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Fluid transients in pipes. Use of air inlet/outlet valves as surge suppression devices

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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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Mr E.M. Curtis	— Central Electricity Generating Board, Marchwood
Dr S.J. Murray	— Atkins Research and Development
Dr D. Pollard	— GEC Power Engineering
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(Continued on inside back cover)

FLUID TRANSIENTS IN PIPES. USE OF AIR INLET/OUTLET VALVES AS SURGE SUPPRESSION DEVICES

CONTENTS

	Page
1. NOTATION AND UNITS	1
2. BACKGROUND	3
2.1 Notes	3
2.2 Scope and Applicability of the Item	3
3. GUIDE TO THE USE OF AIR INLET/OUTLET VALVES	5
3.1 Air Valve Usage Under Normal Operating Conditions	5
3.2 Alleviation of Pressure Surges Using Air Inlet/Outlet Valves	6
3.2.1 Use of air valves in otherwise unprotected lines	6
3.2.2 Use of air valves in conjunction with air vessels	8
3.3 Air Valve Maintenance	9
4. PERFORMANCE OF AIR INLET/OUTLET VALVES AS SURGE SUPPRESSION DEVICES	11
4.1 System Model for Graphical Presentation	11
4.2 Non-dimensional System Representation	12
4.3 Estimation of Maximum Air Inflow Mass Flow Rate	13
4.4 Estimation of Maximum Volume of Air Cavity	14
4.5 Calculation of Minimum Line Pressure and Air Release Time	14
5. WORKED EXAMPLE: PUMP TRIP IN A RISING WATER MAIN	15
5.1 Non-dimensional System Representation	16
5.2 Estimation of Air Valve Parameters	17
5.2.1 Maximum air inflow mass flow rate	17
5.2.2 Maximum air volume	17
5.3 Comparison of Calculated Air Valve Data With Manufacturers' Data	18
5.4 Listing of Example Output from ESDUpac A8727	19
5.4.1 Pump trip example - line protected by air inlet/outlet valve	19
5.4.2 Air vessel example - line protected by air inlet/outlet valve	24
6. DERIVATION AND REFERENCES	30
FIGURES 1a to 2d	31 to 36
APPENDIX A EQUATIONS FOR AIR FLOW THROUGH AIR INLET/OUTLET VALVES	37
A1. INTRODUCTION AND ASSUMPTIONS	37
A1.1 Subsonic Air Flow in	37
A1.2 Choked Air Flow In	38

This page Amendment A

A1.3	Subsonic Air Flow out	38
A1.4	Choked Air Flow out	38
A1.5	General Gas Law	38

FLUID TRANSIENTS IN PIPES.

Use of air inlet/outlet valves as surge suppression devices

1. NOTATION AND UNITS

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

		SI	British
A	internal cross-sectional area of pipe	m^2	ft^2
A_{in} , A_{out}	cross-sectional areas of air valve inlet and outlet orifices, respectively	m^2	ft^2
a	speed of propagation of pressure waves (speed of sound) in liquid	m/s	ft/s
C_{in} , C_{out}	non-dimensional discharge coefficients for flow through inlet and outlet orifices, respectively	—	—
D	internal diameter of circular pipe	m	ft
D_E	equivalent internal diameter of pipe of non-circular cross section, defined as $D_E = 4A/P_E$	m	ft
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_0	local value of absolute static head (see Section 4)	m	ft
H_d	static lift from sump to downstream tank or reservoir	m	ft
H_f	friction head loss (see Equation (4.3))	m	ft
$\bar{H}$	†atmospheric head, $\bar{H} = 10.3 \text{ m}$ or 33.8 ft of water at sea level	m	ft
ΔH	maximum head change (see Section 4)	m	ft
h_{av}	elevation of pipe above atmospheric datum at location of air valve	m	ft
K	friction head loss term (see Equation (4.4))	—	—
L	pipeline length (see Section 4.1)	m	ft
m_a	air mass (see Equation (A1.5))	kg	‡slug
$\dot{m}_{max}$	maximum air mass flow rate (see Section 4.3)	kg/s	‡slug/s
$\dot{m}$	air mass flow rate	kg/s	‡slug/s

For footnotes see end of Notation section.

