

## Abstract

*This paper focuses on the hydrodynamic behavior of liquid pipelines in the presence of air valves. The aim of installing such valves on pipeline systems is twofold: on one hand, they release the accumulated air content and on the other hand, they allow the outer air to entrain the system when the internal pressure falls beneath ambient pressure (i.e. vacuum formation). We study the hydraulic transients in the presence of such air valve by means of experimental and numerical methods. The experiments were performed using a special test section where the pipeline close to the air valve was built from plexi-glas allowing visual access. Furthermore, pressure signals were recorded at several locations of the pipeline. Numerical analysis was also performed using the commercially available CFD software (ANSYS CFX). It was revealed that the entrained air separates well from the primary liquid and the mixture behaves as two distinct phases.*

## Keywords

*air valve, hydraulic transients, multiphase flow, CFD simulations*

## 1 Introduction

### 1.1 Purpose of air valves

In hydraulic systems (e.g. water distribution systems, sewage systems) there are numerous phenomena during the dynamical behaviour that needs to be coped with as early as in the phase of design. Most importantly, pump shutdown due to failure in the power supply is a common origin of hydraulic transients: loss of the pump creates pressure waves with high amplitude that could lead to the dilapidation of the system. Such transients can lead to two typical wave characteristics. The first typical case is when there is a positive pressure wave that adds to the operational pressure of the system causing a high pressure peak that cannot be tolerated by pipes material, resulting in pipe rupture or burst. The other regular source of the error is the negative pressure wave when vacuum is formed inside the pipes that typically leads to buckling. In this case, the integrity of the pipe is usually intact (i.e. there is no leakage), thus it is more difficult to detect.

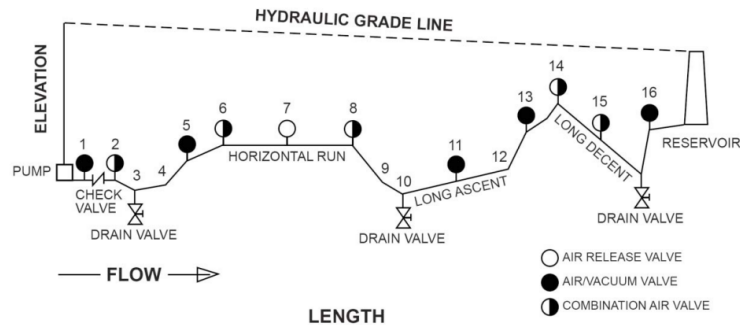
Another important aspect of water and wastewater systems that makes the use of air valves necessary is the presence of air in a pipeline. Air in pressurized systems may have several sources. First, once the pipeline was built, prior to first start-up, it is full of air. Once the system is started, most of the air content will be washed out by the liquid, but a remarkable amount of air remains trapped at system high points. Secondly, dissolved air content of water might also accumulate at high points. Finally, air also enters the system through mechanical elements: pumps, fittings or valves. These air pockets cause reduced flow-through area and hence act as „valves”, causing additional energy loss.

### 1.2 Literature overview

Researching the manufacturers catalogues [1-3] revealed that the methodology of sizing air valves is usually based on empirical data. Most of them suggest the use of a pipe burst analysis using one of the common flow formulas, such as the Hazen-Williams equation, the Darcy-Weisbach equation, the Manning formula, the Chézy formula or a similar equation derived from these ones. These methods all use empirical

<sup>1</sup> Department of Hydrodynamic Systems,  
Faculty of Mechanical Engineering,  
Budapest University of Technology and Economics,  
H-1521 Budapest, P.O.B. 91, Hungary

\* Corresponding author, e-mail: [rweber@hds.bme.hu](mailto:rweber@hds.bme.hu)



SAMPLE PIPELINE PROFILE ILLUSTRATING VALVE LOCATIONS					
No.	Description	Recommended Types	No.	Description	Recommended Types
1	Pump Discharge	Air/Vacuum for Pumps	9	Decr. Downslope	No Valve Required
2	Incr. Downslope	Combination	10	Low Point	No Valve Required
3	Low Point	No Valve Required	11	Long Ascent	Air/Vac or Combination
4	Incr. Upslope	No Valve Required	12	Incr. Upslope	No Valve Required
5	Decr. Upslope	Air/Vac or Combination	13	Decr. Upslope	Air/Vac or Combination
6	Beg. Horiz.	Combination	14	High Point	Combination
7	Horizontal	Air Rel or Combination	15	Long Descent	Air Rel or Combination
8	End Horiz.	Combination	16	Decr. Upslope	Air/Vac or Combination

Fig. 1 Typical location of air valves, taken from [2].

formulae in order to estimate the velocity in the pipelines based on the friction factor, the pressure difference, hydraulic radius or the slope of the pipe. However, a widely accepted and validated sizing technique that is built on theoretical foundation in order to evaluate the amount of air content in the hydraulic system does still not exist.

