic

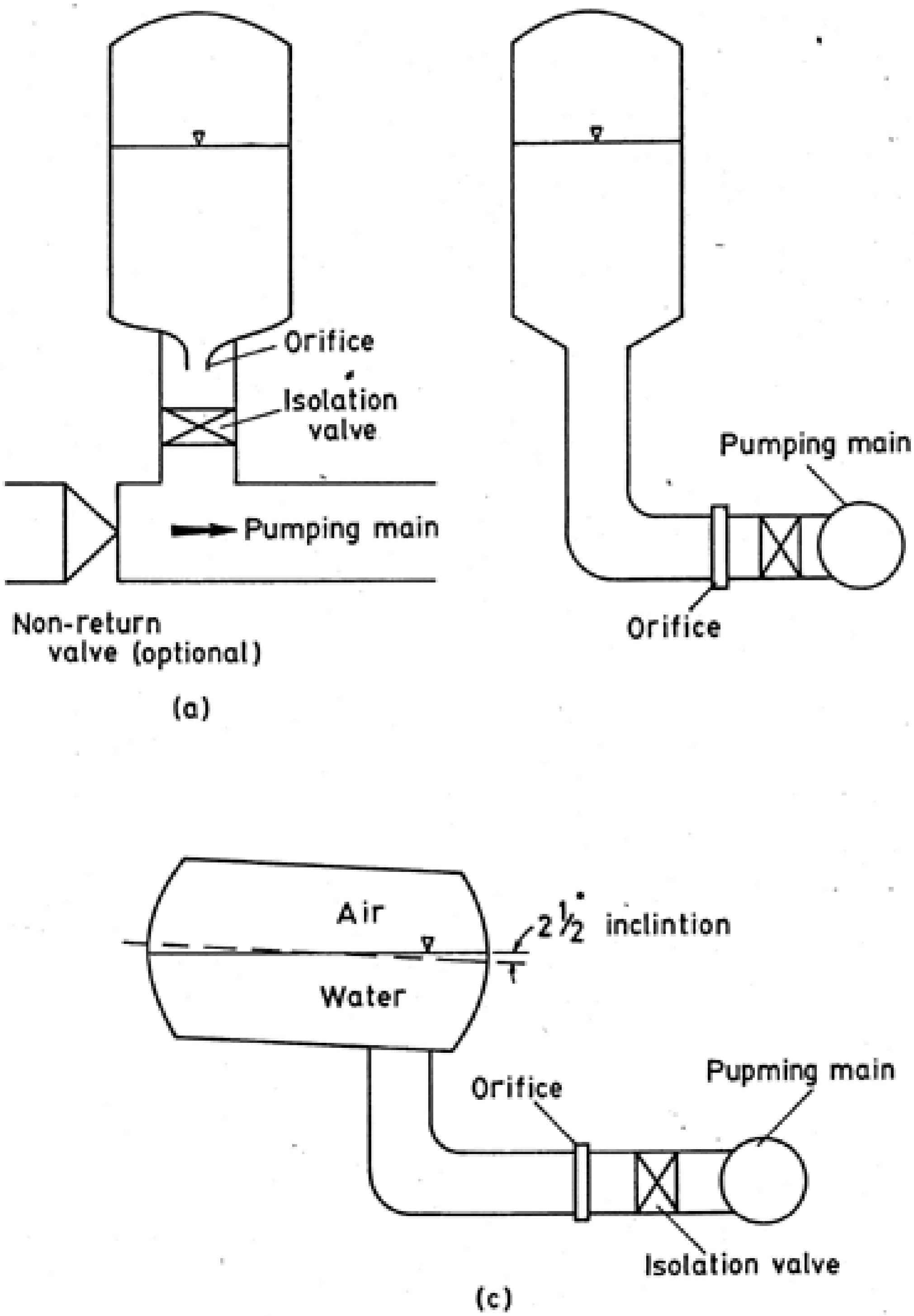


Fig. 11 Schematic Diagram of Options for Air Vessel Orientation

plumbing, dissolution of air in the water, and also due to air volume change associated with temperature variations. It is thus necessary to replenish small quantities of compressed air periodically, when the water level crosses the upper control level (Fig. 10). For this, and also for initial charging of the air vessel (or for recharging the air vessel after a maintenance shut down), a compressor is required as an accessory. The designer has to decide whether one compressor is adequate or whether a standby compressor is necessary. During normal operation, the compressor may have to work only for a few minutes (less than 30 minutes) a day.

Fig.12 presents a schematic diagram of the compressor, pneumatic plumbing and the air vessel. In the figure, two compressors (1 working + 1 standby) are shown. The air receiver is a small cushion storage of compressed air. In small projects, the storage tank integral to the compressor may itself be adequate and the additional air receiver may not be required. The pneumatic plumbing size may vary from 15 mm for small projects to 40 mm for very large projects. The designer has to decide whether the water level control system will be fully operated manually or whether an automatic level control system with necessary instrumentation and solenoid valves are to be provided. In most situations, manual control option may be adequate.