Issued May 1985 - 38 pages
Reprinted at Amendment A - March 2007

P_E	internal perimeter of pipe	m	ft
p	absolute internal pressure ^{**} in pipe	N/m ²	lbf/ft ²
p_0	atmospheric pressure ^{††} , $p_0 = 101\,325\text{ N/m}^2$ or 2116.22 lbf/ft^2	N/m ²	lbf/ft ²
R	gas constant, typical value for air = 287 J/kg K or $3090\text{ ft lbf/slug K}$	J/kg K	ft lbf/slug K
T	absolute temperature of air in air cavity	K	K
T_0	absolute ambient air temperature	K	K
V_0	steady-state flow velocity of liquid	m/s	ft/s
v_a	air volume (see Equation (A1.5))	m ³	ft ³
v_{max}	maximum volume of air cavity	m ³	ft ³
$\dot{v}_{max}$	maximum volume flow rate of air	m ³ /s	ft ³ /s
x	distance along pipeline from pump outlet valve to air valve	m	ft
α	non-dimensional initial head/flow conditions parameter, $\alpha = aV_0/(gH_0)$ (see Equations (4.1a) and (4.1b))	—	—
β	non-dimensional air valve elevation parameter, $\beta = (h_{av} + \bar{H})/H_0$ (see Equation (4.5))	—	—
μ	non-dimensional mass flow parameter, $\mu = \dot{m}_{max}/(\rho_a AV_0)$ (see Equation (4.6))	—	—
σ	non-dimensional air volume parameter, $\sigma = 2av_{max}/(ALV_0)$ (see Equation (4.8))	—	—
ρ	liquid density	kg/m ³	‡slug/ft ³
ρ_a	air density, typically $\rho_a = 1.23\text{ kg/m}^3$ or $2.38 \times 10^{-3}\text{ slug/ft}^3$ at sea level and 15°C	kg/m ³	‡slug/ft ³

* 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 7.

† $\bar{H}$ is taken as the value of head of water in the International Standard Atmosphere at sea level and 15°C.

‡ 1 slug = 32.174 lb (pounds mass).

** In some cases, pressures are quoted in bar. $1\text{ bar} = 10^5\text{ N/m}^2$.

†† p_0 is taken as the pressure in the International Standard Atmosphere at sea level and 15°C.