One of the few articles on numerical modelling of air valves are [4] and [5]. [4] handles the flow as one-dimensional with the idea that the entrapped air can be modelled using boundary conditions and the fully filled up pipeline can be solved using the standard method of characteristics. Unfortunately, [5] does not give enough detail about the modelling aspects, but both articles have promising results.

## 2 Air valves

### 2.1 Air valve types

Air valves are one of the simplest devices for the protecting the pipeline against hydraulic transients. Basically there are three different types of air valves in the aspect of the function:

- **Air/vacuum valves** are capable of letting ambient air in the case of vacuum (ca.  $-2...4 \text{ mmH}_2\text{O}$ ), this way on one hand it limits the pressure, on the other hand the admitted air makes the system softer, therefore reduces the amplitude of the pressure waves.
- **Air release valves** are able to vent the entrapped air out to the ambient environment, thus they prevent its accumulation at high points.
- **Combination air valves** are the fusion of the previous two.

Air valves must be placed at locations where there is a high probability of the issue that the air valve is able to prevent. The AWWA Steel Pipe Manual [6] recommends air valves at the following points along a pipeline:

- **High points:** Combination air valve.
- **Long horizontal runs:** Air Release or Comb. Valves from 380 to 760 m interval.
- **Long descents:** Combination Valve from 380 to 760 m interval.
- **Long ascents:** Air/Vacuum Valve from 380 to 760 m interval.
- **Decrease in an up slope:** Air/vacuum valve.
- **Increase in an up slope:** Combination Valve.

Obviously every air valve with single function can be substituted with a combination air valve.

Fig. 1 shows a simplified sample pipeline to represent how the different types of air valves should be distributed along the system that contains typical specifics.

### 2.2 The examined air valve

In this study we used an *ARI D-040* air valve for experiment and numerical analysis, which is a combination air valve. Its cut-away can be seen in Fig. 2 (source: [1]). The venting operation lets the air out to the ambience in small packages due to the construction. This function is necessary during the filling or emptying of a newly deployed pipe system. Furthermore, the valve reduces the negative pressure waves with admitting ambient air.

Fig. 2 shows the detailed construction of the examined combination air valve. The most important part of this device is the float indicated with brown and the elastically connected closing element (disk). On the left-hand side figure the air valve is closed which means the pressure of the system is larger than the ambient pressure, moreover there is no air inside the pipes. The right-hand side figures show when the air valve is open, i.e. the float is at the lower position. This can occur in two different cases: either when the system is in vacuum thus the ambient

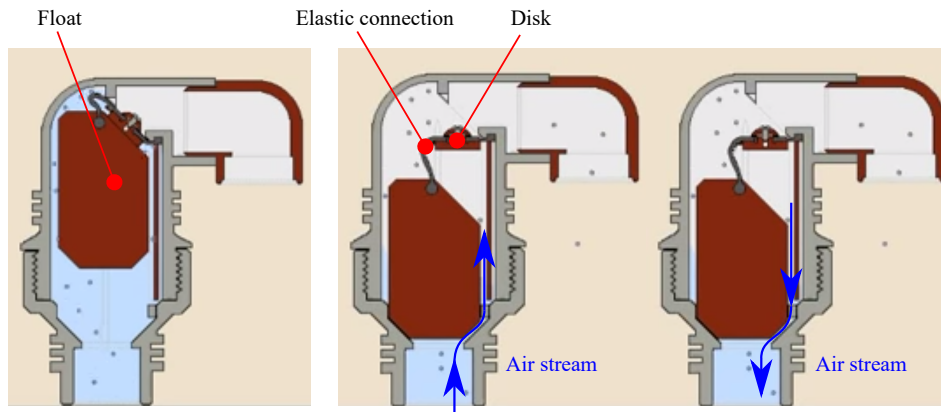


Fig. 2 Cross-section of the air valve in the three states, source: [8]. Left: closed, overpressure in the pipe without air content. Centre: open, overpressure in the pipe with air content, Right: open, vacuum in the pipeline.

air is entering or when the air content of the system is vented through the open valve.

When sizing such valves, the most important piece of information is its capacity, i.e. the flow rate as a function of the pressure difference through the valve. The characteristic of the combination air valve is available at website of the manufacturer, see [1].

### 3 Experiments

#### 3.1 Measurement layout

The air valve was built in an already existing transient measurement system at the laboratory of the Department of Hydrodynamic Systems. That segment of the pipeline, to which the valve was mounted, was re-designed in such a way that it allowed visual access to the pipeline (for details, see Section 3.2).

