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Fluid transients in pipes Pressure surge following pump trip in rising mains and other similar discharge lines. Suppression using air vessels

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THE PREPARATION OF THIS DATA ITEM

This Item was developed in the Noise and Structural Dynamics Group on behalf of the Internal Flow Panel. The work of the permanent professional staff of the Engineering Sciences Data Unit on this particular Item was monitored and guided by the following Working Party:

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(Continued on inside back cover)

FLUID TRANSIENTS IN PIPES PRESSURE SURGE FOLLOWING PUMP TRIP IN RISING MAINS AND OTHER SIMILAR DISCHARGE LINES. SUPPRESSION USING AIR VESSELS.

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FLUID TRANSIENTS IN PIPES

**Pressure surge following pump trip in rising mains and other similar discharge lines.
Suppression using air vessels.**

1. NOTATION AND UNITS

Any consistent system of units may be used in the equations in this Item.

		<i>SI</i>	<i>British</i>
A	internal cross-sectional area of pipe	m^2	ft^2
a	speed of propagation of pressure waves (speed of sound) in a liquid	m/s	ft/s
a_0	speed of propagation of pressure waves in an unconfined body of water (see Figure 1)	m/s	ft/s
$C_{in},$ C_{out}	non-dimensional discharge coefficients for flow into and out of air vessel respectively (see Equation (7.5))	—	—
D	internal diameter of circular pipe	m	ft
D_E	equivalent internal diameter (also known as hydraulic diameter) of pipe of non-circular cross section, $D_E = 4A/P_E$	m	ft
E	Young's modulus of elasticity of pipe wall material	N/m^2	$^*\text{lbf/ft}^2$
E_{ref}	reference value of Young's modulus of elasticity of pipe wall material, $E_{ref} = 10 \text{ GN/m}^2$ or $2.09 \times 10^8 \text{ lbf/ft}^2$	N/m^2	$^*\text{lbf/ft}^2$
f	† Fanning friction factor, $f = gH_f D_e / (2LV_0^2)$ (Note: $D_E = D$ for circular pipe.)	—	—
g	acceleration due to gravity, $g = 9.81 \text{ m/s}^2$ or 32.2 ft/s^2	m/s^2	ft/s^2
H	head of liquid	m	ft
$\bar{H}$	atmospheric head, $\bar{H} = 10.3 \text{ m}$ or 33.8 ft of water	m	ft
H_a	throttle head loss (see Section 6)	m	ft
H_d	static lift from sump to downstream tank	m	ft
H_f	friction head loss (see Section 6)	m	ft
H_0	local elevation of head profile at steady-state conditions	m	ft
H_R	pump rated head	m	ft
ΔH	change in head due to pump trip	m	ft

For footnotes see end of Notation.

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ΔH_D	maximum downsurge head (see Section 7.3)	m	ft
ΔH_U	maximum upsurge head (see Section 7.3)	m	ft
I	inertia of rotating components of pump	kg m ²	‡slug ft ²
K	pipe and air vessel throttle loss characteristic (see Equation (6.3))	—	—
K_3	pipe loss characteristic (see Equation (6.4))	—	—
K_4	air vessel throttle loss characteristic (see Equation (6.5))	—	—
L	pipe length	m	ft
M_R	pump rated torque	N m	*lbf ft
N_R	pump rated rotational speed	**rev/min	rev/min
P_E	internal perimeter of pipe	m	ft
P_R	rated pump shaft power	W	††ft lbf/s
Q_0	initial volume flow rate at steady-state conditions	m ³ /s	ft ³ /s
Q_R	rated volume flow rate of pump	m ³ /s	ft ³ /s
t	pipe wall thickness	m	ft
t_{rev}	time for pump discharge to fall to zero following pump trip	s	s
V	flow velocity	m/s	ft/s
V_0	initial flow velocity at steady-state conditions	m/s	ft/s
ΔV	change in flow velocity	m/s	ft/s
v	total volume of air vessel (see Equation (7.4))	m ³	ft ³
v_0	initial volume of air in air vessel (see Section 6)	m ³	ft ³
x	distance along pipe axis from upstream end	m	ft
z	elevation above datum	m	ft
z_u	head at pump inlet above datum	m	ft
α	non-dimensional parameter, $\alpha = gH_d / (aV_0)$ (see Equation (4.1))	—	—
β	non-dimensional pipeline characteristic (see Equation (6.1))	—	—
δ	head change factor (see Equation (4.3))	—	—
η_R	pump efficiency at rated conditions (in the range 0 to 1)	—	—

For footnotes see end of Notation.

ρ	density of liquid	kg/m^3	slug/ft^3
σ	non-dimensional air vessel characteristic (see Equation (6.2))	—	—
τ	non-dimensional pump run-down parameter (see Equation (4.2))	—	—

* $1 \text{ lbf/ft}^2 = 1/144 \text{ lbf/in}^2$

† Another form of the friction factor that is four times as large as the Fanning friction factor is in common use. As the same symbol, f , is often used for the other (larger) form, great care should be taken to ensure that the friction factor used is consistent with the definition of the friction head loss used in this Item. More guidance and charts for the estimation of the friction factor used in this Item are given in Reference 4.

‡ $1 \text{ slug} = 32.2 \text{ lb (pounds mass)}$.

** The pump speed is given in rev/min for the pump data given in this Item.

†† $1 \text{ ft lbf/s} = 0.001818 \text{ hp (horsepower)}$.

Subscripts

max/min refer to maximum and minimum values respectively.

