EFFECTIVE DE-AERATION OF PIPELINES AND THE USE OF CAPTURED AIR TO MITIGATE DYNAMIC PRESSURES

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Abstract

Pipelines operate optimally when effectively de-aerated. The reality is that pipe failures, intermittent operation, and maintenance will result in sections of a pipeline to be partially or fully drained. During charging and operation, air has to be captured and released in a controlled manner to minimize the induced pressures. This requires an understanding of the hydraulic transportability, sizing and location of air valves and the dimensioning of the discontinuity to intercept the transported air.

Trapped air enhances the system's elasticity, reducing the pressure spikes resulting from operational changes. These interrelated aspects should be considered to achieve hydraulic effective, sustainable and safe operating systems.

Keywords:
De-aeration of pipelines, required size of the discontinuity to capture free moving air, transient's suppression by air.

1 INTRODUCTION

The optimization of the hydraulic capacity of water transfer systems has the underlying assumption that the pipeline is effectively de-aerated. Pipe failures, intermittent operation, and maintenance will result in sections of a pipeline to be partially or fully drained from time to time. During the filling and charging of the lines, air has to be released in such a manner to control the induced pressures associated with the slam of the air valve and the deceleration of the approaching water column towards a vent at the point in time when all the air has been released. The misconception related to benefit of a high discharge capacity of air valves, have resulted in various pipe failures.

Effective de-aeration of a pipeline requires that:

- Free air should be transported hydraulically in the pipeline to positions where it can be released;
- A discontinuity in the crown of the pipeline should be provided, to allow the free air to enter into a holding space (the accumulator) below the air valve where the water can be displaced, providing storage capacity for the air before being released through the air valve;

- A facility with sufficient volume (accumulator) should be provided for temporal storage of the air which has been intercepted through the discontinuity; and
- Correctly sized air valves or vents should be positioned along the pipeline at the required locations.

In this article the hydraulic transportation of air, the required features to capture the transported air during operation and the beneficial presence of air to soften/reduce the dynamically induced pressures are discussed.

2 CONSEQUENCES OF AIR IN PIPELINES

2.1 Introduction

The consequences of air in pipelines and how it is introduced and expelled from the pipeline can either be detrimental or beneficial. In the following paragraphs a selected number of these aspects are discussed (Van Vuuren, et al., 2004).

2.2 Detrimental consequences of air in pipelines

2.2.1 Reduction of hydraulic capacity

Pipelines, which are not effectively de-aerated, can experience a substantial loss of hydraulic capacity. When an air pocket is present in a pipeline the flow is restricted and an additional secondary head loss occurs. The quantification of the extend of the secondary energy loss was based on the notion that the air pocket creates a reduction in the cross sectional flow area and that the head loss is proportional to the size of the air pocket (Wisner, 1982). Pipelines with steep gradients and numerous peaks are prone to experience these additional secondary head losses. Correctly sized and placed air valves can, however, prevent the secondary losses related to presence of free air. Deny and Young (1957) in Wisner (1982b) found that 1% of free air in a pipe system can reduce the hydraulic capacity by up to 15 %. In extreme cases, the air pockets can completely block the flow, the so-called air lock condition (**Figure 1**), where the sum of the vertical dimension of the water columns (A+B+C) is more that the shutoff head of the pump.