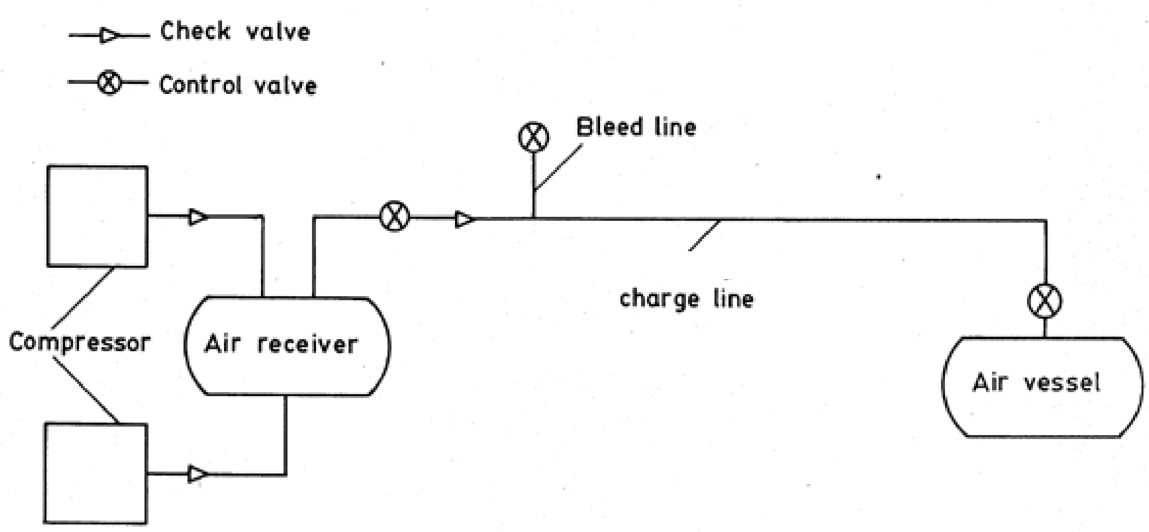


Fig. 12 Schematic Diagram of Pneumatic Plumbing for Air Vessel

The designer has to decide the flow and pressure rating of the compressor. These decisions are not based on surge analysis. The pressure rating of the compressor must have a margin over the maximum pressure in the transmission main at the air vessel. For this, the likely lowest elevation of the air vessel during installation, and the maximum piezometric head at the location of the air vessel based on maximum water level in the sump plus pump head, are to be considered. The flow rating of the compressor is to be decided based on the time that maybe allowed for charging the air vessel for initial commissioning (or re-commissioning after maintenance shut down). For this purpose, if a standby compressor is provided, the combined flow capacity of both compressors should be considered, as during initial commissioning, both the compressors may be used together. The requirement of compressed air delivery per minute must be converted to free air delivery per minute based on the system pressure.

13.7 Specifications for air vessel

The principal technical specifications for the air vessel are obtained from surge analysis. The specifications for accessories may be finalised as discussed in Section 13.6. For the design, fabrication, inspection and testing of the air vessel, the required codal and other specifications are to be provided. The design, fabrication, inspection, testing and installation of the air vessel are to be done as per IS 2825 - Code for Unfired Pressure Vessels. The designer has to decide whether he will use Class 1 or Class 2 vessel as per the code. The principal differences between Class 1 and Class 2 vessels are: a) Weld joint efficiency factor is 1.0 for Class 1 vessel and 0.85 for Class 2 vessel; b) Class 1 vessel is fully radiographed, while Class 2 vessel requires spot or check radiographic examination of welded joints for atleast 10% of the whole length.

The writer prefers to specify a minimum corrosion thickness of 1.5 mm, besides a minimum thickness for the shell based on the vessel diameter. Also, if there is indication of vapour pressure occurrence under surge near the pump house for the no surge protection case, the writer recommends that stiffening rings may be provided for the air vessel to withstand external pressure corresponding to full vacuum. This precaution is desirable to deal with the contingency situation where the maintenance of water level control system is ignored for a long period and the vessel gets fully filled up with water.

The designer has to decide the design pressure for the air vessel. This has to be decided keeping in view: a) maximum pressure under surge condition; b) design pressure for the pipe; c) test pressure for the pipe, and d) shut-off pressure of the pump.

Another decision to be made by the designer is the pressure rating of the non-return valve on the transmission main (if it is provided), and the pressure rating of the non-return valves and butterfly/sluice valves in the pump house. When a non-return valve is provided on the transmission main just upstream of the air vessel, there will a local pressure rise at the valve when it closes. If the closure occurs with some delay, allowing some reverse flow, this pressure rise may be more. This high pressure will be very local and will not affect the pressure at the air vessel connection and further in the transmission main. In order to estimate this pressure, the following procedure is suggested while using SAP: a) Finalise all the design details of air vessel; b) Now, in the air vessel data, choose the negative option for the check box "Is NRV provided on the raising main"; c) For the pump house non-return valve, choose swing check valve (code 1 type closure) with 0.5 or 1 sec delay; d) For analysis, choose the power failure option; e) The maximum pressure obtained at the start chainage (pump house) now gives the maximum pressure likely at the transmission main non-return valve upstream of the air vessel. From these results, the pressure rating of the valve can be finalized.

If the transmission main non-return valve proposed is of a smaller size than the transmission main, in the above procedure, the data for size of the pump delivery pipe should be given such that the combined area of cross section for the number of working pumps equals the area of cross section corresponding to transmission main non-return valve size. With this adaptation, surge analysis is to be done for "all pumps failure" option. As before, swing check valve (code 1 type closure) should be chosen, with 0.5/1 sec delay in closure. The maximum pressure obtained at the start chainage (pump house) gives the maximum pressure likely at the transmission main non-return valve, which is of reduced size.

If the transmission main non-return valve is not provided (as decided by the designer), analysis may be done for both power failure and single pump failure to determine the maximum pressure at the pump house non-return valves. For power failure analysis the "all pumps failure" option should be chosen. For the data for pump house delivery pipe size, actual size of delivery pipe is to be provided (unlike in the adaptation explained in the previous paragraph).

One final comment regarding analysis for the air vessel case is in order. If the option of providing non-return valve on the raising main is chosen, some locally high maximum pressure and low minimum pressure may be indicated by the results of the analysis, depending on the choice of the type of pump house non-return valve and its closure pattern. Once the non-return valve on the transmission main upstream of the air vessel is closed, the small length of the pipe from pumps to this closed non-return valve will have rapid oscillations of pressure (high and low) due to the very small travel time of pressure wave for this small length. The associated maximum and minimum pressures may not have much practical value. For the same reason, in SAP.RES output file, the output for details regarding pumps and speed vs time plot (ctrl +s option of graphical plot) may be difficult to interpret. It is suggested that these possibly confusing signals from the results may be ignored when the option of providing non-return valve on the rising main is chosen.