The modified construction can be observed in Fig. 3. The overall length is approximately equal to 133 m. A centrifugal pump (placed slightly under the ground) transfers the water from the lower tank through the whole pipeline to the upper container (fixed on the wall of the lab). The pump is driven by an electric motor that is controlled by a variable-frequency drive, thus the volume flow rate could be easily set. After the pump there is a hydraulic gate valve, which is capable of closing the flow rate with high speed, therefore it creates the negative pressure wave (vacuum) which is necessary for the activation of the air intaking. The gate valve is controlled by a hydraulic system allowing simple and accurate repeatability of the measurements.

The position of the measurement device (that includes the air valve) is indicated with the blue arrows, while the red arrow depicts the position of the air valve. The colored stars illustrate the pressure measurement points. The first (red) one is just after the pump, the second (blue) is inside the measurement device under the air valve and the third one (green) is farther from the valve, in approximately 60 m distance.

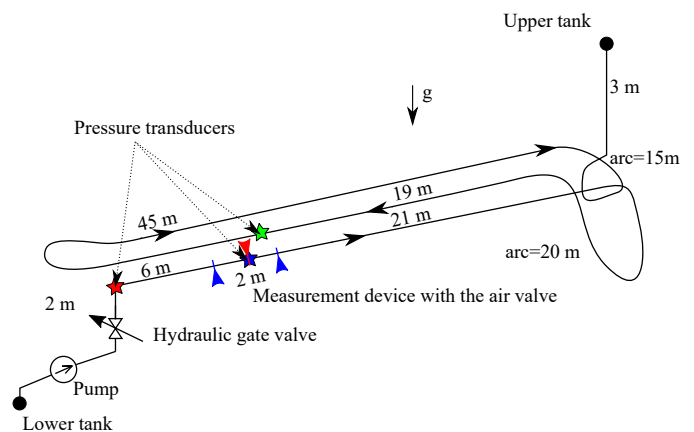


Fig. 3 Axonometric picture of the measurement system

#### 3.2 Design of the measurement segment

When designing the experiments, allowing visual access to the neighborhood of the valve was the primary aim, therefore plexiglas was chosen for the material of the mounting element. The most important part of the measurement segment (see Fig. 4) is the block that creates the T junction. It was glued using two pieces of plexiglas after the surfaces have been worked precisely parallel. As it can be observed there are two measurement points created in the plexiglas block. The pipes before and after the junction are also transparent and the air valve is sitting on top of the segment. Since there is also a ball valve between the air valve and the junction, it is possible to perform experiments with and without the air valve.

In order to protect the measurement device, the whole module was fixed to a welded structure. A metal plate was fastened with four screws to the back of the plexiglas block. Hollow sections, those are lead on beside the plexiglas pipes to support them, are also fixed to this plate. In overall we fasten the plexiglas structure in five locations to the metal sections in order to create a rigid block that is capable of protecting the device from its own weight and any additional load (e.g. hydraulic transients).



Fig. 4 Combination air valve sitting on the measurement segment.

### 3.3 Instrumentation and data acquisition

Two different volume flow rate were used with both states (open/closed) of the ball valve, thus we had four different cases. Every constellation was repeated min. 3 times in order to ensure the repeatability that was expected high due to the hydraulic controlled gate valve (that takes place after the pump at the beginning of the pipeline) and we found out that our measurement repeatability is sufficient. The first measurement was at the maximum performance of the electric motor where the volume flow rate was about 263 l/min. In the second case we reduced the performance to 80%, where the volume flow rate was approx. 198 l/min.

The type of the pressure transducers is P6A, manufactured by HBM. Every sensor was calibrated to absolute pressure. The data acquisition hardware was a HBM Spider8 device, sampling frequency was set to 9.6 kHz using with a Bessel-type low-pass filter.

### 3.4 Measurements

In this section we present four measurements series: two with high flow rate (with and without the air valve) and another two with lower flow rate (again, with and without air valve). Table 1 details the technical data of the measurement series. The final column provides an estimate of the pressure amplitude by means of the classic Joukowski theory ( $\Delta p_{Jouk} = \rho a \Delta v$ , see [9]), where the  $a$  represents the speed of the propagating waves,  $\rho$  stands for the density and  $\Delta v$  is the change in the velocity.

Table 1 Technical data of the measurement series.

case	initial flow rate litre/min	initial flow velocity m/s	bar
high flow rate	253	2.75	39.81
low flow rate	198	2.07	29.97

#### 3.4.1 Measurement without air valve

The first measurement was performed on higher volume flow rate with closed ball valve, i.e. without the air valve. After starting the data acquisition, we closed the pipe with the hydraulic gate valve to create the negative pressure wave (vacuum). Once the transient hydraulic pressure waves died away, we reopened the gate valve in order to examine the effect of sudden valve opening.

Fig. 5 shows one measurement data taken on higher volume flow rate without the air valve. The dashed line represents the atmospheric pressure (1 bar) and the horizontal axis the vacuum (0 bar). We can divide the experiment into three different parts:

- the direct effect of the gate valve closure (first second),
- the transient hydraulic waves (from 1 to 17 s) and
- finally, the reopening of the gate valve (from 17 s).