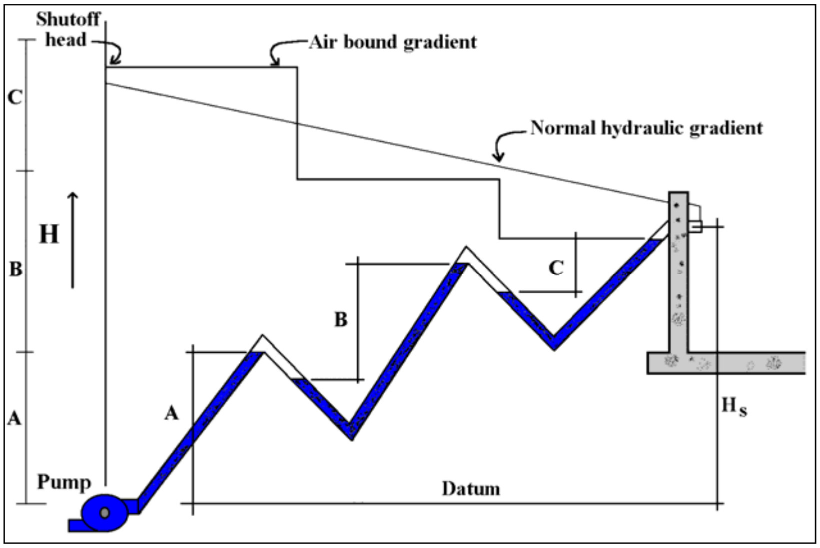

Figure 1: Undulating profile which could create an air block

2.2.2 High induced pressures during uncontrolled air release

Air valves are sized for intake conditions, limiting the negative pressures inside the pipeline to prevent sonic intake conditions from occurring. With the intake size determined, it might be possible that during discharge under moderate to high internal pressures, the high discharge rates could lead to high induced pressure spikes (uncontrolled air release).

When air is released from a pipeline in an uncontrolled manner (too high discharge rates), pressure surges are induced, which could lead to pipe failure (Van Vuuren, 1993). The viscous and density difference between air and water will result in an almost instantaneous deceleration of the approaching water column at the point when all the air has been released. This is especially true for incorrectly sized (too large) vents/air valves.

The inclusion of a dynamic shield in some air valve designs to maintain large discharging flow rates, accentuated this problem (Van Vuuren, 1993). Three-stage air valves were developed to discharge air through the intake orifice and then switch to a smaller intermediate orifice at a low differential pressure. The intermediate orifice restricts the discharge rate and hence the induced pressure resulting from the deceleration of the water column.

In a simplified conceptual model of a nearly horizontal pipeline, shown in **Figure 2**, (Van Vuuren, 1989) where air is released from the pipeline under a pressure of 2 Bar absolute through an opening with diameter, d_0, the outlet velocity will be sonic, say 300 m/s. Assuming a discharge coefficient of 0,7 the volumetric discharge through an opening with area, $\pi \frac{d_0^2}{4}$ will approach $210\,\pi \frac{d_0^2}{4}$. The volume of water approaching the opening from both sides through which the air is released, should be equal to the air volume released. It therefor follows from continuity, that:

$$2\pi \frac{D^2}{4} V_{water} = 210\,\pi \frac{d_0^2}{4} \text{ and hence } V_{water} = 105 \frac{d_0^2}{D^2} \tag{1}$$

Continuity of energy for flow through an orifice yields:

$$V_{water} = C_v \sqrt{\frac{2P}{\rho_{water}}} \tag{2}$$

With:

V_{water} = average velocity of water released under a pressure differential of P, m/s
C_v = velocity coefficient

At the point in time when all the air has been discharged, the water approaches the opening at about the same volumetric flow rate as that of the expelling air. Due to the higher density of the water it will be decelerated from the discharge rate of the air to that of water. The deceleration will be inversely proportional to the following relationship:

$$\left(\frac{\rho_{water}}{\rho_{air}}\right)^{0.5} = 28 \tag{3}$$

This almost instantaneous deceleration of the water column will lead to high induced pressures.

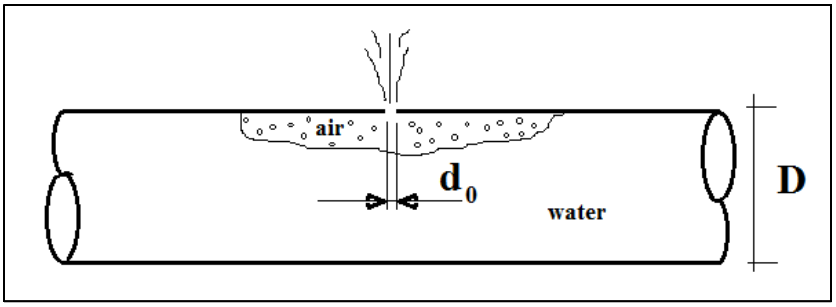

Figure 2: Simplified model layout to demonstrate the potential induced pressure spikes resulting from air release

Lingireddy, et al., (2004) proposed the following relationships for the expected increase in pressure, ΔH for the un-choked (H_A/H_{atm} < 0,529) and choked conditions (H_A/H_{atm} > 0,529):

$$\frac{\Delta H}{\frac{C}{g}} = 0.3944\left\{e^{-0.029(\ln H_A)^2+0.425(\ln H_A)+5.206}\right\}\left(\frac{d_o}{D}\right)^2 \tag{4}$$

$$\frac{\Delta H}{\frac{C}{g}} = 0.3944\{0.425H_A+494\}\left(\frac{d_o}{D}\right)^2 \tag{5}$$