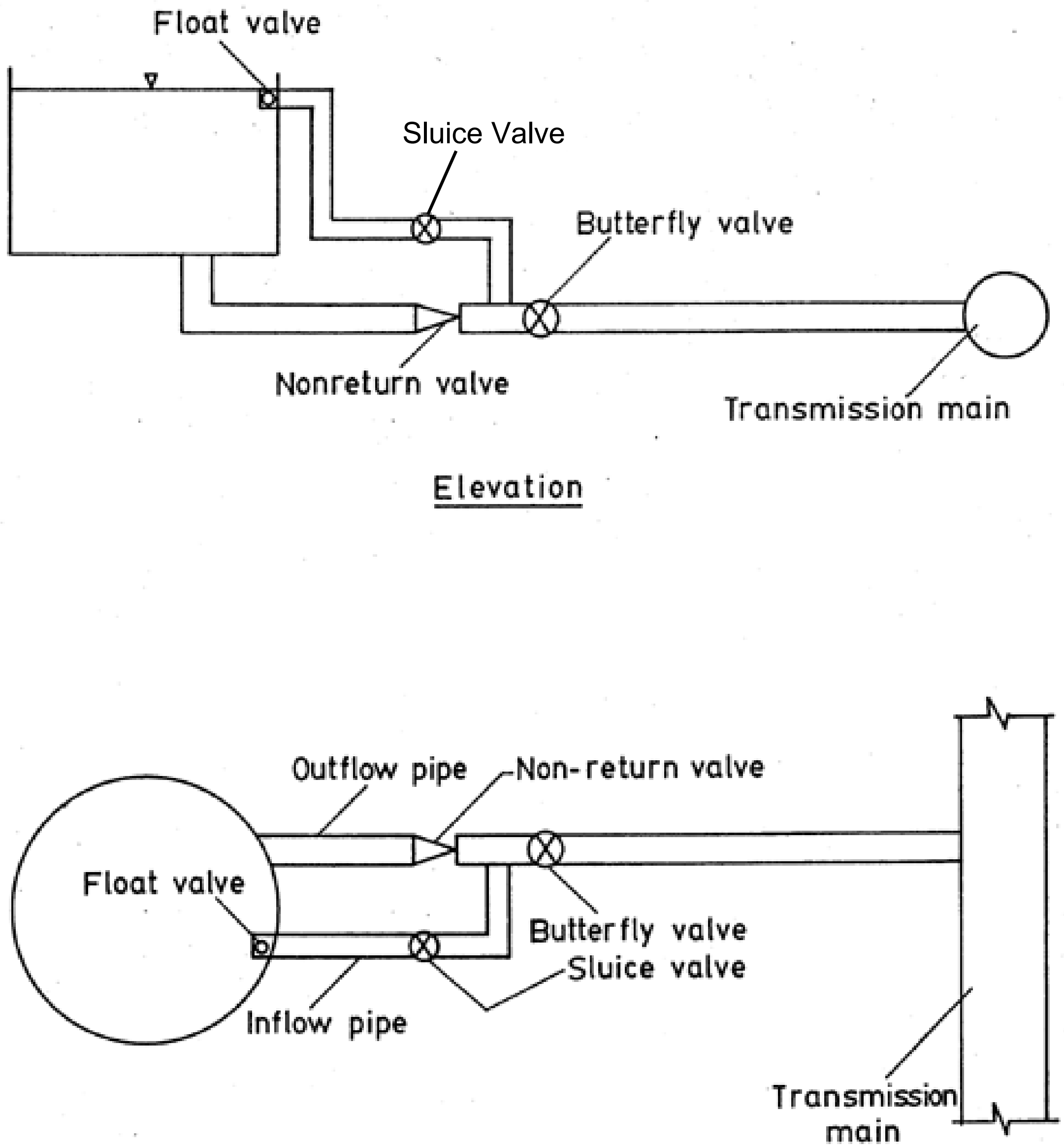
14. GUIDELINES FOR ONE WAY SURGE TANK DESIGN

14.1 Description of one way surge tank

The one way surge tank is a surge protection device which controls the downsurge directly, and the upsurge gets controlled indirectly as a result. The one way surge tank is also referred as feed tank or discharge tank. It is an RCC tank usually located at relatively elevated points along the alignment. The one way surge tank may be a ground level tank or an elevated tank with a staging height. The tank may get drained partly or wholly following power failure and has to be refilled on the starting of pumps. The refilling can be done with a filling line with float valve arrangement as shown in Fig. 13. Alternately, the refilling can be done with a bypass filling pipe with the valve on the pipe opened manually for refilling, on starting of pumps. This arrangement, shown in Fig.14, is convenient when the one way surge tank is located near the pump house. Fig. 15 shows the schematic diagram of an elevated one way surge tank with bypass filling arrangement. In Figs. 13 to 15, the over flow pipe and scour pipe are not shown, but these are to be provided as per standard practice.

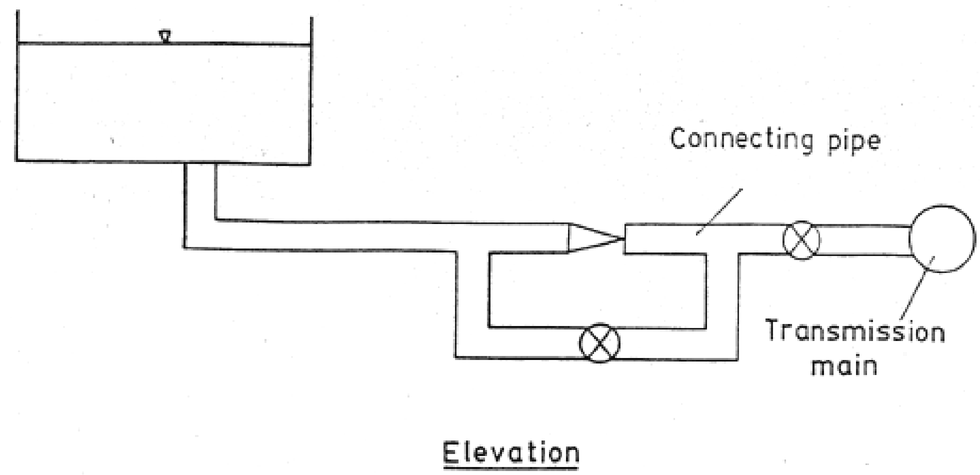
The one way surge tank is designed such that the water level in the tank is well below the hydraulic grade line elevation at the location. It is because of this that a non-return valve has to be located on the connecting pipe between the one way surge tank and the transmission main (Figs. 13 to 15). The non-return valve allows only outflow from the one way surge tank and prevents inflow and it is because of this, the device is referred as one way surge tank. It must be noted that the valve on the filling line will be closed during normal working condition.