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2. BACKGROUND

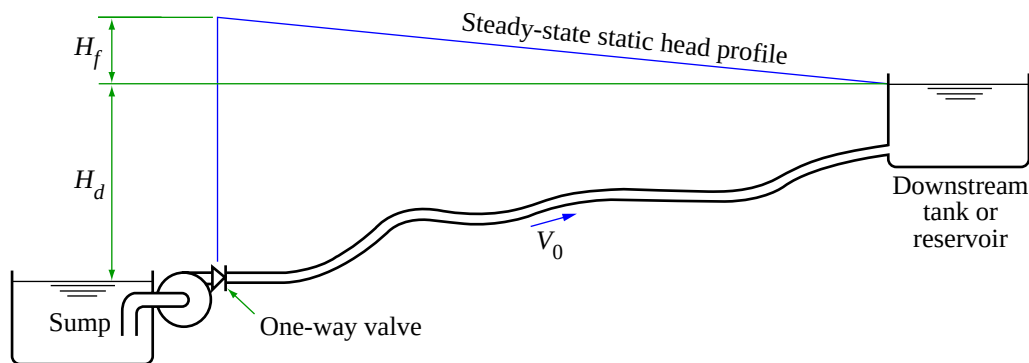
2.1 Notes

This Item is one in a series of ESDU Data Items concerning fluid transients in pipes. In this Item, data are presented that may be used to estimate the magnitude of the surge pressures (expressed in head of liquid) following pump trip in liquid-filled pump discharge lines such as rising water mains or cross-country oil pipelines. A method of sizing air vessels to protect the line against excessive surge pressures is also presented. The data are applicable to discharge lines with centrifugal pumps running full of liquid. General data for the estimation of pressure transients in liquids contained in pipelines are presented in ESDU 84013.

Fluid transients are the pressure changes that propagate through a fluid contained in a pipe or tunnel following a dynamic event, or disturbance, in the fluid such as a change in the flow rate. Other commonly used terms for these pressure changes include pressure surges, water hammer and hydraulic transients. In pumping lines, these pressure changes, or pressure surges, will occur when the pump runs down, following complete loss of power to the pump motor. The pressure drop associated with the run-down phase of pumps may lead to sub-atmospheric pressures in the pipeline, which can lead to unacceptable conditions such as seepage of contaminants through pipe joints or air valve inlets (particularly unacceptable in the water supply industry), and may cause column separation and the formation of vapour cavities. The pressure rise that will occur after the discharge of the pump has fallen to zero may be high enough to cause local damage to the pipeline or fittings. Repeated pressure cycles may lead to fatigue failure.

2.2 Scope and Applicability of the Item

This Item is intended to provide the engineer with simple, approximate, methods that may be used to estimate the magnitude of surge pressures in pump discharge lines following pump trip. It is also intended to show that, without careful attention to certain details of the system (particularly the pipeline profile), results of approximate methods of analysis may be misleading (see Section 3.2).

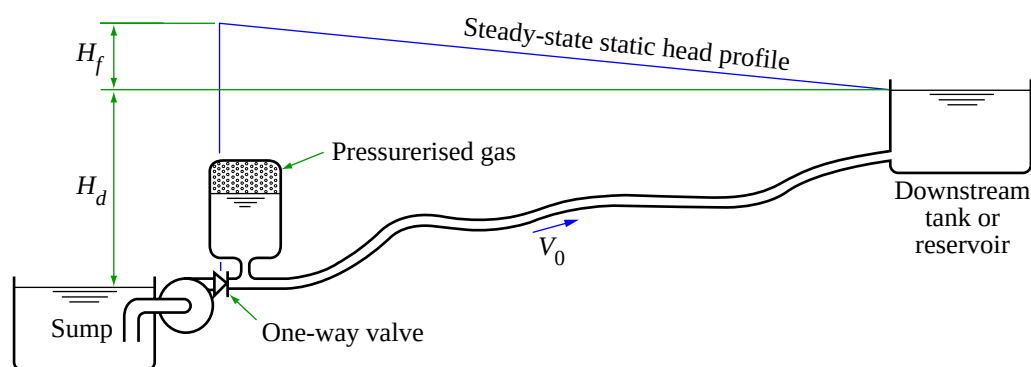


Sketch 2.1 Pump discharge line model

A simple, idealised model of a pump discharge line is considered in this Item. In this model, shown in Sketch 2.1, it is assumed that the pump discharges liquid along a single line (or a group of identical lines) from a large sump to a constant pressure point, such as a large tank or a reservoir, at the downstream end. It is assumed that the pipe diameter and friction factor are constant, and that there are no reflections of the pressure waves from pipe bends and fittings. Minor friction losses are assumed to be small compared to pipe losses and are therefore neglected. The pump is protected by a one-way valve (commonly referred to as a check valve or reflux valve in the water industry) that prevents reverse flow through the pump by closing when the discharge falls to zero. It is assumed that the one-way valve stays shut and does not cause any further flow disturbance. The model will allow systems with pressurised tanks to be considered, provided suitable adjustments are made to the tank head values.

Some guidance on the nature of pressure surges in pump discharge lines is given in Section 3 of this Item. In Section 4, data are presented that allow estimates of the wave speed, a , in water and the pressure changes following pump trip in a pump discharge line of the type shown in Sketch 2.1 to be made. These data are expressed in terms of head of liquid, and a non-dimensional chart is discussed in Section 5 that allows the system profile and steady-state and surge head values to be represented graphically as a guide to the interpretation of the data. This graphical presentation may clearly indicate certain problems in the system arising from pump trip. If unacceptably high or low values of head are indicated, it may be necessary to investigate means of reducing the magnitude of the head changes by, for example, increasing the pump inertia or using a larger pipe to reduce the flow rate. Alternatively, a stronger pipe may be used that will accept the pressure changes. These effects may be investigated using the data presented in Section 4. A common method of surge suppression in rising water mains is to use air vessels, situated just downstream of the pumps and one-way valves. Air vessels can limit the magnitude of the pressure changes following pump trip by maintaining some flow during downsurge and allowing flow to enter the vessel during upsurge. An example of a pump discharge line protected by an air vessel is shown in Sketch 2.2. Air vessels are discussed in Section 6, and a graphical means of estimating air vessel sizes is also presented in that Section.

A worked example is presented in Section 7 that illustrates the use of the non-dimensional chart discussed in Section 5 in the interpretation of the results of a surge analysis carried out using the graphical methods. These results are compared with those obtained using the computer program presented in ESDU 87027.