2. BACKGROUND

2.1 Notes

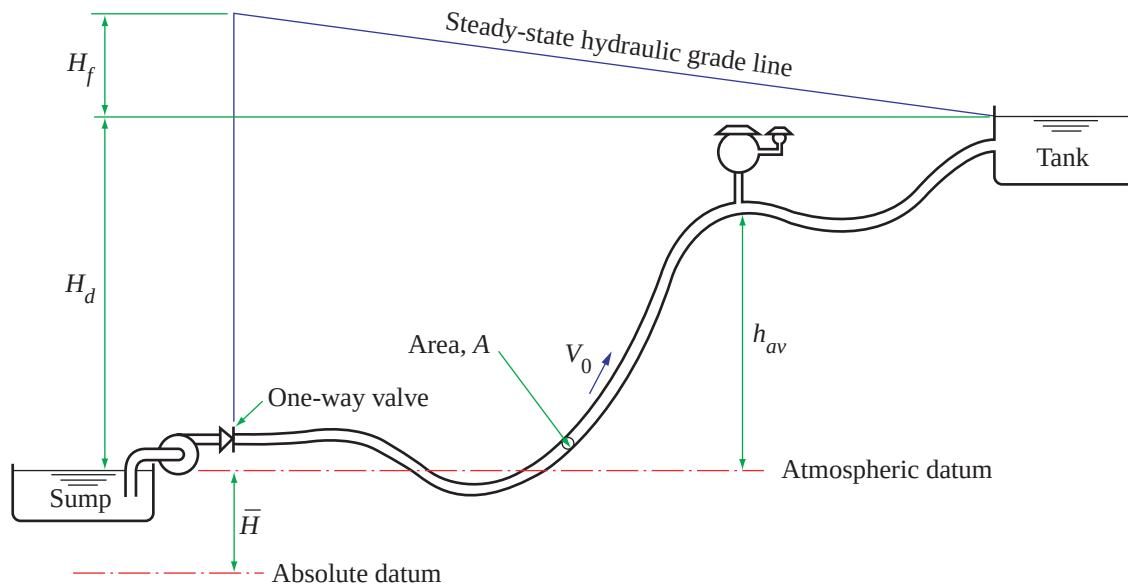
This Item is one in a series of ESDU Data Items concerning fluid transients in pipes. In this Item, data are presented that may be used to guide the selection of air inlet/outlet valves for use in the protection of pipelines that are running full of liquid against excessive surge pressures. Air inlet/outlet valves are frequently used in long pipelines at points where the pressure may fall below atmospheric following the loss of pumping power or following valve closure. Data are presented in ESDU 84038 that allow estimates to be made of the magnitudes of surge pressures in pipelines following pump trip. These data may be used to indicate the likelihood of sub-atmospheric pressures at locations along the pipeline. Data are also presented in that Item that allow estimates to be made of air vessel size for the protection of the pipeline against these sub-atmospheric pressures. General data for the estimation of pressure transients in liquids contained in pipelines and guidance on the various methods of suppression are presented in ESDU 84013.

Fluid transients are the pressure changes that propagate through a fluid contained in a pipe or tunnel following a change in the flow rate. Other commonly used terms for these pressure changes include pressure surge, water hammer and hydraulic transients. These pressure changes, or pressure surges, occur when, for example, pumps run down following complete loss of power to the pump motors in pumping lines. The pressure drop associated with the run-down phase of pumps or closure of valves may lead to sub-atmospheric pressures at high points along the pipeline profile (or even along the whole length of the pipeline), which can lead to unacceptable conditions such as seepage of contaminants through pipe joints and the formation of vapour cavities. Air inlet/outlet valves may be used to limit the pressure drop by holding the pressure at a value close to atmospheric, thus preventing these unacceptable conditions. Air inlet/outlet valves, intended for use during filling and emptying, may be inadequate for surge protection. The pressure rise that occurs after the discharge from a pump has fallen to zero may be limited by the presence of the resultant air cavity, but 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 provides simple, approximate methods that may be used to guide the selection of air inlet/outlet valves required to protect liquid-filled lines from excessive sub-atmospheric pressures following pump trip or valve closure. Graphical data are provided that allow conservative estimates to be made of the maximum mass flow rate, and hence volume flow rate, of dry air through the valve and the maximum volume of the resulting air cavity.

The data given in this Item are applicable to air valves that are located along a liquid-filled line such as that shown in Sketch 2.1. In this model, it is assumed that liquid is discharged from the pump along a single line from the upstream sump to a downstream constant pressure point, such as a large tank or reservoir. It is assumed that the pipe diameter and pipe wall friction factor are constant along the length of the line and there are no reflections of the pressure waves from the pipe bends and fittings, including the air valve inlet. Component losses are assumed to be small compared with the pipe friction losses and are neglected. The pump is protected by a one-way valve (commonly referred to as a reflux valve or check valve in the water industry) that prevents reverse flow through the pump by closing completely when the pump discharge falls to zero. It is assumed that the one-way valve remains shut and does not allow any further forward flow. The model will allow systems with pressurised tanks to be considered, provided suitable adjustments are made to the tank head values. The data given in this Item are also applicable to the downstream side of a closing valve in a liquid-filled line.