Where:

H_A = internal absolute pressure of the air, m
H_{atm} = absolute atmospheric pressure head, m
d_o = orifice size, m
D = pipe diameter, m
c = wave speed (sometimes referred to as celerity- or sound-speed – in this example the value was set at 1000 m/s), m/s

The potential rise in pressure resulting from discharging air at a pressure head of 10 m through a 50 mm air valve on a 600 mm diameter pipeline ($d_o/D = 0.0833$), could be 139 m! If the air valve was equipped with an intermediate orifice of say 10 mm, then the rise in pressure would have been only 5.6 m. This emphasizes the necessity to release air in a controlled manner, a feature which is provided by the 3 stage air valves.

2.3 Beneficial consequences of air in pipelines

2.3.1 Reduction in wave celerity reduces the transient pressures

The presence of free air in the water reduces the pressure surges due to the reduction of the wave celerity that can be calculated as follows (Wylie et al, 1993). The wave celerity in an elastic pipeline, with a mass of air of m per unit volume, compressing isothermally with a gas constant R, an absolute temperature of T and compressible fluid could, be determined by:

$$c = \sqrt{\frac{K}{\rho}\left(\frac{1}{1+\frac{K}{E}\frac{D}{t}+\left(\frac{mRT}{p}\right)\left[\left(\frac{K}{p}\right)-1\right]}\right)} \tag{6}$$

Where:

D = Internal diameter of pipe, (m)
E = Modulus of elasticity of the pipe material, (N/m^2)
K = Bulk modules of water, (N/m^2)
p = absolute pressure, (m)
m = mass of air per unit volume, (kg)
t = wall thickness of the pipe, (m)
T = absolute temperature, (°K)

2.3.2 Trapped air in an accumulator reduced the induced pressure spikes

The compressibility of the trapped free air, functioning similar to a pressure vessel or bladder tank, enhances the system's elasticity and reduces the pressure spikes resulting from operational changes. The available storage volume, initial air volume and system elasticity will be reviewed for each specific case to determine the reduction in the induced pressures.

3 DESIGN CONSIDERATIONS

3.1 Introduction

The hydraulic transportation of air, the required discontinuity to capture the transported air during operation and the beneficial presence of air to soften/reduce the dynamically induced pressures are an integral part of a pipeline design.

3.2 Hydraulic transportability

A sound understanding of the factors affecting the hydraulic transportation of air in a pipeline is paramount for locating air valves. The movement of large air pockets in pipelines has been subject to a number of investigations falling into the following categories:

- Rising velocity of an air pocket, V_{g0}, in a closed conduit with a layout at different slopes under stationary or dynamic conditions, and;
- The required average water velocity, V to sweep the air pocket downstream with the flow, for various pipe inclinations and bubble sizes.

Although surface tension, inertia forces, viscosity and buoyancy forces influence the movement of air in water carrying conduits, it has been shown that in the context of pipeline engineering, only the inertia forces and buoyancy forces are significant. Wisner et al. (1975) have indicated that viscous effects were dictated up to Reynolds numbers, R_e, $\left(\frac{VD}{\upsilon}\right)$ of 10^5. For the case where buoyancy and inertia forces are dominant ($R_e > 10^5$), it follows from the balance of forces on the bubble that:

$$\frac{1}{2}\rho_L C_D A_g V^2 = (\rho_L - \rho_g) g Vol \qquad (7)$$

With:

ρ_L = density of the liquid, kg/m^3
ρ_g = density of the gas, kg/m^3
V = average velocity of the liquid, m/s
Vol = volume of the gas bubble, m^3
A_g = projected area of the air bubble in a plane normal to the direction of the velocity, m^2
C_D = drag coefficient

By simplification and substitution it was shown that the rising velocity, V_{g0} of the air pocket can be determined by:

$$V_{g0} = K_1\sqrt{gD} \quad \text{where } K_1 \text{ is a constant} \tag{8}$$

Kalinske & Bliss (1943) as well as Wisner, Mohsen & Kouwen (1975) suggest empirical formulae defining the critical velocity to hydraulically remove the air. The formulae were derived from the results obtained in tests performed on inclined pipes transporting a range of different sizes of air bubbles. The proposed formulae based on different air bubble sizes, yielded different values for the critical velocity to hydraulically transport air and are related to the slope and diameter of the pipeline:

$$\frac{Q_c}{gD^5} = 0{,}707\ \tan\theta \tag{9}$$

During the hydraulic transport of the air bubbles, it can either be 'swept' (removed as a whole) or entrained into the solution. The water velocity required to transport the air is referred to as the clearing velocity, V_c.