Sketch 2.2 Pump discharge line protected by an air vessel

3. EFFECTS OF SURGE PRESSURES FOLLOWING A PUMP TRIP

3.1 Sequence of Events Following a Pump Trip

Following power failure to a pump discharging liquid along a pipeline, expansion pressure waves form at the location of the pump outlet after pump trip, propagate along the pipeline, and are reflected at the downstream tank inlet at a later time as compression waves. The magnitudes of the pressure waves are dependent primarily upon the time taken for the pump to run down and the pipeline period, $2L/a$, where a is the speed of propagation of the pressure waves and L is the pipe length (see Section 4). If the deceleration of the liquid is “slow” (*i.e.* the time taken for the discharge to fall to zero occupies several pipeline periods) the magnitude of the expansion waves will be reduced by the beneficial effects of compression waves reflected from the downstream end of the pipe.

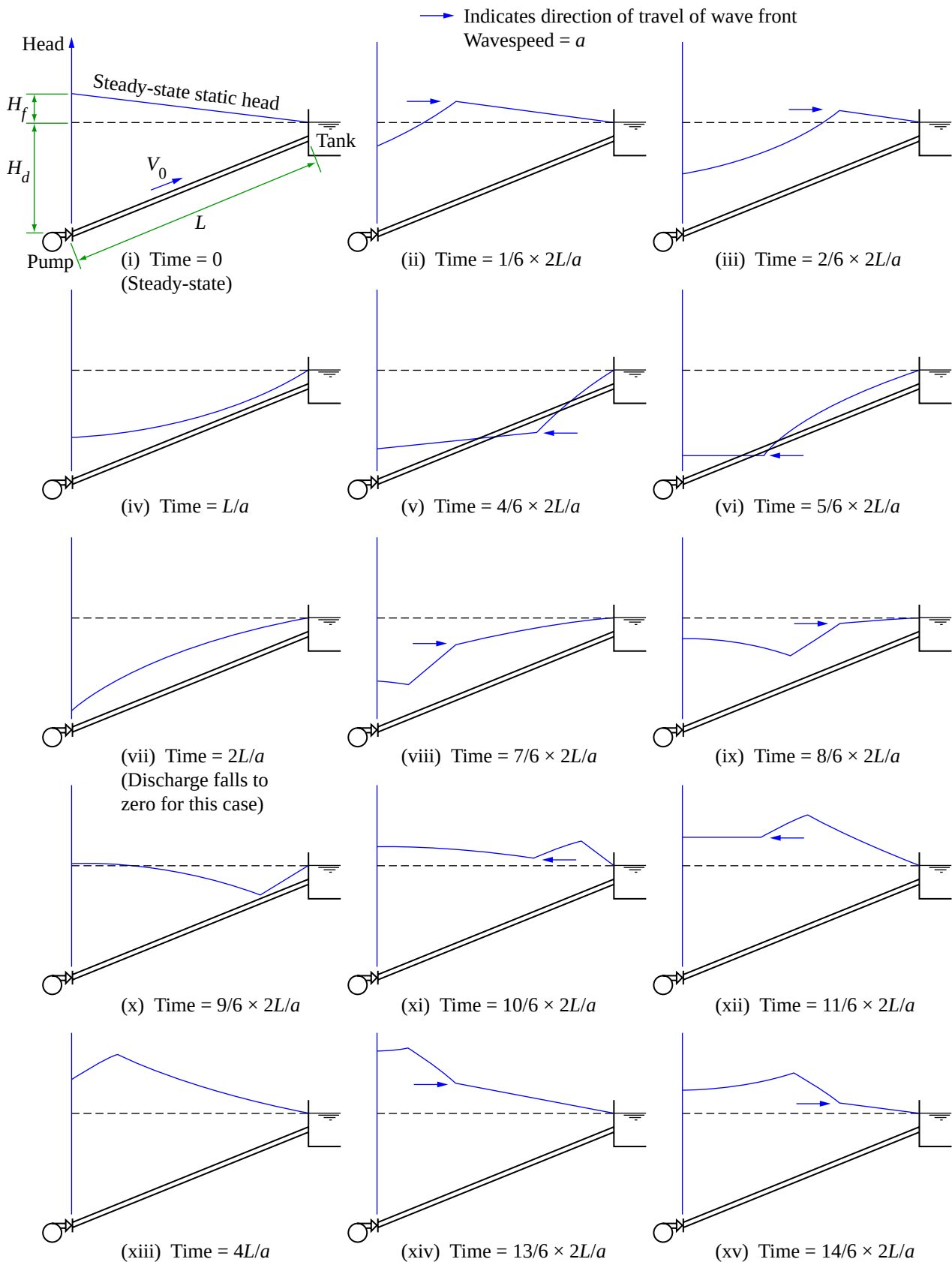
After the discharge from the pump falls to zero, flow reversal occurs and the pressure builds up again, frequently to a value above the steady-state value. In most cases, the magnitude of the pressure rise, relative to the downstream tank or reservoir head, approaches the magnitude of the pressure drop, relative to that head. However, if column separation occurs, the pressure rise resulting from collapse of the vapour cavity may lead to a pressure rise that is considerably higher than the initial drop. The maximum and minimum head conditions at a location in the pipeline may occur after a number of pipeline periods. A typical sequence of events following pump trip is shown in Sketch 3.1.

In general terms, the maximum and minimum head conditions that occur at a location in a pipeline as a consequence of pump trip must be within the upper or lower design limits specified for that location in the pipeline. Usually, this requirement means that the maximum head should not exceed the maximum design head and the minimum head should not fall to vapour head or gas release head. The maximum design head is usually specified to prevent damage to the pipe or fittings, although for occasional occurrence of surge, maximum head values may be allowed to exceed this value. As surge effects are greater for higher flow rates, it is recommended that the maximum design flow is used in a surge analysis.