Following power failure, when the pressure in the transmission main drops below the water level in the tank, the non-return valve on the connecting pipe opens, and water flows out of the tank moderating further pressure drop in the transmission main. If, due to upsurge later, a pressure rise occurs, the non-return valve closes preventing inflow into the one way surge tank. If the control of downsurge is effective, occurrence of water column separation and associated pressure rise may be prevented.



Note: The filling pipe line with float valves are
shown with lateral displacement for clarity

Fig. 13: Schematic Diagram of One Way Surge Tank Float Valve Filling Arrangement



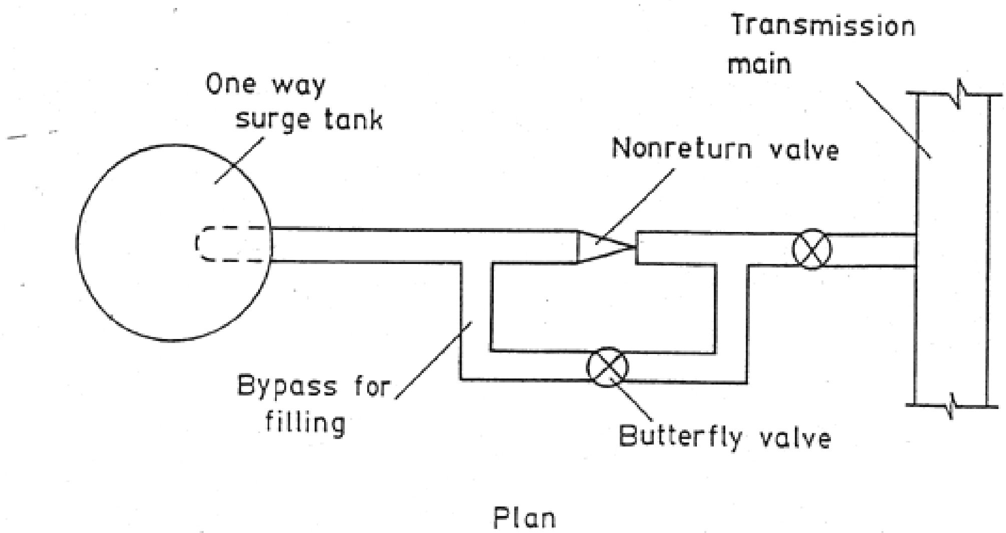


Fig. 14 Schematic Diagram of One Way Surge Tank Bypass Filling Arrangement

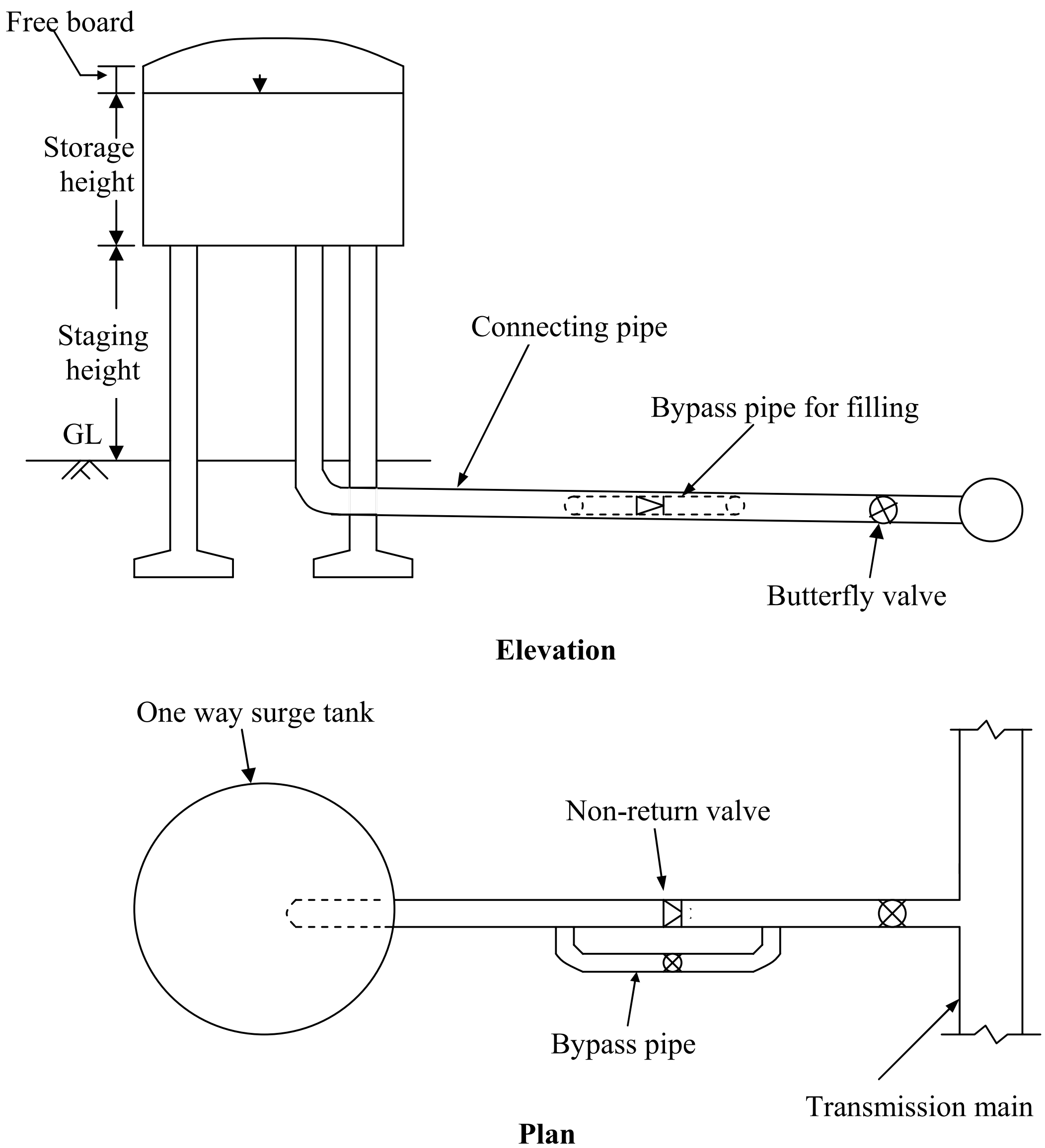


Fig. 15 Schematic Diagram of Elevated One Way Surge Tank With Bypass Filling Arrangement

The shape of the one way surge tank is not important. A circular RCC tank as shown in Figs. 13 to 15 is a convenient design.