The maximum bubble volume reviewed by Wisner et al was approximately 0.67 times the representative conduit volume $\frac{\pi D^3}{4}$ and the results were presented in a graphical format, with $\frac{V_c}{\sqrt{gD}}$ plotted on the vertical scale and $\sqrt{\sin\theta}$ plotted on the horizontal axis. In **Figure 2** the results obtained by Kent (1952) are also shown.

The observed data were enclosed in an envelope line, which was then proposed as the design relationship (Wisner, et al., 1975) for the clearing velocity, V_c:

$$\frac{V_c}{\sqrt{gD}} = 0{,}25\sqrt{\sin\theta} + 0{,}825 \tag{10}$$

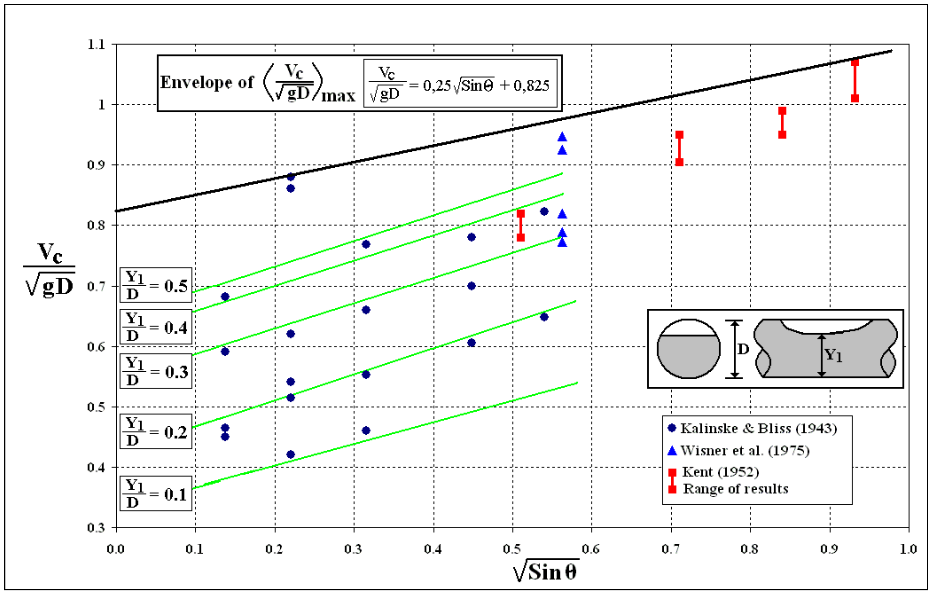

Figure 2: Comparison of Kent's formula with his experimental results

The clearing (sweeping) velocity to remove an air pocket has been investigated by several authors Mechler (1966), Kent (1952) and Ahmed, et al. (1984). When their findings are plotted in a non-dimensional form of $V_c/\sqrt{gD}$ against the angle of the conduit (θ) it is noted that the clearing velocity to remove air pockets is generally larger than the rising velocity of air pockets in stationary water.

The clearing velocity increases with relatively larger air pockets, denoted in **Figure 3** by *n*, which is the ratio of the air pocket volume to a representative conduit volume $\frac{\pi D^3}{4}$. Gandenberger's (1957) results indicate a maximum clearing velocity required at a conduit angle of about 50°. Kent's results do not indicate any such maximum value, probably due to the fact that the value of θ was not increased beyond 60° by Kent (1952) and hence he proposed the following relationship for clearing velocitiy:

$$V_c = 1{,}62\sqrt{\xi}\,\sqrt{gD\sin\theta} \qquad (11)$$

where the value of ξ is 0,58 when the air pocket reaches a certain size (L_b / D >1,5 – with L_b the length of the air bubble).