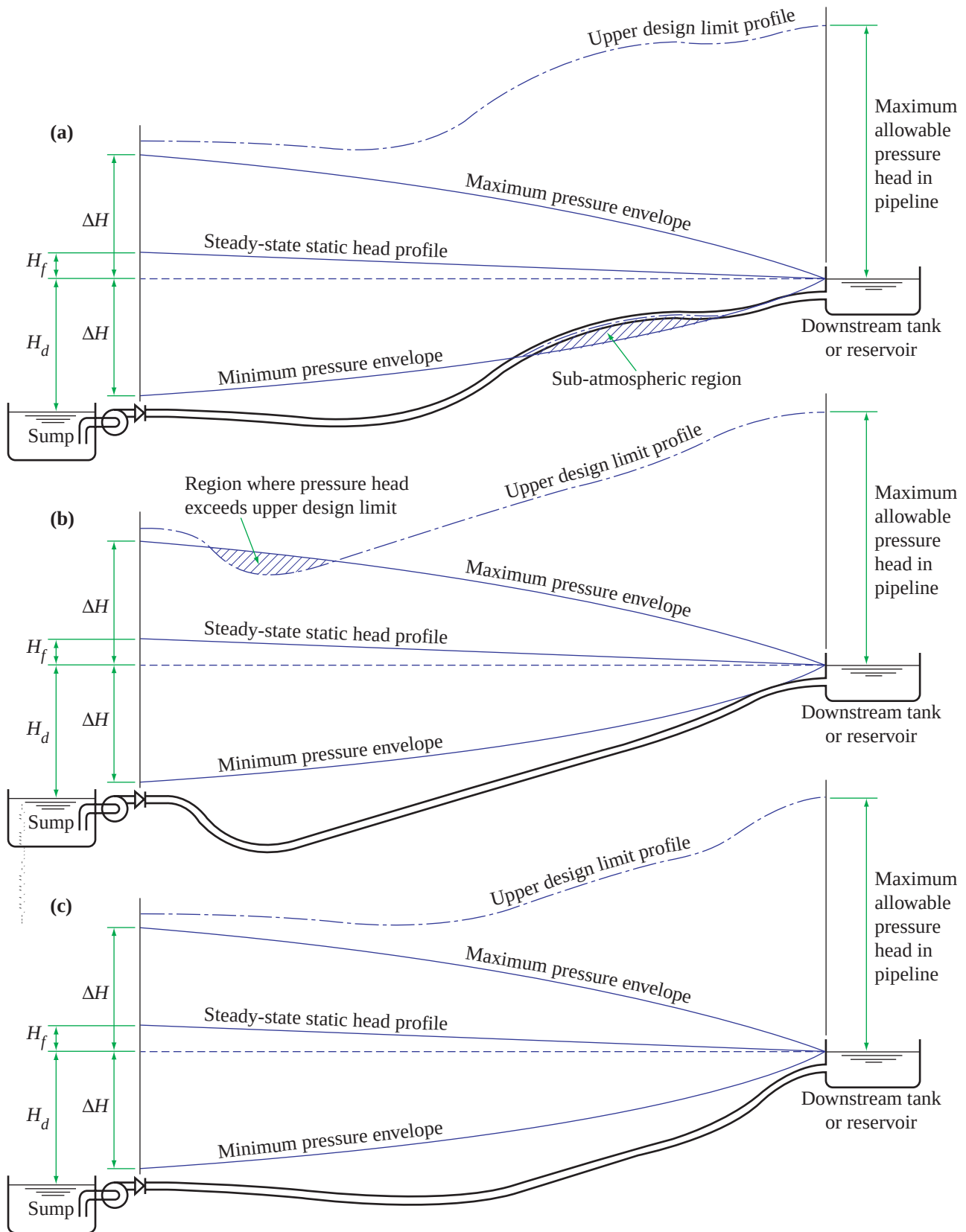
3.2 Effects of Pipeline Profile

In the analysis of pressure surge in pump discharge lines such as rising water mains, it is essential that head change data are obtained to enable estimates to be made of the head at a suitable number of points in the line. The local values of the maximum and minimum pressure head (*i.e.* relative to atmospheric head) are dependent upon the local pipe elevations above a given datum; the minimum pressure head at a high point may fall to zero or the maximum pressure head may be excessive at a low point in a line whilst acceptable head conditions occur at all other points in the line. These points are illustrated in Sketch 3.2.

The three systems shown in Sketch 3.2 are identical in all respects except that the pipeline takes different routes. The effect of the pipeline profile on the calculated values of head and flow following pump trip are negligible in most cases. The maximum and minimum head conditions following pump trip are illustrated graphically by the “envelopes” of the maximum and minimum head values along the pipeline, referred to as the maximum and minimum pressure envelopes. It may be noted that the maximum and minimum values of head do not necessarily occur at the same time in the run-down phase (the maximum head values always occur some time after the pump discharge has fallen to zero and the one-way valve has shut). The maximum allowable pressure head profile is also shown on these sketches, and is based upon a maximum allowable pressure head in the pipe. This maximum allowable head is referred to as the Upper Design Limit profile. For the purpose of these sketches, it is assumed that the maximum allowable pressure head is the same for all points in the line and may therefore be represented by a line above and parallel to the pipe line profile, separated by this maximum allowable pressure head. The maximum value may generally be determined using appropriate pipeline codes and is usually based upon the peak-pressures above steady-state that may be allowed for short durations.



Sketch 3.1 Typical sequence of events following pump trip



Sketch 3.2 Illustration of pipe profile effects

It may be seen from the three sketches that unacceptable conditions occur in the first two cases. In Sketch 3.2a, the minimum head profile impinges upon the pipeline profile at a high spot in the pipeline. Hence, there will exist a region of negative pressure head indicating that sub-atmospheric conditions will occur at that point. In the region of these sub-atmospheric conditions, indicated on Sketch 3.2a by the shaded region, the liquid column will break if the pressure head falls to vapour pressure head, and a vapour cavity will form. Collapse of this cavity may lead to excessively high pressures and possible pipeline failure at that location. Additionally, contamination may enter the line either by seepage through joints or by the action of air valves that may be required to protect against sub-atmospheric conditions at that location, or the pipes might fail as a consequence of the negative pressure gradient between the liquid in the pipe and the surroundings (especially in buried pipes). In general, pipes are capable of sustaining larger increases in pressure relative to steady-state pressure than decreases. If the pressure outside the pipe is greater than the internal pressure, pipe wall collapse may occur. The pressure differential required for collapse is usually very much less than that for bursting and, in some cases, pipe failure may occur at pressures significantly greater than vapour pressure. In Sketch 3.2b, it may be seen that the minimum head conditions are acceptable, but the maximum pressure head at a region corresponding to a low point in the pipeline impinges upon the upper design limit profile, and may lead to local failure of the line at that location. However, Sketch 3.2c does not indicate any unacceptable conditions at any point in the pipeline, a condition achieved by rerouting the pipeline.