Sketch 2.1 Simple pump discharge line with one air inlet/outlet valve

A guide to the use and location of air valves in pipelines, both for normal operation and for surge suppression, is given in Section 3 of this Item. Guidance on the nature of pressure surges in pipelines protected by air valves is also given in that Section. In Section 4, data are presented that may be used to estimate the maximum mass flow rate into a line through an air valve located at a high point in a pipeline to protect against extreme sub-atmospheric pressures. Data are also presented in this Section that allow estimates to be made of the maximum volume of air at that location on the pipeline following the surge event. A worked example is presented in Section 5, and the equations that describe the air flow behaviour through air inlet/outlet valves are presented in Appendix A. The computer program, ESDUpac A8727, introduced in ESDU 87027 may be used to investigate the transient pressures following pump trip in a pipeline protected by air valves, and the effect of an air vessel placed at the pump outlet on those pressure changes.

3. GUIDE TO THE USE OF AIR INLET/OUTLET VALVES

3.1 Air Valve Usage Under Normal Operating Conditions

Several types of air valve are commercially available and are required to perform certain functions during the operating cycle of a pipeline system. Usually, these functions are as follows, for each part of the normal operating cycle.

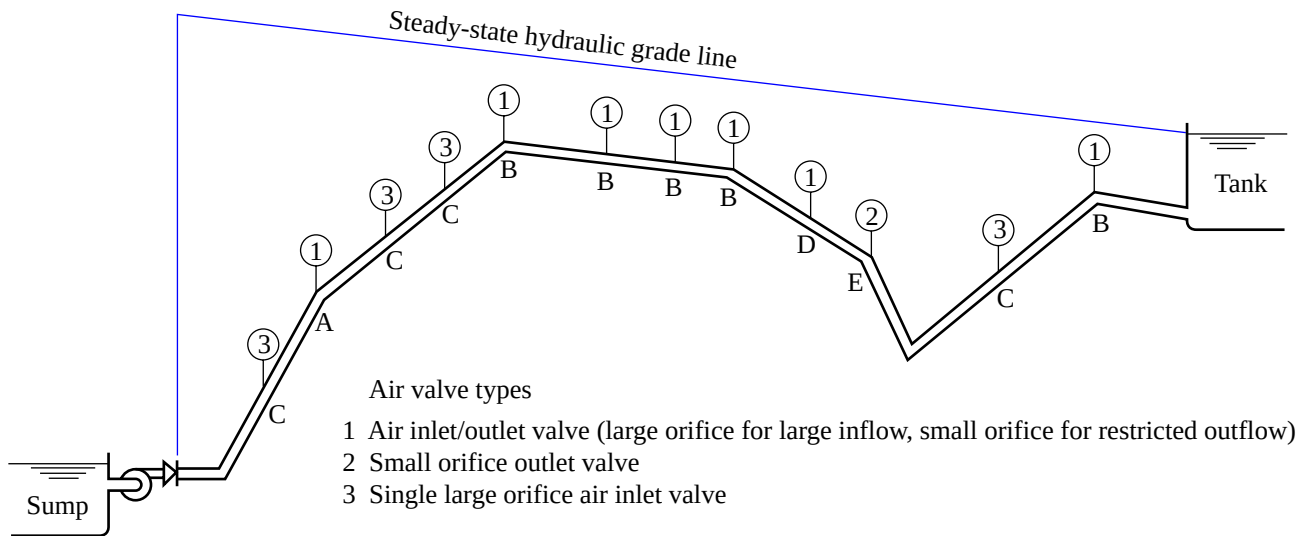
- (i) **Filling.** Air outlet valves should release air that has either accumulated in pockets at high points on the pipe profile or is present over a large section of the line (or even over the whole of the line). The presence of air pockets can severely restrict the flow rate and can even obstruct the flow completely.
- (ii) **Normal operation.** Air outlet valves should release air that has accumulated at certain points in the line in small quantities, thus preventing the air from restricting the flow. Air is usually present in water-filled pipelines under normal operating conditions as it may not be completely purged on filling, and pumps may introduce air (particularly in deep-well pumps) on filling. Air may be drawn through faulty joints or glands or dissolved air may be released from water due to changes in temperature and/or pressure.
- (iii) **Emptying.** Air inlet valves should allow air to be admitted into the pipeline during emptying in sufficient quantities, and at suitable locations, to prevent excessive sub-atmospheric pressures.