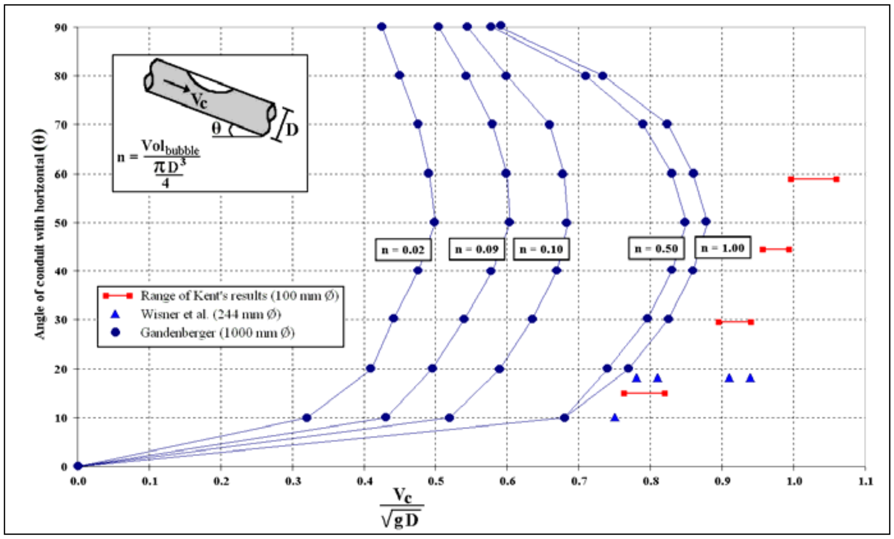

Figure 3: Clearing velocity for the removal of air from a pipeline

When the water velocity under the air pocket becomes supercritical, a weak hydraulic jump is formed on the downstream tail of the air pocket. If this is combined with an average velocity greater than 0,8 m/s in the pipe, entrainment of air bubbles occur and are transported downstream, thus reducing the air bubble. The reducing air bubble might at a point in time be swept along the pipeline. Ahmed, et al. (1984) investigated this for angles between 10° and 90° and found that the velocity upstream from the bubble must be at least 1,5 m/s to transport the air and suggested that to reduce the air pocket, the velocity should be more than 0,9 m/s.

Based on experimental work conducted on a 110 mm and 160 mm diameter transparent uPVC pipeline with the velocities varied between 0,5 and 2,0 m/s, the slope varied between 0 ° and 15 ° and the relative air bubble size ($\frac{Vol_{air}}{\frac{\pi D^3}{4}}$) varied (0,024 < n < 0,540), it was found that the required velocity to hydraulically transport the air could be determined by the following relationship (Van Vuuren, et al., 2004):

$$V_{min} = a\sqrt{gD}\,\theta^{b} \qquad (12)$$

Where;

θ = slope in degrees
a and b = constants shown in **Table 1** for different size air bubbles (n)

Table 1: Values for the constants a and b in Eq. (12) for the different air bubbles sizes reviewed

Bubble size	n	a	b	Goodness of the fit - R^2
Small	0,024	0,2068	0,3716	0,9254
Medium	0,072	0,2178	0,4007	0,9185
Large	0,540	0,2703	0,3686	0,8513

Escaramela, et al., (Escarameia, et al., 2004) proposed the following relationship for the clearing velocity (V):

$$\frac{V}{\sqrt{gD}} = 0.5599\,(\mathrm{Sin}\ S)^{0,5} + a \qquad (13)$$

Where;

S = slope in degrees
a = constant shown below for different size air bubbles

Table 2: Value of the constant a used in Eq. (13) for different air bubble sizes (n)

n	a
<0,06	0.4526
0,06≤ and < 0,12	0.5033
0,12 ≤ and < 0,30	0.5739
0,30 ≤ and < 2,00	0.6065

Figure 4 provides a comparison of the required clearing velocities suggested in Eq.(12) (Van Vuuren, et al., 2004)) and in Eq. (13) (Escarameia, et al., 2004).