14.2 Suitability as surge protection

The suitability of one way surge tank as surge protection device depends critically on the nature of the longitudinal alignment. If the alignment is such that relatively elevated locations are available in the upstream reaches, one way surge tank may turn out to be an economical protection option. Generally, one way surge tank may form the sole or principal protection system only in schemes with low or moderate pump head. In schemes with high pump head, it may form a local protection device, if exceptionally elevated local peaks occur along the alignment.

If the transmission main alignment and hydraulic parameters of the system are such that a one way surge tank near the pump house is found to be effective, the option becomes particularly advantageous. The reasons for this are as follows: a) An installation near the pump house avoids land acquisition problems; b) The installation is more secure within the compound of the pump house area; c)The bypass filling arrangement can be used instead of float valve filling arrangement, as the pump house staff can refill the tank on restarting the pumps; d) There will be no refilling problem due to availability of adequate pressure near the pump house. However, if a one way surge tank protection near the pump house is to be effective, very often it may have to be on elevated tank (Fig. 15). The option of one way surge tank near the pump house is unlikely to be suitable, if the static lift with respect to the delivery pipe elevation is high.

It is possible that a one way surge tank protection system may comprise of more than one tank. In the writer's opinion, one way surge tank protection option with more than two one way surge tanks is unlikely to be economical. Besides, there may be problems of refilling the tanks at elevated locations far downstream along the alignment, due to very low working pressure at such locations. The refilling difficulty due to inadequate working pressure is one problem of one way surge tank located in low pressure reaches.

In considering one way surge tank as a protection option, the designer must be aware that the cost of the protection system comprises of two principal components: (a) cost of construction of the tank; (b) cost of the connecting pipe system with valves. In many cases, it is likely that the cost of piping with valves will considerably exceed the cost of the tank.

14.3 Design variables

The design variables for one way surge tank protection system are as follows:

a) Number of one way surge tanks

b) Location of one way surge tanks

c) Staging height of each tank

d) Diameter of each tank

e) Storage depth of each tank

f) Connecting pipe size for each tank.

14.4 Design procedure

Based on a review of the longitudinal alignment of the transmission main and the hydraulic grade line along the alignment, a few tentative locations of the one way surge tank may be identified. In this exercise, the profile of the minimum piezometric bead for the no protection case also forms an important input. The locations that may be considered are relatively elevated locations along the alignment and where severe vacuum is indicated in the absence of any surge protection. It may be verified that there is adequate working pressure at the location for refilling the tank on start of pumps after power failure. It may also be verified that the working pressure at the location is not too large, as otherwise there will be constant leakage from the float valve. This restriction will not apply for a one way surge tank located near the pump house, as bypass filling arrangement may be used in this case. Based on all these considerations, possible tentative locations for the one way surge tanks may be identified.

Analysis may proceed in stages after tentatively fixing the number of tanks and their locations. As stated earlier, a design which has more than two one way surge tanks may not be economical. Once the locations are fixed, first the requirement of staging, and if required its height, may be determined approximately. For this, initially a tank of very large diameter and a relatively large connecting pipe size may be assumed. The storage depth in the tank is normally fixed in the range of 2 to 3 m. The analysis may be done starting from a ground level one way surge tank (staging height of 0), increasing the staging height as required based on a review of surge picture as revealed by the plot of minimum and maximum piezometric heads following power failure (ctrl + g graphical plot).

Once the staging height is finalised, the tank size may be determined from a series of computations. For this, the diameter of the tank may be varied, analysis repeated and the size finalized so that the one way surge tank is not fully drained, leaving a small height of water in the tank. For this purpose, the details regarding one way surge tanks available in SAP.RES may be used. The output gives the extent of draining of the tank, which should be normally be less than the storage depth. There are some situations where the water level in the one way surge tank is higher than the delivery level at the downstream reservoir. In such situations, the one way surge tank will drain fully and in such cases, the size of the tank should be finalized based on the time of complete draining, which is also provided in SAP.RES. This time should be reasonably large in terms of wave travel time over the transmission main, L/a (L= length of the transmission main, a = pressure wave velocity). When the one way surge tank fully drains, SAP.RES gives the extent of draining which will be larger than the storage depth. This "spurious" result is helpful in deciding the design change for the next output, just like the minimum pressure less than -10 m in the plot of minimum piezometric head profile.

Once the one way surge tank diameter is tentatively finalised, attention may be focused on the connecting pipe size. As the cost of piping with valves usually forms a very significant part of the total cost of the one way surge tank protection system, the choice of connecting pipe size is an important factor. For deciding the connecting pipe size, the maximum velocity in the connecting pipe, which is provided in the output file SAP.RES, may be used. Besides (ctrl + a) to (ctrl + d) graphical plots provide the variation of velocity in the connecting pipe with time, which form a very useful output in fine tuning the connecting pipe size. The maximum velocity in the connecting pipe may normally be in the range of 4 to 5 m/sec.

The procedure as described above provides tentative decisions for all the design variables. From this stage, several surge analysis may have to be done for fine tuning all aspects of the design. Surge analysis may have to be done for several cases at this stage changing one or more variables in each analysis, based on a review of the results.

15. GUIDELINES FOR DESIGN OF SURGE CONTROL VALVES - REFLUX VALVES

15.1 Description of the devices

In this section, three types of reflux valves are considered for surge control: a) Zero velocity valves; b) dual plate check valves; c) swing check valves. These valves are located at intermediate locations along the alignment (as distinct from the non-return valves inside the pump house).