In the beginning the pressure decreases significantly at the pump side (red) and under the air valve (blue). It takes 0.3 seconds to reach the vapour pressure where cavitation appears. The pressure of the third point (green) reduces slower and it does not reach the critical pressure: after examining the numerical values carefully it turns out that its minimum value in the first seconds is about 0.1 bar, while the vapour pressure at room temperature is around 0.025 bar.

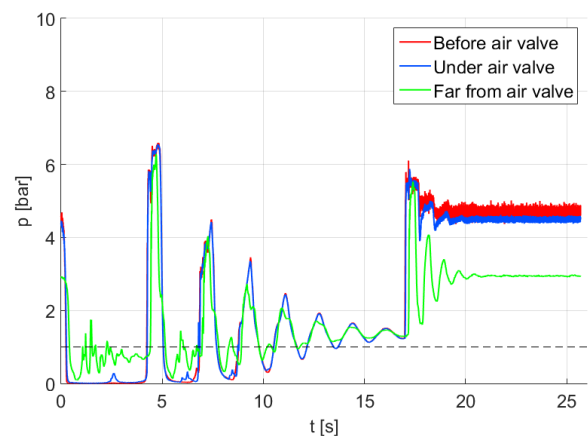


Fig. 5 Measurement data on higher volume flow rate without the air valve. To see the exact position of the pressure transducers see Fig. 3.

In the second part the transient hydraulic waves can be seen after the closure. It is important to notice that the system spends a remarkable time ( $>3$  s) in vacuum. Although far from the pump this phenomenon is attenuated, vacuum is still present in the segment beyond the valve - see the green line. The peak of



the first positive pressure wave reflected from the reservoir-end of the pipeline exceeds the initial steady-state pressure by ca. 45 %. The time intervals between the peaks are the following: 4.94 s, 2.65 s, 1.93 s, 1.73 s, 1.66 s, 1.71 s, 1.56 s. As these values show the velocity of the pressure surges were significantly smaller when the vapour was present in the pipeline and as it disappeared due to the higher pressure the reflection time intervals decreased. The eigenfrequency of the pipeline can be calculated with  $2L/a$  giving 0.18 s, which is smaller by an order of magnitude than the measurement values (after the vapour disappeared). The reason is that the presence of vapour decreases the sonic velocity to a large extent.

Finally, the oscillations tend to a decrease regularly to the new steady-state value, which can be easily approximated with a couple of simple assumptions as follows.

The pressure of the upper tank is atmospheric and the transducers are at the same height (3.3 m) measured the upper tank according to the Fig. 3 therefore

$$p = p_{atm} + \rho gh \approx 1.33 \text{ bar},$$

where  $p_{atm} = 1 \text{ bar}$  is the atmospheric pressure,  $h = 3.3 \text{ m}$  is the height of the water level in the upper tank and  $g$  is gravitational acceleration.

At the reopening (around 17 s) Fig. 5 shows the measurement data when the gate valve is reopened. As it can be observed there is a small overshoot, but the system reaches the operational pressure in approx. 3 s.

### 3.4.2 Measurement with air valve

In the next series of measurements the volume flow rate is the same as in the previous case, however as the ball valve is open, the air valve is now connected to the system. As we did before, first we made sure that the experiment has satisfying repeatability, thus we performed the same measurement several times and it has been revealed that it has truly a high repeatability.

The time history (see Fig. 6) can now be separated into four different parts:

- the direct effect of the gate valve closure (first half second),
- the huge positive pressure waves downstream (from 0.5 until 1.2 s),
- the transient hydraulic waves (from 1.2 until 38 s) and
- finally, the reopening of the gate valve (from 38 s).

Fig. 7 highlights the first moments after the closure. Comparing this to the previous case (see Fig. 5) we see that there are significant differences: there are two positive pressure waves with extremely high peak and one with moderately high amplitude on the red curve (downstream, before the air valve, see Fig. 3), both with very high frequency. These unwanted oscillations are clearly due to the presence of the air valve.

After these huge oscillations moderate pressure waves appeared with lower frequency content. It is important to notice

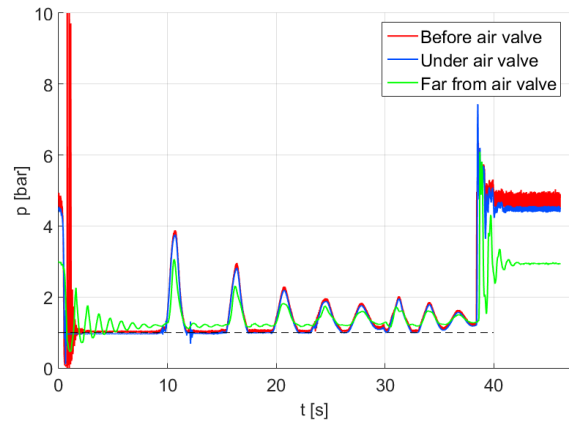


Fig. 6 Measurement data on higher volume flow rate *with the air valve*. To see the exact position of the pressure transducers see Fig. 3.