It may be seen from the above examples that the pipeline profile may dictate whether or not unacceptable conditions occur in a pipeline, and hence an accurate representation of the maximum and minimum head values at a sufficient number of points in the line is necessary for a realistic surge analysis. In particular, it must be noted that in many cases it is not sufficient to calculate head change data only at the location of the pump outlet.

4. ESTIMATION OF MAXIMUM HEAD CHANGES USING GRAPHICAL METHODS OF ANALYSIS

Data are presented in this Section that enable estimates of the maximum head changes in a liquid contained in a pump discharge line following pump trip to be made. These data are applicable to pump discharge lines such as that shown in Sketch 2.1, and may indicate whether unacceptable conditions occur following pump trip, in which case a surge suppression device such as an air vessel may be required. The line is not protected against the effects of pump trip but the pump is protected by a one-way valve that shuts immediately and stays shut when the pump discharge falls to zero.

The magnitude of the pressure changes are dependent upon the initial conditions in the pipeline and run-down characteristics of the pump. The data presented in this Section were derived from a simple computer model. The initial conditions in the system may be expressed by the parameter α , given by

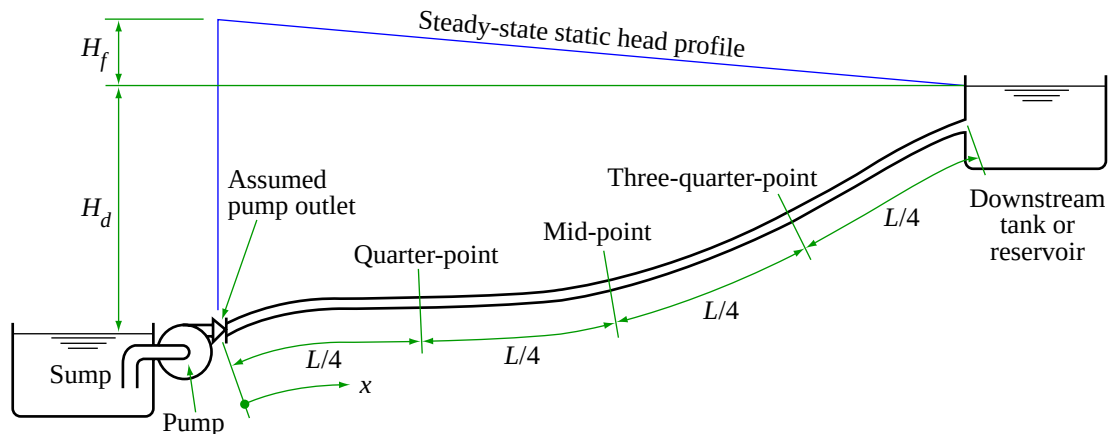
$$\alpha = \frac{gH_d}{aV_0}, \quad (4.1)$$

where g is the acceleration due to gravity (equal to 9.81 m/s² or 32.2 ft/s²), H_d is the static lift from the sump to the downstream tank or reservoir (see Sketch 2.1), a is the speed of propagation of the pressure waves in the liquid and V_0 is the steady-state flow velocity prior to pump trip. The speed of propagation of the pressure waves (or wave speed) may be estimated using the data presented in Figure 1 for water contained in circular pipes with frequent expansion joints. These data are given for a range of values of t/D , the ratio of the pipe wall thickness to internal diameter, and a range of values of E/E_{ref} , the ratio of Young's modulus of elasticity of the pipe wall material to a reference value (10 GN/m² or 2.09×10⁸ lbf/ft²). Some typical values of Young's modulus of elasticity for common pipe materials are given in Table 9.1. The wave speed data are given assuming that no free gas is present in the water. If a small quantity of free gas is present in the liquid, the wave speed will be reduced, sometimes drastically. Similarly, the presence of solid matter in the liquid will alter the wave speed. Further guidance upon the estimation of the wave speed in liquid/gas or liquid/solid mixtures is given in ESDU 83046. Data are also given in ESDU 83046 for the estimation of the wave speed in liquids contained in circular or non-circular, lined or unlined, buried or unburied pipes.

The pump run-down characteristics are expressed by the parameter τ , given by

$$\tau = 2 \left(\frac{2\pi}{60} N_R \right)^2 \frac{I \eta_R}{\rho g H_R Q_R} \times \frac{a}{2L}, \quad (4.2)$$

where I is the rotational inertia of the rotating components of the pump (including gearbox, motor and fittings and the liquid contained in the pump impeller), ρ is the density of the liquid, L is the pipe length and N_R , η_R , H_R and Q_R are the rated (or reference) values of the pump rotational speed (in rev/min), efficiency, head and flow respectively. The rated efficiency, η_R , is a value in the range 0 to 1. The inertia term, I , is usually available from the manufacturer. The pipe length, L , is taken as the distance along the axis of the pipeline (including pipe bends, etc.) from the pump outlet to the inlet of the large tank or reservoir at the downstream end of the line (unlike standard pressure drop calculations, equivalent lengths of fittings are not added to the straight pipe length). It is assumed that the one-way valve is located immediately adjacent to the pump outlet.