The zero velocity valve is a spring loaded non-return valve with compression springs mounted behind the disc. For large size valves, there will be several springs to ensure reliability of operation. The valve closure occurs gradually with the reduction in velocity following power failure, reaching full closure at zero velocity. The Zero velocity valve is invariably provided with a bypass which allows a small amount of reverse flow.

The dual plate check valve is also a spring loaded non-return valve with torsion springs instead of compression springs as in the case of Zero velocity valve. There are two semi-circular discs and the springs are mounted behind the disc on a vertical shaft. Except for small size valves, there are two separate springs, one for each disc. The forward flow beyond a specified velocity keeps the two discs full open, and as the velocity reduces following power failure, the discs close with the reduction in velocity. Dual plate check valves being short length valves (wafer designs are common), are normally not provided with bypass. However, if dual plate check valves are used as intermediate non-return valves along the alignment, it is clearly desirable to provide a bypass in the pipe around the valve.

Swing check valves are sometimes provided at intermediate locations along the alignment. Swing check valves mayor may not be provided with bypass. However, if swing check valves are provided at intermediate locations, it is clearly desirable to provide a bypass.

15.2 Design procedure

Zero velocity valves are used in India in several pumping schemes. These are essentially devices for the control of upsurge. They are not suitable for control of downsurge or pressure drop. Dual plate check valves also being spring loaded non-return valves closing with reduction in velocity, may also be used for control of upsurge, provided a bypass is provided in the pipe. When the Zero velocity valve or dual plate check valve is located downstream of a location where water column separation occurs, it may control pressure rise due to the rejoining of the separated water columns. In a long pumping main, a swing check valve with a bypass may also serve the same purpose. This is in view of the fact that any small delay in closure of the swing check valve has an insignificant effect in view of the large time scale of the system. Besides, the effect of any uncertainty in the closure characteristics of the reflux valves is moderated by the provision of the bypass.

The following procedure may be adopted for the design of surge protection system based on these reflux valves. First, it must be ensured that either the downsurge pressures are within acceptable limits, or the pipe material, size and strength are such that the pipe and the joints can withstand full vacuum. Once this aspect is verified, analysis with Zero velocity valve or dual plate check valve or intermediate non-return valve may be made by locating one or more valves at proposed locations. The pipe reach at the location may be verified to be upward sloping. Locations downstream of possible water column separation locations are likely to be most suitable. If water column separation is indicated, analysis must be done considering column separation effect. If column separation is indicated at more than one location, analysis must be repeated, considering column separation at different locations in each analysis.

The maximum pressures as obtained from the profile of the maximum piezometric head (ctrl + g graphical plot) should be reviewed for all these cases. It must also be checked whether the profile of the minimum piezometric head deteriorates significantly with respect to the no protection case. For this, surges analysis without considering water column separation effect, with and without the reflux valves (Zero velocity valves, dual plate check valves and swing check valves) should be compared. Such reviews of maximum and minimum piezometric head profiles must be made for a number of alternatives, varying the number and location of the valves. These two design variables, namely the number and location of the valves, can be finalized based on several such analyses. If required, the bypass size may also be decided by the designer based on surge analysis. The key aid in deciding these design details is the plot of minimum and maximum piezometric head profiles (ctrl + g graphical plot).

16. GUIDELINES FOR DESIGN OF SURGE CONTROL VALVES - AIR VALVES

16.1 Air valves in a pumping main

Air valves as surge protection devices are intended for control of downs urge in view of their function as vacuum breaker. Air valves are distinct from all the devices discussed so far, in that all the other surge protection devices discussed in this manual have a role to play only with regard to surge control. On the other hand, the primary role of air valves in a cross country water pipe line is not surge control. Air valves are intended to release air at summits along the alignment during filling of the pipe line, release air that may gradually get accumulated during normal pump operation and, assist in draining of the pipe line during shut down for maintenance works. With proper location of air valves, it is expected that the pipe line will be free of air pockets which may cause additional head loss and also possibly harmful pressure fluctuations, particularly during starting of the pumps. Typically, in a cross country water pipe line, air valves may be located at an average spacing of 0.8 to 1.0 km, but not at uniform intervals. The actual location of the air valves will depend on the variations in slope along the longitudinal alignment of the pipe line.

It must be clearly understood that the air valves/ air cushion valves for surge control as discussed in this section do not refer to all the air valves proposed or installed in the pumping main. In the design of surge protection system, it is not prudent practice to take credit for all air valves in the pipe line as vacuum breaker. In fact, if vacuum breaker function of an air valve is assumed to be instantaneous, as in analysis models, no pipe line will require any other protection from downsurge angle, if credit is taken for all air valves. Similarly, if it is assumed that pressure relief valves will respond instantaneously on pressure rise beyond a specified limit, no other protection will be required from upsurge angle. Air valves and Air cushion valves can be very useful supplementary surge control devices if they are used with caution, considering the strength of the pipe and criticality of surge pressures.

16.2 Design considerations

Surge analysis with air valves or Air cushion valves as protection device is to be treated as approximate. When air valves are used as vacuum breaker at locations where severe subatmospheric pressure is expected, some air is let into the system through the air valve. The important aspects which govern this process are: (a) time lag in the vacuum breaker function of the air valve (b) air inlet capacity of the air valve, (c) air exhaust characteristics of the air valve (d) the movement of air along the pipe. Among these factors, analysis procedures focus particular attention on (b) and (c) while items (a) and (d) introduce maximum uncertainty. Besides, related to (d) two phase flow effects pose another problem. In view of these reasons, analysis where air valve effect as vacuum breaker is used, should be treated as approximate. The SAP software does not consider two phase flow effects.

More than relative merits of different modeling techniques, the evaluation of reliability of air valve function based on pressure drop rate picture (in the absence of air valve) is a crucial factor. It is specifically for this reason, option for plotting pressure variation rate at three specified locations (through ctrl+r graphical plot) is provided. These locations may be chosen as proposed air valve locations. If pressure drops from subatmospheric pressure to vapour pressure in less than 1 sec (in the absence of air valve), the air valve function as vacuum breaker will be uncertain. If the drop in pressure from subatmospheric pressure to vapour pressure takes a few seconds (3 seconds or more), air valve function as vacuum breaker may be considered reliable.