Typical locations of air valves along pipelines to achieve the above conditions are shown in Sketch 3.1. This sketch shows a cross-country pump discharge line and indicates the location points for air valve types, but each system must be considered on its own merit. The choice of air valve type and location may be made from the following criteria.

- (A) Changes of pipeline slope. Use air inlet/outlet valves (commonly referred to as double orifice valves, comprising a large orifice air inlet valve for high inlet air mass flow rates and a small orifice air outlet valve for releasing small quantities of air), small orifice air outlet valves being essential.
- (B) Peaks (including lengths parallel to the steady-state hydraulic grade line). Use air inlet/outlet valves at each peak and each end of a parallel length and, if necessary, at regular intervals (typically 800 m or 2600 ft) along the parallel length.
- (C) Ascending stretches (relative to the steady-state hydraulic grade line). Position single large orifice air inlet valves at regular intervals (typically 400 m to 800 m or 1300 ft to 2600 ft apart), provided the gradient is greater than about 1 in 500.
- (D) Descending stretches (relative to the steady-state hydraulic grade line). Position air inlet/outlet valves at regular intervals (typically 400 m to 800 m or 1300 ft to 2600 ft apart).
- (E) Abrupt increase in downward slope (relative to the steady-state hydraulic grade line). Use a small orifice air outlet valve.
- (F) Place an air inlet/outlet valve upstream of reducing tapers, orifice plates or similar obstructions, and place a small orifice air outlet valve downstream of pressure reducing valves.

In general, air valves should be spaced more closely in regions where air may be present in the system or where air may be released from solution due to low pressures (especially in regions close to the steady-state hydraulic grade line).