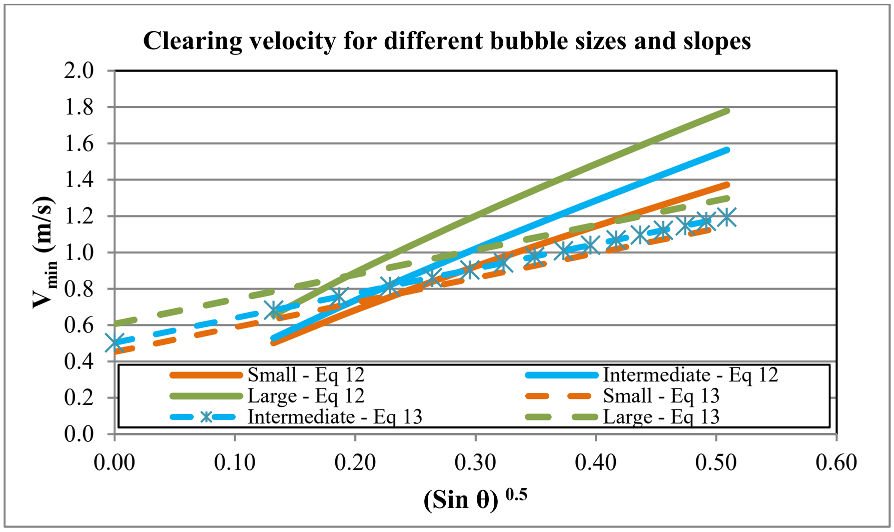

Figure 4: Required velocity to hydraulically transport air bubbles with different sizes

3.3 Discontinuity to capture the air

An important aspect of air valve installations that have been largely neglected is the dimensioning of discontinuities in the pipe, through which free air is intercepted. The size of the discontinuity for effective interception of the air has a cost implication and hence has to be sized optimally. Since no deterministic relationship has been formulated and no literature was available to define the required sizing of the discontinuity, this aspect was experimentally researched.

The parameters that dominate the interception of the free air are:

- Mean velocities of the fluid and air bubbles;
- Relative air bubble sizes;
- Pipe slope; and
- Size of the discontinuity (off take) underneath the air valve.

Experimental set-ups consisted of transparent pipes that were fed from a constant head tank and the flow rate was regulated through a downstream gate valve. Two different pipe diameters, viz, Test 1 with a 110 mm nominal diameter (ND) uPVC and Test 2 with a 160 mm ND uPVC pipe were assessed.

Table 3 reflects details of the tests which were conducted by allowing a known volume of air (special apparatus) into the pipeline and capturing the volume which was either discharged at the end or intercepted through the discontinuity.

Table 3: Summary of some features of the experimental setups to capture the air hydraulically transported

Test	Pipe diameter (mm)	Slopes evaluated °	Velocities evaluated (m/s)	Discontinuity type	Size of the discontinuity (mm)
1	110	0-15	0,5 – 1,5	Orifice	10 to 65
2	160			Vertical off take pipe	20 to 160

Figure 5 shows the off take pipe used in Test 2 to capture the air.

Figure 5: Vertical off take pipe used in Test 2

In both Test 1 and Test 2 it was observed that smaller bubbles entered the discontinuity more easily than the larger bubbles, due to the tendency of larger bubbles to block the discontinuity, making it impossible for the liquid to be displaced by the air bubbles.

The results from both these tests emphasized that the following aspects should be considered when a de-aeration system is designed:

- Firstly, the discontinuity should be sufficient in size to intercept the air bubbles, and
- Secondly, the air which is intercepted at the discontinuity should be contained in an "accumulator" with sufficient volume from where the air would be released under normal operating pressures (small orifice function of the air valve).

All tests on the discontinuities were executed at negative pipe slopes. In the case of positive slopes the bubble velocity will be much greater for the same liquid velocity and hence for a specific discontinuity a smaller portion of the air will potentially be captured. A larger size discontinuity should thus be considered for positive pipe slopes.

The experimental work indicated that the air bubbles did not always travel at the top of the pipe and that a disturbance, which creates turbulence, would break up the air pockets and mix the air through the entire cross section and would reduce the efficiency of the discontinuity to intercept air.

The complex nature of air movement and factors that influence the efficiency of the discontinuity, suggests that a conservative approach should be used when dimensioning a discontinuity to effectively intercept air bubbles in a pipeline. Applying this within the practical and financial constraints of water distribution systems design, the size of the discontinuity for effective de-aeration during pipeline operation should be based on the following recommendations (van Vuuren & van Dijk, 2012):

- The minimum discontinuity required for small pipes diameters (D < 300 mm) should be set equal to the diameter (an equal T). An equal T-piece is a standard pipe fitting for these diameters (**Figure 6**).
- For diameters between 300 mm and 1 500 mm the discontinuity should be equal to 60% of the pipe diameter but always greater than 300 mm.
- Pipes with diameters in excess of 1 500 mm the discontinuity should at least be 35% of the pipe diameter, with a minimum of 900 mm, serving as an access point.