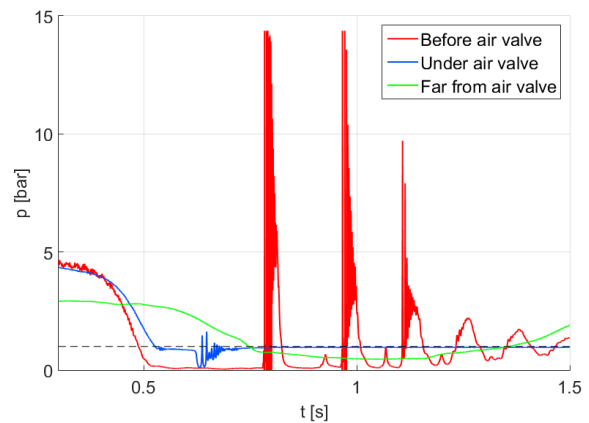


Fig. 7 First moments of the measurement data on higher volume flow rate *with the air valve*. To see the exact position of the pressure transducers, see Fig. 3.

the second remarkable difference: the pressure does not spend any time significantly below atmospheric pressure, like it did in the previous case without the air valve, this simply means that the air valve works properly. Furthermore - as expected - the pressure converges to the already calculated 1.33 bar value.

Finally, the reopening shows slightly higher pressure waves compared to the previous case, but the differences are small.

Similar conclusion can be drawn from the measurement with the lower volume flow rate. In this case without the air valve the system spends significant time under atmospheric pressure, where cavitation appears. On the other hand, with the air valve positive pressure waves with huge amplitude appear without the presence of the vapour bubbles.

### 3.5 The conclusion of the measurement

Due to the specially designed measurement device the experiments and the phenomena inside the pipeline could be seen directly. We were able to examine the relationship between the two phases (water + vapour) during the opening of the air valve. The experiments revealed that the admitted air is gathered at the upper side of the pipeline. A well-defined interphase is present between the air and the water, i.e. instead of a homogeneous mixture as this can be seen in Fig. 8.

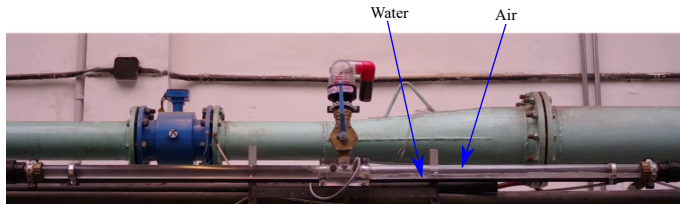


Fig. 8 Illustration of the relation between the phases (water + air).

Due to the ball valve measurements could be performed with and without the air valve thus its effect to the pressure waves could be clearly demonstrated. It became clear that it reduces the vacuum inside the pipeline, furthermore it prevents the appearance of the cavitation. However, this type of air valve also has a drawback, because it generates huge, high-frequency positive pressure waves on the downstream side. Having said that, it has to be added that this specific air valve is one of the simplest constructions and there are more demanding designed air valve that can solve this problem.

#### 4 CFD analysis of the pipeline dynamics in the presence of the air valve

This chapter will present the numerical analysis of the experiment when the ball valve was open thus the air valve was part of the pipeline system. This means that besides water, air will be present in the pipe and the numeric techniques has to be able to cope with the presence of two phases. We decided to use the commercially available ANSYS CFX for such simulations.

The simulations are concentrating on the pipeline, therefore the air valve and the gate valve was modelled as simple boundary conditions. Only the horizontal part of the pipeline was analyzed (containing the air valve), the neglected vertical part and its pressure drop will be compensated at the outlet with a higher pressure.

In order to ensure the stability of the simulation the first order numerical schemes had to be applied with standard k-ε turbulence model. The gravitational force has an important role in the separation of the phases thus it was turned on. There was a second phase (air) added to the simulation with the ideal gas material model.

##### 4.1 Geometry

The geometry of computational domain can be seen in Fig. 9 with the block structure of the mesh and boundaries. The geometry contained 7 m straight pipe before the valve and 123 m length after the valve. The actual values of the geometrical parameters can be seen in the Table 2, these were given according to Fig 3. Since ANSYS CFX can only handle three dimensional case, the geometry had to be extruded into three dimension with arbitrary w thickness.