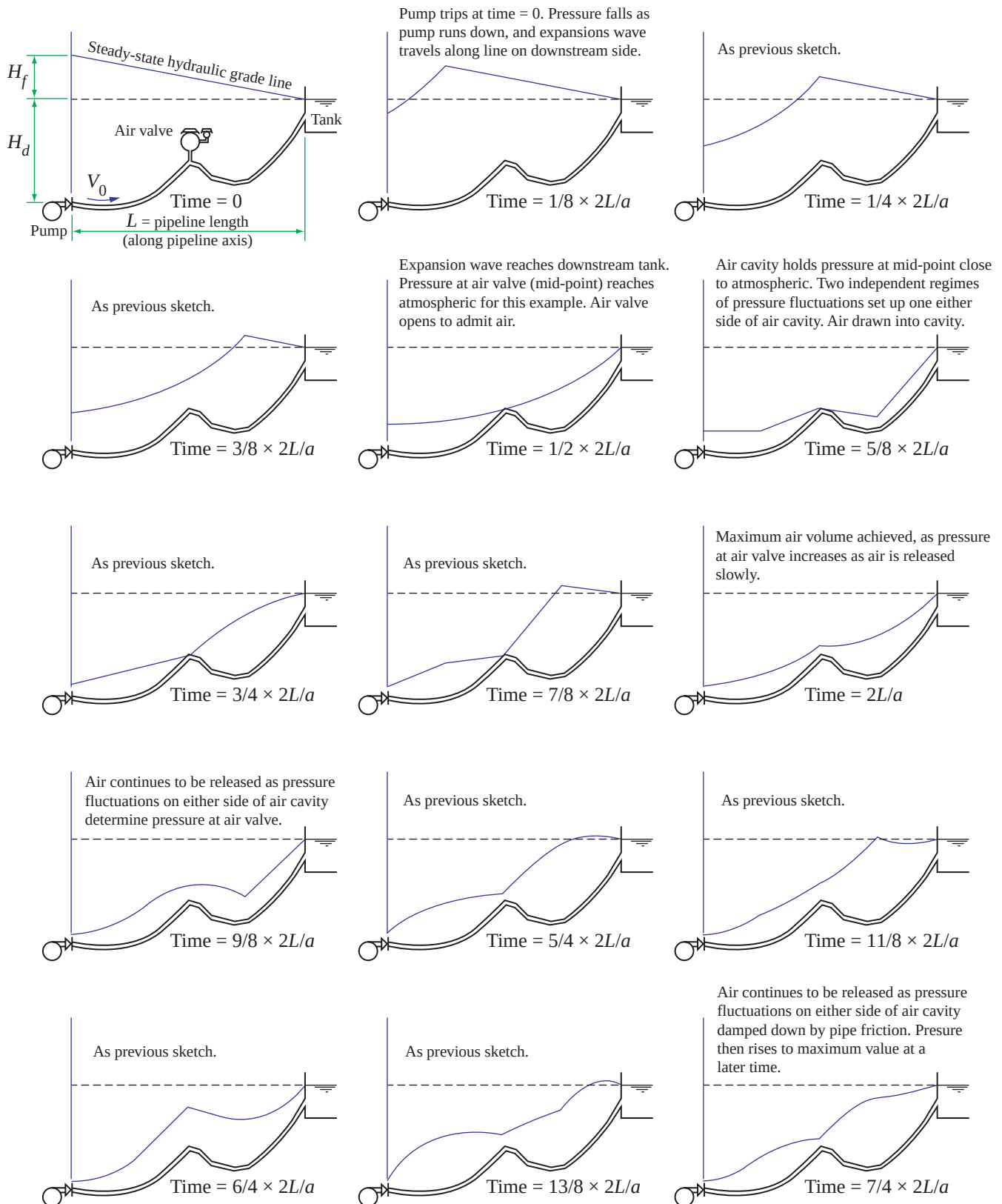
Further guidance on the use of air valves for normal operating conditions is given in Derivations 1, 2, 3 and 4, and air valve manufacturers provide guidance on the sizing and location of suitable air valves. Air valves suitable for normal operation may not be suitable for surge protection, particularly when air valves allow a rapid outflow of air following the inflow of air into a pipeline.



3.2 Alleviation of Pressure Surges Using Air Inlet/Outlet Valves

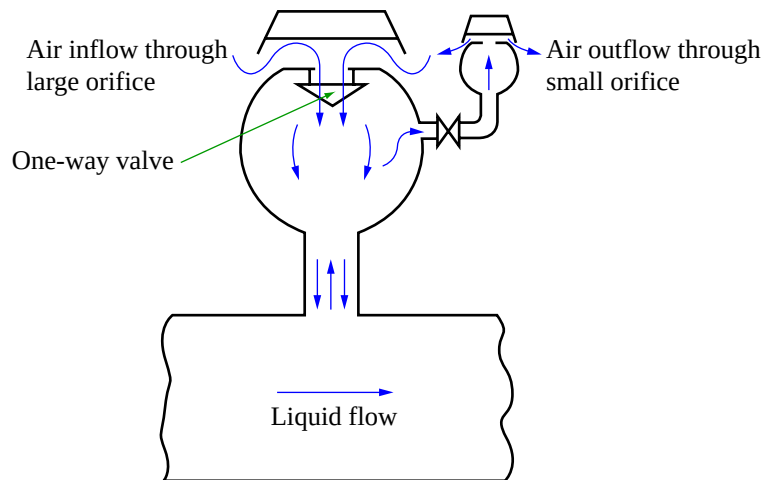
3.2.1 Use of air valves in otherwise unprotected lines