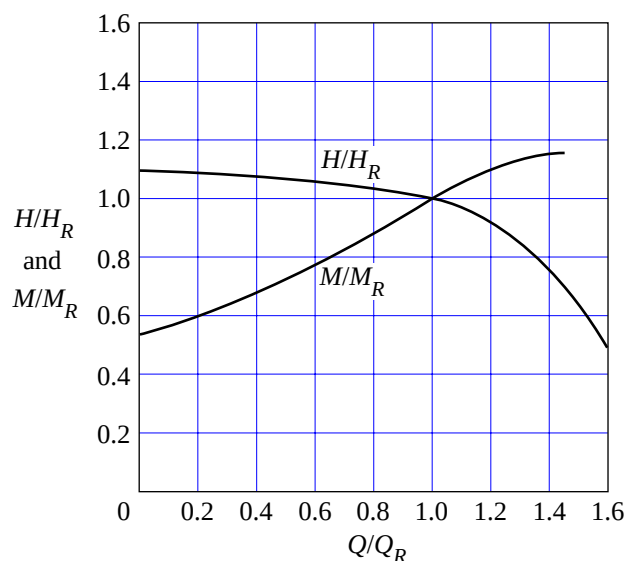


Sketch 4.1 Typical pump discharge line

Data are presented in Figures 2, 3, 4 and 5 that enable estimates to be made of the maximum head changes, expressed as a proportion, δ , of the maximum theoretical head change (which is known as the 'Joukowsky Head', and is given by aV_0/g), at four points in the pipeline. These data are presented for a range of values of α between 0.001 and 50 and a range of values of τ between 0.1 and 100, and are given in Figures 2, 3, 4 and 5, respectively, for the following four points, as illustrated on Sketch 4.1; the location of the pump outlet, the quarter-point, the mid-point and the three-quarter point. The head at the downstream tank or reservoir is constant. The head change at any one of these points may be determined from the data presented on the appropriate figure, and using the equation

$$\Delta H = \delta \times \frac{a}{g} V_0, \quad (4.3)$$

where δ is estimated from the graphical data presented in the Figures. The head change data were derived specifically for centrifugal pumps with the head/torque/flow characteristics under normal operating conditions shown on Sketch 4.2, but may be used to give estimates of the pressure changes following pump run-down of other centrifugal pumps or mixed-flow pumps with similar characteristics at the operating point. Further guidance on the calculation of the pressure change data presented in this Section is given in ESDU 84013.



Sketch 4.2 Pump head, torque and flow characteristics under normal operating conditions

The effect of altering pump run-down parameters, such as the pump inertia, may be investigated using the data presented in this Section. Alternatively, the effect of altering the wave speed in the liquid, by using different pipe materials for example, may readily be investigated. Further guidance upon pump run-down in pump discharge lines is given in References 2, 5, 6, 7, 8 and 11.

For centrifugal pumps that are not protected by a one-way valve situated at the outlet of the pump, the reverse flow that will occur after the flow changes direction may lead to very high reverse speeds of rotation of the pump. Some data are presented in Figure 6 that may be used to estimate the time taken for the discharge to fall to zero (*i.e.* the flow reversal time, t_{rev}). These data are given for the same range of α and τ as the data in Figures 2 to 5. The flow reversal time is expressed by the non-dimensional parameter $t_{rev}a/2L$.

Some data concerning the choice of suitable one-way valves for the protection of pumps against reverse flow is given in Reference 9. The selection of one-way valves should be made with extreme care, especially in high-head systems. The valve will need to be chosen to match the characteristics of the system, as the pressure rise generated by the closure of badly-selected one-way valves may be disastrous.

5. NON-DIMENSIONAL SYSTEM REPRESENTATION

As an aid to the interpretation of the results of a graphical surge analysis, it is convenient to represent the system non-dimensionally and to superimpose the results from graphical analyses, expressed in terms of head of liquid, on this system representation. This approach allows easy identification of unacceptable head conditions. For example, the data shown in Sketch 3.2a indicate clearly that sub-atmospheric conditions are likely to occur in a section of the pipeline.

A chart of the form shown in Figure 8 may be used to represent the data. The chart allows the pipe profile, steady-state head profile and upper design limit profile to be constructed. The results of graphical analyses, such as that given in Section 4, superimposed on the chart will indicate the likelihood of unacceptable head conditions. If unacceptable conditions are indicated, estimates of the maximum and minimum permissible head values in the system may be made. This value may then be used in the estimation of air vessel size for surge protection.

The procedure for using the charts is detailed in the worked example of Section 7.

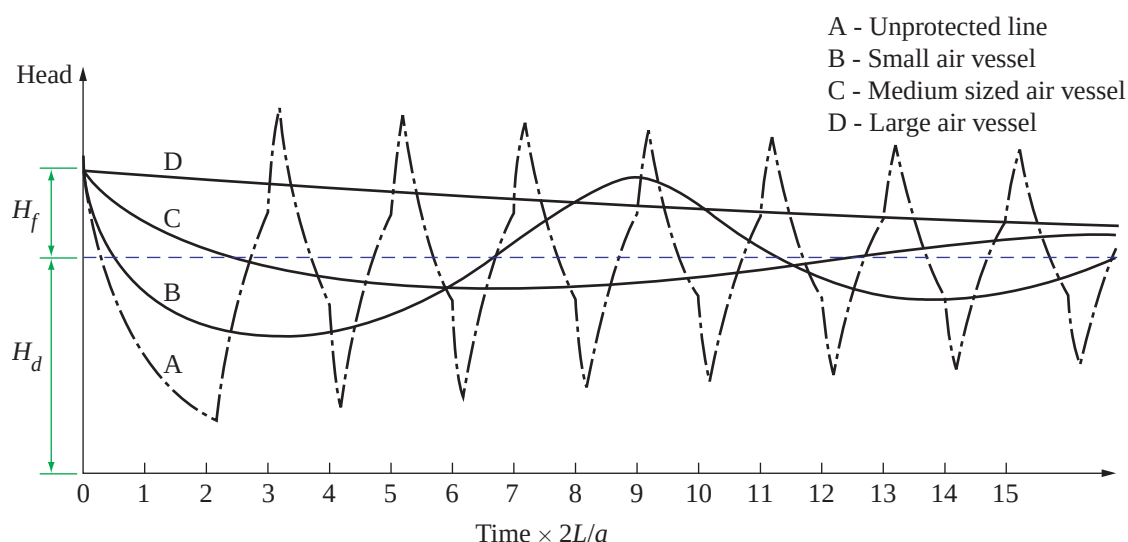
6. PRESSURE SURGE SUPPRESSION USING AIR VESSELS - ESTIMATION OF AIR VESSEL SIZE

6.1 Pressure Surge Suppression Using Air Vessels

6.1.1 General

Following pump trip in a pump discharge line, the liquid in the pipeline decelerates and eventually reverses direction. Initially, the pressure at the location of the pump outlet decreases and if the pressure falls to vapour pressure, column separation will occur. The subsequent collapse of the vapour cavity following flow reversal may lead to very high pressures and possible pipe or fittings failure. Even if a vapour cavity does not form, the subsequent pressure rise following flow reversal may be high (see Sketch 6.1). In certain systems, notably rising water mains, an air vessel (or a group of air vessels) situated just downstream of the pump outlets and their one-way valves may be an efficient and effective means of reducing the magnitudes of the surge pressures following pump trip. They may also be used to protect the upstream side of a line from surge pressures following valve closure; in this case they are located just next to the valve on the upstream side. This second application of air vessels is not considered in this Item.