##### 4.2 Mesh

For mesh generation, the Gmsh (free) software was used. There are two aspects that had to be taking into consideration

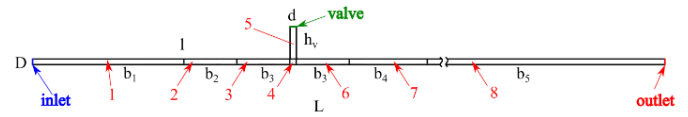


Fig. 9 Geometry of the computational domain with the block structure and boundaries.

while creating the mesh. Firstly, the largest gradient of the field variables is expected in the neighbourhood of the junction, so the grid should be here the finest and far from it should be coarser. Secondly, the maximum number of vertices or cells cannot exceed 500k in order to keep the CPU time relatively low. To meet these expectations, the geometry was divided into eight rectangular blocks as it can be seen in Fig. 9 with the parameters listed in Table 2. The meaning of the properties is the following: the *progression* creates a linearly growing distribution of nodes and the number gives the ratio between the neighbouring cells, the *bump* does the same in both direction, but the number gives the ration between the largest and the smallest cell.

Table 2 Parameters of the mesh

Geometry	Size	Nodes	Property
D	45 mm	27	Bump 0.25
d	50 mm	31	Bump 0.25
b <sub>1</sub>	5 m	450	Progression 1
b <sub>2</sub>	1 m	200	Progression 1.01
b <sub>3</sub>	1 m	800	Progression 1
b <sub>4</sub>	2 m	300	Progression 1.009
b <sub>5</sub>	119.95 m	6500	Progression 1
h <sub>v</sub>	0.5 m	300	Progression 1.005
w	50 mm	1	Progression 1

These settings with the linearly growing transitions ensure that the sudden size changes are lower than 30 % (as suggested in [7]).

##### 4.3 Boundary Conditions

There are two phases present in this simulation: the air is modelled as ideal gas, but the water cannot be handled with the default incompressible liquid, because the effect of the closure would be unphysically sudden and numerically unstable. We defined its density as a function of the absolute pressure as follows

$$\rho_{water} = \rho_0 (1 + p/B)$$

where the  $\rho_0$  is equal to the density of water at 25 °C (997 kg/m<sup>3</sup>) and  $B$  is the Bulk modulus (2.1 GPa).

Fig. 9 shows the names of the boundaries of the geometry. The front and back faces were set to symmetry in order to create a two dimensional model. The inlet was a velocity inlet with the time function

$$v_{in}(t) = \max\left(v_0 - \frac{v_0}{t_{cl}}t, 0\right)$$

where  $t \geq 0$ ,  $v_0$  is coming from the measurement with the higher volume flow rate (2.75 m/s) and  $t_{cl} = 1$  s that is estimated based on measurement and numerical simulations.

The outlet boundary was set to opening with prescribed 1.33 bar pressure. The opening allows the flow in both directions which is expected in our case. Based on simulations the wall had a roughness with 3 mm in order to create the operational pressure distribution along the major pipeline that was experienced during the measurement.

The most important boundary condition is the valve, since it had to model the complexity of the combination air valve: intake the ambient air in case of vacuum and model the trapped air in the pipeline system in case of overpressure. We used prescribed velocity based on volume fraction ( $\alpha = V_{air}/\Sigma V$ , equals one in case of pure air, equals zero in case of pure water and if there is a mixture it is between one and zero) and the pressure difference ( $\Delta p$ ) between the average at the valve ( $\bar{p}_{valve}$ ) and the atmospheric ( $p_0$ ). The velocity has to be zero if there is an overpressure without air, positive (vent) if there is vacuum and negative (intake) if there is overpressure and presence of air inside the pipe. This can be also seen in Table 3.

**Table 3** Velocity inlet boundary modelling the air valve.

$v_{valve}$	$p_{valve} \geq p_0$	$p_{valve} < p_0$
$\alpha_{valve} = 1$	positive (vent)	negative (intake)
$\alpha_{valve} < 1$	zero	negative (intake)

The velocity can be determined by the capacity [1] (pressure difference – volume flow rate diagram) of the combination air valve that can be assumed it is built up by two parabolic functions, one for the intake and one for the vent, thus both can be written as

$$\Delta p = CQ^2$$

where the  $C$  is a constant value and  $Q$  is the volume flow rate. Since we will use a prescribed velocity depending on the pressure difference at the boundary we need to substitute  $Q = vA$  ( $A$  is the cross section) and rearrange, thus

$$v = \text{sign}(\Delta p) \frac{Q_x}{\sqrt{\Delta p_x}} \frac{1}{A} \sqrt{|\Delta p|}$$

where  $Q_x$  and  $\sqrt{\Delta p_x}$  are coming from the catalogue of the air valve.