Air inlet/outlet valves may be installed in certain types of pipelines to admit air into the line when the pressure in the pipe falls to atmospheric following a surge event such as pump trip. In order to maintain the pressure near atmospheric, the air valve should open automatically to allow air freely into the line. The liquid column breaks at the peak and the cavity is filled with air, reducing the pressure differential between the pipeline and the atmospheric pressure at the inlet vent of the valve. The air is retained in the pipeline temporarily and must be released slowly as the pressure increases. The throttled outflow of air acts as a cushion to prevent the violent collapse of the cavity between the two ends of the broken liquid column and the throttled outflow helps prevent the large surge pressures that are associated with cavity collapse. A typical sequence of events following pump trip in a pump discharge line protected by a single air valve is shown in Sketch 3.2. In this example, it is assumed that the discharge from the pump gradually falls to zero as the pump runs down and, because immediate closure of the one-way valve situated at the pump outlet is assumed, no reverse flow occurs through the pump.



Sketch 3.2 Sequence of events following pump trip in discharge line protected by air inlet/outlet valve

In order to achieve the beneficial effects described above, air inlet/outlet valves must be used that allow sufficient air to flow freely into the line and to ensure that the air is released slowly. This may be achieved using a differential throttle arrangement, with outflow through a small orifice for slow air release. It may be necessary to use a one-way valve arrangement to prevent outflow through the large inlet orifice. A typical air valve arrangement suitable for surge control is shown in Sketch 3.3. It is recommended that air valves of this type replace air valves specified only for normal operation at locations along the line where sub-atmospheric conditions are expected following flow shut-off. Conventional air inlet/outlet valves may allow adequate air inflow rates but may not restrict the air outflow, which may result in large pressure increases as the air cavity collapses rapidly. Data are presented in ESDU 84038 that may be used to estimate the magnitudes of pressure changes in a pump discharge line following pump trip. These data indicate the locations along the line where the pressure falls below atmospheric.



Sketch 3.3 Air inlet/outlet.