Figure 6: Provision made for an air valve on a 700 mm diameter water main

Based on the earlier comment that the air bubble will be transported at a higher velocity in pipelines with positive slopes, a conservative selection of the diameter of the discontinuity should be considered.

3.4 Reduction of transients by trapped air

The design of the air valve installations for larger diameter pipelines, where multiple air valves are required, is to ensure that the closure of the air valves does not create high induced pressures and that the captured air volume can be employed to reduce the induced pressures.

This can be achieved by ensuring that air valves are closed in a staggered manner and by doing so, the remaining air which is captured above the air valve, is used as a closed surge tank to reduce the pressure spikes. The benefit of such a staggered layout of the air valves and the captured volume of air could be determined by conducting the necessary surge analyses. This concept has been incorporated with success and some of the installations are reflected in **Figure 7** and **Figure 8**.

Figure 7: Staggered installation of air valves on a 1,9 m diameter pumping main

Figure 8: Installation in preparation for a staggered installation of air valves on a 3,5 m diameter pipeline

Figure 9 diagrammatically indicates how air valves could be arranged to ensure sequential closing and also to trap a certain air volume in the riser pipe, reducing the dynamic pressure fluctuations by functioning as a closed surge tank.

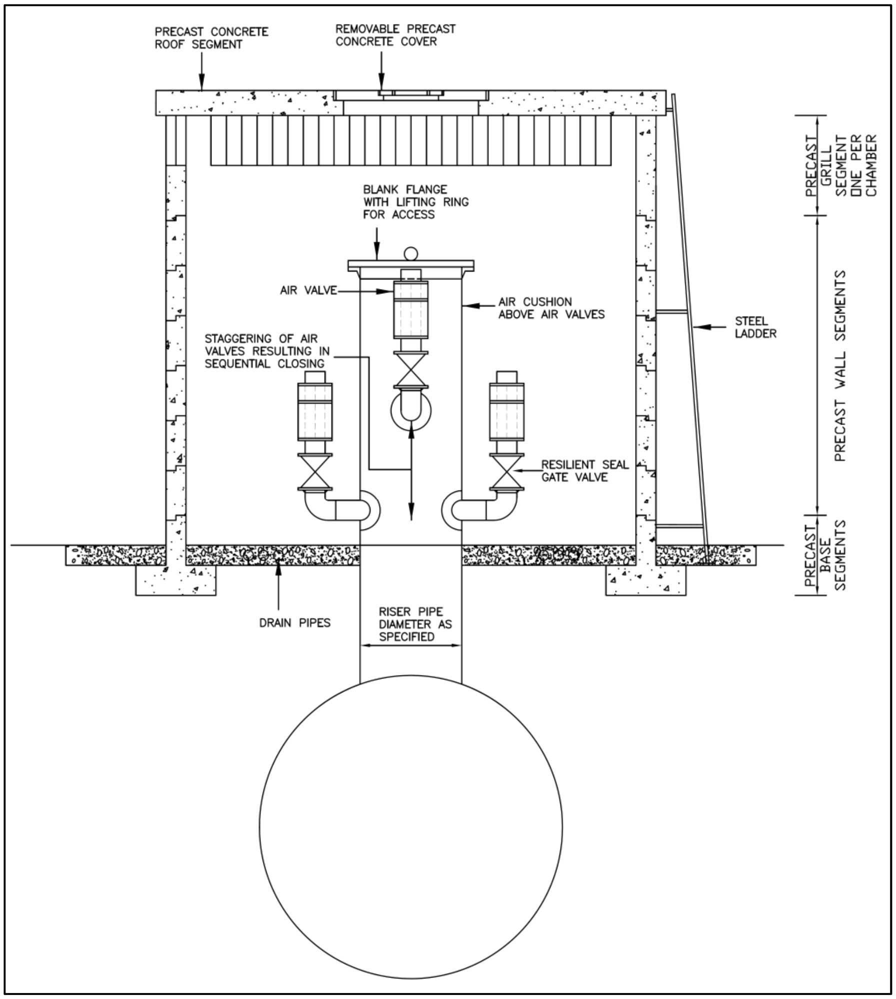

Figure 9: Air valve arrangement to ensure sequential closing and providing air cushions to reduce the induced pressures

4 CONCLUSION

The optimization of the size, location and layout of air valve installations should be considered during the design of pipelines to achieve an optimal operating system, but also harness the installations as surge alleviating devices.

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