Considering all these factors, it is expected that air valves/air cushion valves may form supplementary protection devices, rather than sole protection devices. A surge protection system full dependent on air valves should be used only under expert advice after detailed consideration of the nuances of the surge picture and the strength of the pipe. It is for this reason that SAP limits the use of air valves/air cushion valves to a maximum of three, with reference to surge analysis. It is again reiterated that in fixing this limit, there is no intention to convey that only three air valves should be provided in a pumping main. As stated earlier, air valves may be provided at an average spacing of 0.8 to 1.0 km. What is proposed is that credit should not be taken for air valve function as vacuum breaker for more than three air valves.

If air valves/air cushion valves are used as supplementary protection devices, analysis should be done ignoring their effect as vacuum breaker and the surge picture should, still be acceptable. This is particularly important if the rate of pressure drop from start of subatmospheric pressure to full vacuum is very rapid (less than 1 see) at the proposed locations of the air valve/air cushion valve as seen from analysis in the absence of these valves.

17. GUIDELINES FOR DESIGN OF SURGE CONTROL VALVES. SURGE RELIEF VALVES

17.1 Description of the device

Surge relief valves handled by SAP is a special type of piloted pressure relief valve. Normal spring loaded pressure relief valves of the direct type may not function effectively as a surge control valve due to sluggish action. The surge relief valve coming under the scope of SAP, is a special type of piloted pressure relief valve with a low pressure pilot and a high pressure pilot. When the pressure goes below the low pressure pilot setting or above the high pressure pilot setting, the valve opens, and when the pressure comes back within these limits, the valve closes. The opening of the valve is rapid, while the closure is slow to avoid secondary surges due to closure. The surge relief valve is taken to be provided near the pump house. The surge relief valve is mounted on a tee branch with an isolation valve upstream of it. More than one valve may be provided on the same branch or on separate branches to improve the reliability of function. Usually an air valve also may be provided on the branch. Fig. 16 provides a schematic diagram of the installation of a surge relief valve.

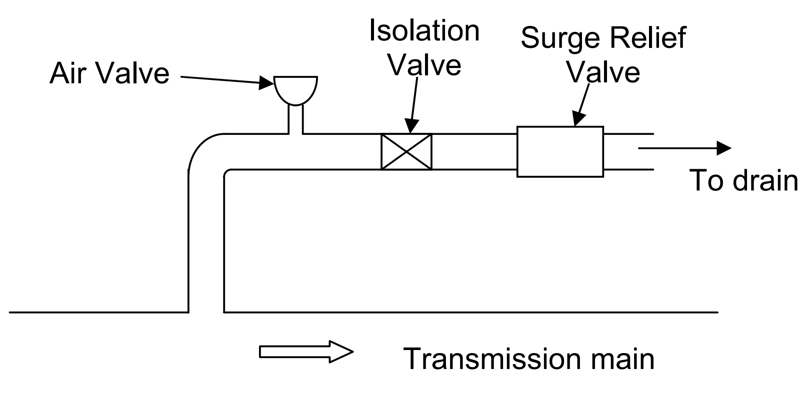


Fig.16: Schematic Diagram of the Installation of Surge Relied Valve

17.2 Function of the surge relief valve

The surge relief valve is a device for control of upsurge. Like the Zero velocity valves and dual place check valves, they are also not suitable for control of downsurge. The low pressure pilot will be set to a pressure value lower than the static head at the location of the valve. When the power fails and pressure drops, the low pressure pilot opens the valve as soon as the pressure drops below this set limit. This opening with associated discharge from the pipe, may accentuate the downsurge and as a result, the minimum piezometric head profile with surge relief valve is likely to be worse than without the valve. In designing the protection system, it must be ensured that this deterioration in minimum head profile is within acceptable limits.

Once the action of the low pressure pilot has resulted in opening of the valve, when the high pressure wave occurs due to the return surge, the valve is in open position, thus discharging the reverse flow water and controlling the pressure rise. This favourable situation is achieved by rapid opening and gradual closure of the valve. This keeps the valve open, ready to receive the upsurge wave and dissipate it, unlike a direct type pressure relief valve, which does not respond till the upsurge wave arrives.

After discharging water for a few seconds to a few minutes, the surge relief valve closes gradually when the pressure comes back to the static head following stoppage of pumps.

17.3 Design variables

In SAP, the surge relief valve is to be located near the pump house, as it is the most effective and convenient location for the valve. The design variables for the surge relief valve are as follows:

a) Number of valves

b) Size of the valves

c) Low pressure pilot setting

d) High pressure pilot setting

e) Closure time.

Basically, the low and high pressure pilot settings and closure time are tuned at site by the surge relief valve supplier. But it is desirable that the designer decides these variables to ensure that the protection system will potentially perform satisfactorily.

17.4 Design procedure

The design of surge relief valves is relatively more complex than that of special type of reflux valves discussed in Section 15. The reason is not only due to the fact that the number of design variables is more. Fixing the number and size of the valves, closure time and low pressure pilot settling require a good appreciation of the hydraulics of surge relief valves. In deciding the number of surge relief valves, it may be desirable to use two valves instead of one as even if one valve fails to function, some protection is available to the transmission main. Surge analysis may be done with both one and two valves in such cases. The valve size itself must be decided based on surge analysis for a range of sizes.

The minimum and maximum pressure limits for the function of the low pressure and high pressure pilots, can be set based on surge analysis taking into consideration the stipulated design criteria for surge pressures. The low pressure pilot has to be set to a pressure below the static lift, and the high pressure pilot has to be set to a pressure above the maximum working pressure. Generally, the setting of the high pressure pilot should not pose much problem, as it can be set, slightly above the maximum operating pressure for all normal operating conditions. The setting of the low pressure pilot has to be made carefully taking into consideration its effect on the downsurge picture, and the possibility of steady state reverse flow through the system after power failure.