The principles of air vessel operation for the protection of a pump discharge line from the effects of pump trip are as follows. At the instant of pump trip, the pressure at the pump outlet falls as the liquid decelerates. Liquid is forced out of the air vessel into the pipeline, the pressure in the air vessel is reduced and the pressure in the liquid is maintained to some degree by this extra liquid reducing the deceleration of the flow. Eventually the velocity of the flow in the line falls to zero and the flow reverses. The pressure at the upstream end of the line starts to rise, exceeds the pressure in the air vessel, and reverse flow into the vessel occurs until the liquid eventually decelerates and reverses direction again. The cycle of events then continues with decreasing pressure amplitudes as frictional effects in the pipe and energy losses in the chamber damp out the pressure changes. It may be seen from Sketch 6.1 that an air vessel reduces the rate of change of pressure in this typical pump discharge system, damping out the rapid fluctuations that occur in the unprotected case at time intervals of $2L/a$.



Sketch 6.1 Effect of air volume on surge suppression

The rate of change of flow of the liquid, and hence the rate of change of pressure, is primarily dependent upon the initial volume of air in the vessel; the lower the initial air volume, the more rapidly the pressure falls after pump trip. The total volume of liquid in the vessel must be large enough to prevent air being

drawn into the pipe during downsurge. The effect of air vessel size on the head changes in a typical system is shown in Sketch 6.1. The rate of change of pressure is also governed to a lesser degree by the details of the losses associated with flow into and from the vessel. Air vessels are generally throttled to increase the frictional damping effects. Usually, the resistance to flow into the vessel is made greater than that for flow out. This arrangement is beneficial in the reduction of the maximum upsurge and downsurge pressure changes, and may be achieved by using a pipe with a one-way valve to allow flow out of the vessel and a small by-pass to allow flow in (see Sketch 6.2). Alternatively, a multi-door one-way valve (or check valve) with one or more doors missing may be used to achieve this effect.

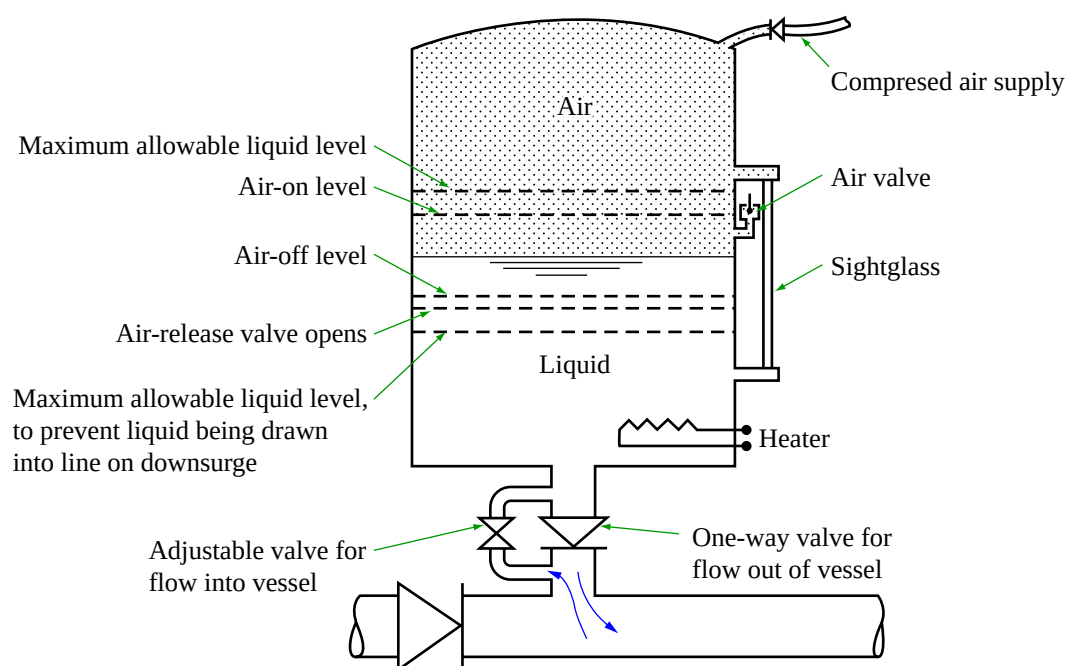
6.1.2 Air vessel design and maintenance

Data are presented in Section 6.2 that may be used to estimate the size of air vessels to protect against pump trip. Although the effects of pipeline friction and orifice losses may be included in the analysis, a computer simulation may indicate that a particular arrangement of differential throttling gives a more efficient design of vessel. The throttle characteristics may be modelled by the use of discharge coefficients, calculated from head drop data across the throttling valves (see Equation (7.5)), for the purposes of a computer model. These head loss data are usually available from valve manufacturers. The graphical data presented in Section 6.2 may ideally be used to provide initial estimates for a computer study if a program is available. Manufacturers' handbooks may also provide charts for the estimation of air vessel size, but it must be ensured that the data allow the conditions along the line to be considered, and are not simply applicable to the location of the pump outlet.

In an air vessel calculation successive values of the initial air volume may be considered until acceptable conditions are predicted at all points in the line. The corresponding maximum air volume is the total volume of the vessel for that case. In practice, it is recommended that an extra volume of air of 20 to 25 per cent of the calculated volume be added to the initial air volume to allow for fluctuations in the liquid level during operation. A second estimate of the maximum volume of air may then be made using this larger value of the initial air volume, and it is recommended that an extra 10 to 15 per cent be added to the resulting liquid volume as a safety factor to ensure that the vessel does not drain down following pump trip. However, it must be noted that the specification of oversized vessels may be uneconomic.