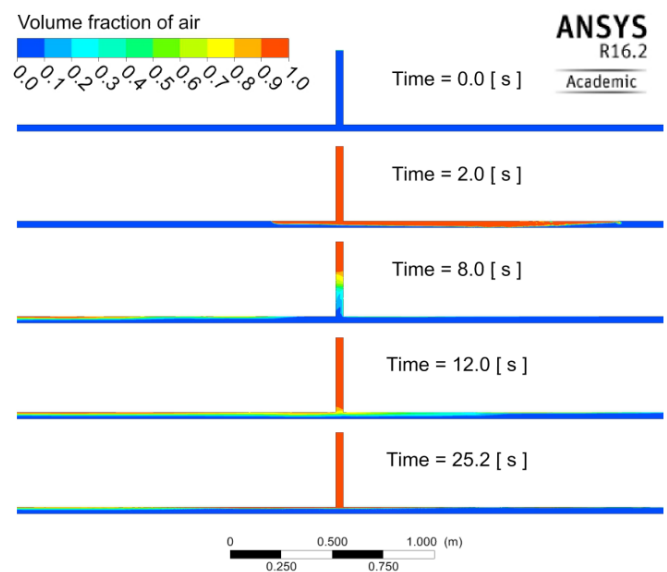
Since two phases appear in the simulation it is necessary to define a proper boundary condition for the volume fraction. At the inlet boundary only the water can enter therefore we prescribed a constant value. The valve boundary got also a prescribed value, but here the air is the only phase presented.

However, we do not know which phase leaves at the outlet (both water and air can be present at that surface), thus “zero gradient” was chosen.

To obtain the initial values for the transient case we used the wall boundary condition at the valve and the whole pipeline system was filled up with water, except we placed some air at the valve, because based on the first runs at the beginning of the intake the simulation can be unstable if there is no air in the pipeline. Because of this the air venting function was turned off in the first 0.5 seconds (which does not generate any problems because the first venting is expected when the first returning wave reaches the valve and that will be after seconds). The time step was set to constant  $10^{-3}$  s, where the Courant number was around 3. The simulation calculated 25.2 s and it took 20 days on a PC with average performance.

#### 4.4 Results

Fig. 10 shows the volume fraction distribution of air around the junction in five different time instances. The fluid flows from the left to the right. At  $t=0$  s the initial conditions can be seen (the whole pipeline is filled with water except a thin layer at the valve boundary). The next figure at  $t=2$  s depicts a snapshot of the first air intake. It is important to notice that the phases are separated with a well-defined surface as it was experienced during the experiments. The third figure in the series shows the effect of the first returning pressure wave: it can be seen that the air flows either backwards (to the left from the valve) or leaves the system through the air valve. The next one ( $t=12$  s) presents the second air intake, the free surfaces can be still observed. The last figure of the series introduces the last calculated time step which shows that almost the whole horizontal part of the pipe is filled again with water.



**Fig. 10** Volume fraction of air distributions around the junction in different time steps.

Fig. 11 presents the pressure distributions along the axis of the major pipeline in the same time instances as the volume fraction distributions in Fig. 10. Basically, due to the air valve the pressure is maintained around the atmospheric pressure without any significant vacuum. After a couple of seconds, the pressure distribution converges to the prescribed pressure at the outlet (1.33 bar).

Observing Fig. 10 and Fig. 11 together a small mistake can be noticed related to the valve boundary condition: there is some air trapped inside the pipeline while there is overpressure and no water at the boundary. On one hand, this is due to the horizontal layout of the pipeline, on the other hand, the problem is related to the fact that the average volume fraction of air at the valve is not equal to one but some numerical error occurred. Therefore, in further simulations this has to be considered and a slightly modified condition is necessary to be applied e.g.  $\bar{\alpha}_{valve} > \alpha_0$  where  $\alpha_0$  is a constant value below 1.

Three absolute pressure monitor points were also defined at the axis of the major pipeline to the positions where the measurements were also taken, see Fig. 3. The pressure time history at these points are depicted in Fig. 12: the red and blue lines (before and under the valve boundary condition) intersect in most of the points, but more important is that the pipeline does not spend a significant time below atmospheric pressure. The green data series indicates oscillations with high frequency, but these are physically irrelevant and in reality the ambient structure (material of the pipeline, fixation of the construction etc.) around the fluid would have a damping effect to reduce these waves.

### 5 Comparison between the measurements and the numerical analysis

This chapter will represent the comparison between the numerical analysis and the experiment, when the ball valve was open i.e. the combination air valve was part of the system. The basis of the analysis will be the pressure data thus I will use monitor points from the simulation.

Fig. 13 shows the pressure data in the first 25 seconds: the brighter line is from the measurement, the darker one is from the numerical simulation and the same color refers to the same point (to see the exact position of the measurement and monitor points see Fig. 3).