If the closure time is set too small the surges resulting from the closure will cause alternate 'open' and 'close' signals for the valve, resulting in chattering of the valve. If the closure time is set too large, there will be more water loss due to reverse flow.

The software SAP has its output module designed specifically to deal with all these issues. When surge relief valve is chosen as a protection option, the output file SAP.RES contains "Details regarding status change of surge relief valve". This output module gives details of each status change of the valve. The nature of status change, the time of occurrence, and if the status change is from closed/closing to open, whether the open signal is due to low pressure pilot action or high pressure pilot action, are all indicated in the output. For a good design, the following conditions must be satisfied: a) First status change must be from "closed to open status" due to low pressure pilot action. This ensures that the low pressure pilot opens the valve in the downsurge phase; b) The last status change must be from "open to closing" status. This ensures that the valve will close following pump shut down; c) There must not be too many changes in the valve status from closed to open, open to closing, and closing to open. In the extreme case, there can be continuous chattering of the valve with periodic status change; d) Subject to the requirement in item (c) and the requirement of control of upsurge pressure, the valve closure time should not be unduly large, to minimise water loss.

These guidelines may be used to finalise all the design variables, based on a review of results of surge analysis for a number of cases.

18. GUIDELINES FOR DESIGN OF STAND PIPE

The stand pipe may be a suitable surge protection device or a supplementary surge-protection device for some special cases. It is unlikely to find common use. Though software

SAP allows multiple number of stand pipes in practice more than one stand pipe is most unlikely. Stand pipe may be considered only at a location along the alignment where the hydraulic grade line is within a few meters (usually 3 to 4 m) of ground elevation. Also, the downsurge at the location must be severe enough to require a local protection. Such locations are usually likely to occur towards the delivery end. Fig. 17 gives a schematic diagram of the stand pipe.

The design variables for the stand pipe are:

a) location of the standpipe

b) diameter of the stand pipe

c) elevation of the top of the stand pipe

Where it is found to be suitable, the design is relatively straight forward. The location is generally obvious and is based on considerations discussed in the previous paragraph. The diameter of the stand pipe may be the same as the air valve size used for the transmission main. The top of the stand pipe should be fixed 1 to 2 m above the maximum elevation of hydraulic grade line at the location.

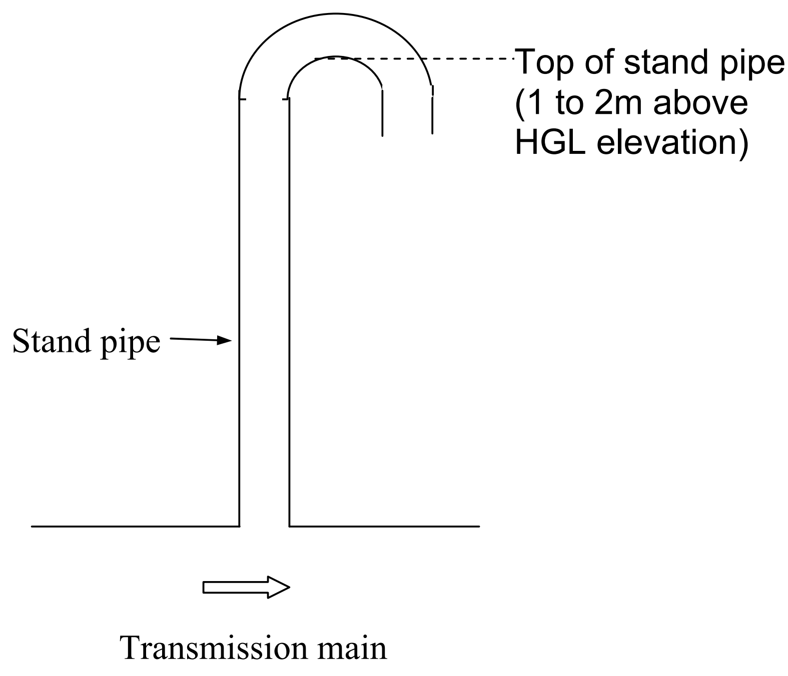


Fig. 17 Schematic Diagram of Stand Pipe

19. COMBINATION OF PROTECTION DEVICES

Usually, surge protection system may comprise of more than one protection device. In this respect, air valves and air cushion valves may commonly form supplementary surge protection devices along with the other major devices, such as air vessel, one way surge tank, zero velocity valve, surge relief valve, etc. A judicious and cautious use of air valves, with other devices, may help in reducing the cost of the surge protection system. Other combinations of devices are also possible. However, the following combinations are specifically ruled out in SAP: a) a combination of air vessel and surge relief valve; b) a combination of zero velocity valve and dual place check valve at intermediate locations along the alignment. The air vessel - surge relief valve combination is to be avoided, as both are located near the pump house, and the discharge through the surge relief valve will affect the efficacy of the air vessel. Zero velocity valve - dual place check valve combination is ruled out from practical considerations, including cost factor, as there is no advantage in mixing both the types of valves, in the same scheme.

For design of surge protection system combining different protection devices, the same principles discussed in sections 13 to 18 hold good. Only the number of computational cases with iterations in design will be much larger.

20. CONCLUSION

This manual providing guidelines for design of surge protection system in pumping mains is a companion manual to the User Manual of SAP (Surge Analysis Program). Though the manual is specifically intended to assist the design process using SAP, it is, by and large, self-contained, and the principles of design explained here are generally valid. The manual includes design guidelines for the following surge protection devices: a) air vessel; b) one way surge tank; c) zero velocity valves; d) dual place check valves; e) intermediate non-return valves; f) air valves; g) air cushion valves; h) surge relief valves; i) stand pipe. The manual also provides several details of surge protection system which are not related to surge analysis, such as the appurtenances of an air vessel. Specific attention is focused on a proper interpretation of the results from surge analysis. In this respect, situations where analysis may project a more critical picture than likely in the field, or a rosier picture than likely in the field, are both considered. Design examples are a deliberate omission in the manual, as one example for each device may type cast the design approach. In fact, in practice, a combination of more than one protection device may be the most suitable option. The purpose of this manual is to assist in learning the design process and the intricacies of design, rather than provide a step-by-step approach to design, which is not practical in this area.