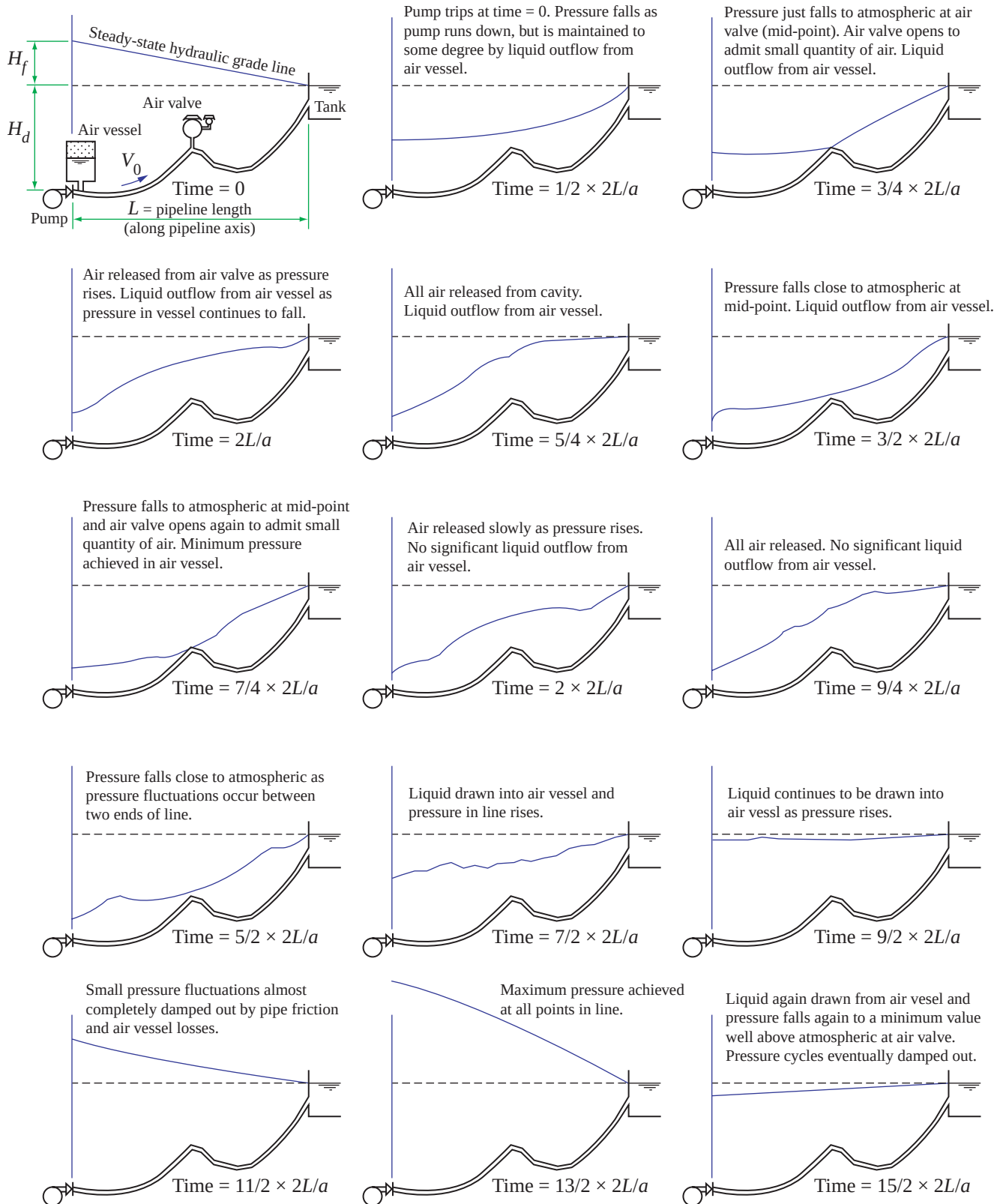
It is important that all the air is released as the presence of even a relatively small quantity of air may alter the characteristics of the system in both normal operation and during subsequent surge events. Careful design of pipelines, to incorporate sufficient air outlet valves at locations where air is likely to be present, should avoid this problem (see Section 3.1).

3.2.2 Use of air valves in conjunction with air vessels

Air inlet/outlet valves may have a beneficial effect when used in pipelines that are protected against pressure surge by specially designed surge suppression devices such as air vessels or surge shafts. Air valves are often used as surge suppression devices on pump discharge lines protected by air vessels. Generally, smaller air vessels are required when high points in the line are protected by air valves. A typical sequence of events following pump trip in a pump discharge line protected by an air vessel located at the pump outlet and an air inlet/outlet valve at a high point is shown in Sketch 3.4. In this example, it is assumed that a one-way valve isolates the pump at the instant of pump trip and flow is maintained to some degree by outflow of liquid from the air vessel. Data are presented in ESDU 84038 that may be used to estimate the size of air vessels for the protection of pump discharge lines. Further guidance on this use of air valves is given in Reference 8. It may be noted that, in some cases, the presence of air in a line may cause secondary reflections of pressure waves that could significantly alter the performance of the air vessel (or surge shaft).

3.3 Air Valve Maintenance

The air valves described in Sections 3.2 and 3.3 are by necessity of automatic operation. In order for the valve to function correctly at all times, regular maintenance is required. Most air valves are enclosed in chambers that should, under most conditions, protect the valve from environmental effects. However, problems may arise due to damage to the inner surface of the float chamber or the accumulation of deposits, preventing the valves from seating properly. In some cases, particularly with large orifice valves sealed by ball floats, adhesion can occur between the float and the seat preventing correct operation when the pressure falls. This adhesion can occur if the valve remains closed for long periods. It is advisable to provide an isolating valve to allow the valve to be removed from the pressurised line for maintenance purposes. Valve manufacturers provide guidance on the use and maintenance of air valves.



Sketch 3.4 Sequence of events following pump trip in discharge line protected by air vessel and air inlet/outlet valve