It is essential that the liquid level in the vessel at steady state does not fall below the minimum allowable liquid level (as air may be drawn into the line) or rise above the maximum allowable liquid level. To achieve this, a pressurised air supply is required that may be used to lower the liquid level if the level rises to the maximum allowable level. Similarly, an air release valve should be set to open to reduce the pressure head in the air and hence allow the level to rise if the minimum allowable level is reached. These limits are illustrated on Sketch 6.2. After pump trip, air may be absorbed by water, which may subsequently alter the system behaviour. A gas such as nitrogen is sometimes used to prevent this. In some cases, it may be necessary to separate the liquid and the gas in the vessel by using an impervious layer such as a rubber diaphragm or a layer of oil on the liquid surface.

Air vessels must be properly maintained to protect against pump trip at all times, and may not prove to be an effective surge protection device if they are not regularly monitored. Reliable maintenance is essential. Alarms to indicate when the liquid level reaches unacceptable limits may be essential in some installations, especially if remote, and the devices for sensing these conditions should be located outside the vessel where possible to allow easy maintenance. A sight glass is usually provided to indicate the liquid level (which is especially useful after complete power failure). It must also be ensured that the liquid in the vessel does not freeze in cold weather. A heating element may be used to maintain suitable temperatures.



Sketch 6.2 Typical air vessel arrangement

6.2 Estimation of Air Vessel Size

When designing air vessels to protect a line against the effects of pump trip, it is usually intended that the pressure head along the line should not fall to vapour pressure head or exceed design limits at any location in the line. This analysis is easily performed using suitable computer programs that enable the conditions along the line to be investigated. Such a program is presented in ESDU 87027 for simple one-line systems protected by air vessels. However, it may be necessary to obtain an initial estimate of the size of air vessels to protect against pump trip. Data are presented in this Section that allow those estimates to be obtained graphically.

The air vessel data enable estimates of the air vessel size to be made to protect simple one-pipe discharge lines such as that shown in Sketch 2.2. In this system, the pump is protected by a one-way valve that is assumed to close immediately when the discharge from the pump falls to zero. This assumption is valid for long pipelines in which the inertia of the pump is low. It is further assumed that the air vessel is situated close to the pump, and is connected to the pipeline by a pipe fitted with an orifice. The total head losses for the same flow into and out of the chamber are in the ratio 2.5:1 (*i.e.* there is less resistance to flow out of the vessel, and this ratio is typical of most practical cases).

The data are presented in the form of charts in Figures 7a to 7l, and allow estimates of the air vessel size to be made by the specification of maximum and/or minimum allowable head change values at either the location of the pump outlet or the mid-point of the line (which is particularly useful for systems such as that shown in Sketch 3.2a). To use the data, it is necessary to define non-dimensional parameters describing the initial conditions in the pipeline, the initial conditions in the air vessel and the system losses (due to pipeline friction at steady-state and theoretical losses in the air vessel inlet/outlet orifice assuming the full, steady-state flow into the chamber). These parameters are the pipeline characteristic, given by

$$\beta = \frac{aV_0}{gH_0}, \quad (6.1)$$

where H_0 , expressed in absolute head, is shown in Sketch 6.3, and the air vessel characteristic, given by

$$\sigma = \frac{2gv_0H_0}{ALV_0^2}, \quad (6.2)$$

where v_0 is the initial volume of air in the vessel (to be estimated) and A is the cross-sectional area of the pipe. The friction losses are accounted for by the loss parameter, given by

$$K = K3 + K4, \quad (6.3)$$

where $K3$ and $K4$ are the components due to pipeline friction losses and orifice losses respectively. The pipeline friction loss component is given as

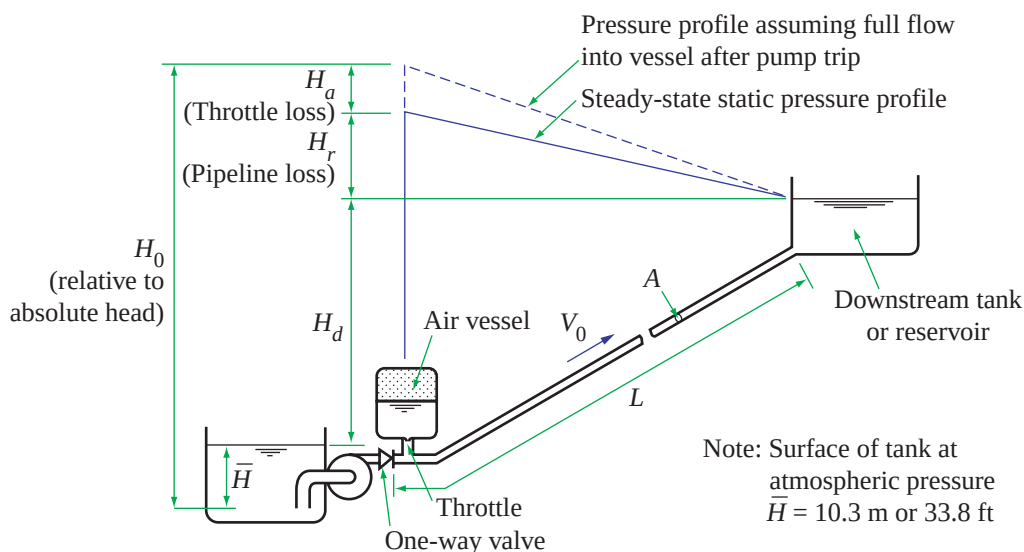
$$K3 = \frac{H_f}{H_0}, \quad (6.4)$$

where H_f is the head loss due to pipe friction. The orifice losses are represented by the parameter

$$K4 = \frac{H_a}{H_0}, \quad (6.5)$$

where H_a is the head loss in the air vessel inlet orifice assuming full steady-state flow into the vessel. The parameters required for the estimation of these head loss terms are illustrated on Sketch 6.3.

The air vessel charts are used as follows; first specify the maximum upsurge and downsurge allowable head changes, and then use the data presented in Figures 7a to 7l and Equations (6.1) to (6.5) to estimate the initial volume of air in the air vessel. The procedure for the estimation of air vessel size is illustrated in the worked example of Section 7.



Sketch 6.3 Simple pump discharge line protected by an air vessel