The difference in the first few seconds indicates that the numerical method was not able to catch the high positive pressure waves occurring during the experiments downstream to the combination air valve, however, to identify the origin of these requires more research. Otherwise, the simulation follows the qualitative behaviour of the measurement although the reflection time, the frequency and the amplitude of the waves are slightly different. This can be explained as follows. The numerical method was restricted into two dimensions with symmetry boundary conditions which means it is only valid

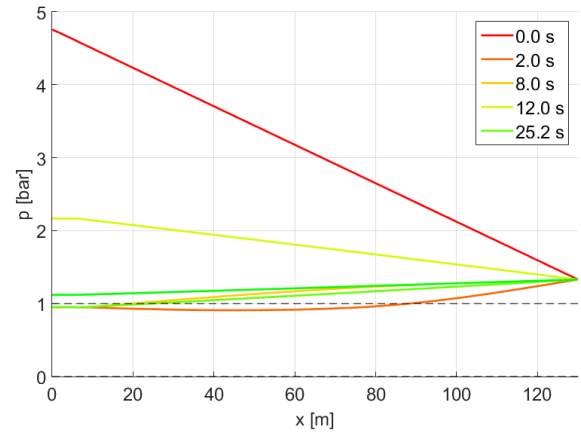


Fig. 11 Pressure distributions along the axis of the major pipeline in different time instants.

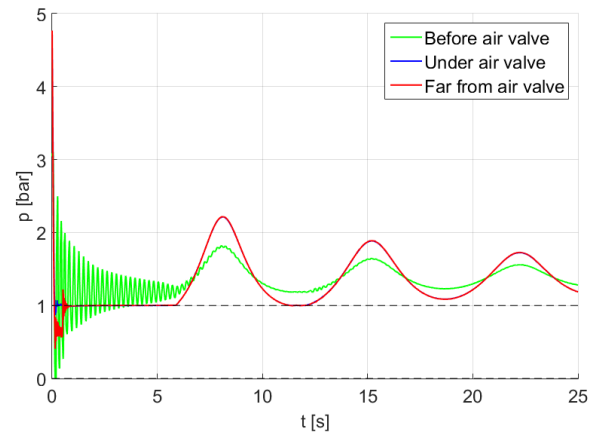


Fig. 12 Pressure monitor points of the simulation at the same positions where measurements were taken. To see the exact position of the pressure transducers during the experiment, see Fig. 3.

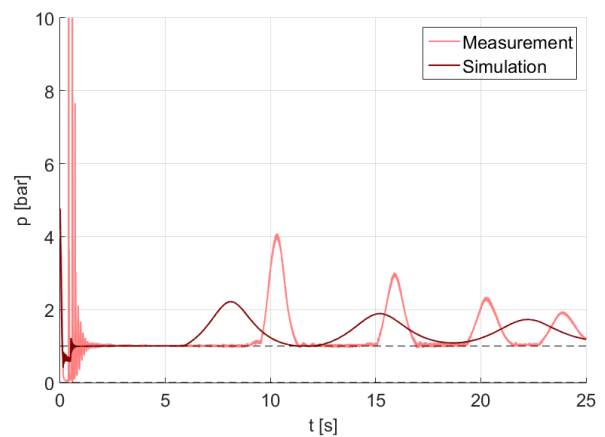


Fig. 13 Comparison between the measurement data and the CFD simulation at the first point, before the combination air valve. To see the exact position of the pressure points, see Fig. 3.

in the middle plane of the system. On one hand the flow in the pipeline is certainly three dimensional, but it is more important that the experiments were performed in a pipeline with circular cross section. The mismatch in the variables strongly depends on the amount of air inside the system (the height of the water



level) and in a cylinder it is varying horizontally that could not be taken into consideration in the simulation.

In overall this CFD simulation gives a good approximation for the experiment with a couple of restrictions e.g. the positive pressure waves downstream, reflection time etc. The discrepancies are likely to be due to the following issues.

- Lack of air valve internal dynamics. (Motion of the floating element, small-scale fluid dynamics inside the valve.)
- Residual air inside the pipeline in the CFD simulations makes the system “softer”, whereas in the reality, this does not happen.
- Simplified upstream boundary conditions.

Three dimensional simulation could give a more accurate solution, although it requires more cells thus the CPU time increases and that will require an advanced computer.

## 6 Conclusions

This paper introduced the experimental and numerical analysis of a combination air valve. The experiments were designed in such a way that the fluid mechanical phenomena inside the pipe could be accessed visually. It was revealed that the phases are not mixing but remain well separated giving rise to open-surface water flow inside the pipe. On the other hand, we performed pressure measurements with high frequency transducers at three different points simultaneously. The effect of the combination air valve was found to be twofold: on one hand, it protected the pipeline against significant vacuum, but it also created extra loading (positive pressure peaks) downstream to the valve. However, it is important to notice that there exist combination air valves with more demanding design those are capable of preventing those loads.

In the second part the CFD simulations revealed that it can be a working technique to calculate the effect of a combination air valve locally with the presented settings (slightly compressible water, pressure dependent velocity condition modelling the valve), but it requires a large amount of CPU efforts even in a two dimensional case. To obtain more precise results in aspect of the reflection time a three dimensional simulation is required and also the internal dynamics of the valve should be added to the model.

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