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Hydraulic Transients Caused by Air Expulsion During Rapid Filling of Undulating Pipelines

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Received: 15 October 2015; Accepted: 12 January 2016; Published: 19 January 2016
Academic Editor: Andreas N. Angelakis

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Abstract: One of the main issues arising during the rapid filling of a pipeline is the pressure transient which originates after the entrapped air has been expelled at the air release valve. Because of the difference in density between water and air, a pressure transient originates at the impact of the water column. Many authors have analyzed the problem, both from the theoretical and the experimental standpoint. Nevertheless, mainly vertical or horizontal pipelines have been analyzed, whereas in real field applications, the pipe profile is a sequence of ascending and descending pipes, with air release/vacuum valves at high points. To overcome lack of knowledge regarding this latter case, laboratory experiments were carried out to simulate the filling of an undulating pipeline, initially empty at atmospheric pressure. The pipe profile has a high point where an orifice is installed for air venting, so as to simulate the air release valve at intermediate high point of a supply pipeline. In the experiments, the diameter of the orifice and the opening degree of both upstream and downstream valves were varied, in order to analyze their effect on the pressure transient. The experiments were also carried out with a longer descending pipe, in order to assess the effects on the pressure surge of the air volume downstream of the orifice.

Keywords: air valve; hydraulic transients; entrapped air; experimental data; pipes system

1. Introduction

Entrapped air is an important issue in hydraulic engineering because of the serious operating problems arising with air expulsion. Air release/vacuum valves [1] are commonly used to release entrapped air accumulated during normal operation or the filling of a pipeline.

High pressure surge originates at the end of the filling phase, because of the impact of the liquid column on the valve, after the air has been expelled, due to the difference in density between air and water [2,3]. On the other hand, the presence of air can be beneficial in some conditions because of the cushioning effect of the air pocket, which operates as an air chamber, especially during the transient first phase. The drastic increase in the mixture elasticity [4] can result in a lower water hammer celerity causing pressure surge to decrease.

Air release valves play a key role in the transient following air expulsion from a pipeline. Despite their widespread application, data regarding efficiency and effectiveness of air release valves are still lacking, and little or no attention has been paid to maintenance and operational issues [5].

Theoretical and experimental analysis of hydraulic transients induced by air release from a rapidly filling pipe have been widely described in the technical literature. During air release, three pressure oscillation phases can be distinguished [6–9]: (a) a first rigid column phase during the pipeline filling until the air is completely expelled; (b) a second water hammer phase following the impact of the water column on the orifice; (c) a third phase with pressure oscillations around the steady state value, with progressively reducing pressure peaks because of flow friction. The maximum pressure surge is achieved in the second phase, when severe transients can arise at the impact.

By means of experiments in a rapidly filling horizontal pipe, Zhou *et al.* [10] showed the main role of the orifice size and driving head on each phase. When no air is released, or when the orifice size is small, water hammer effects are negligible because of the air pocket cushioning effect. When the orifice is very large, the cushioning effect of entrapped air vanishes and the water column can easily impact the pipe end, causing a significant pressure surge. For intermediate orifice sizes, the cushioning effect of the air pocket decreases as the air release rate increases.

In the experiments, three types of pressure patterns were identified, which correspond to different air-water interface shapes: for the first pattern, the water front is relatively free of entrained air and the water reaches the pipe end along the bottom first, whereas a vertical air-water interface occurs for the second one and an intermediate situation for the third case. The authors also showed that the air-water interface is steep for high filling velocity, whereas, for smaller orifices, a non-vertical interface occurs. In this case, a certain amount of air was entrapped as air pockets in the flow, thus causing the long period pressure oscillation to persist. Consequently, the Froude number of the flow becomes a critical issue governing the pressure transients that develop and should be taken into account when analyzing experimental results and extending laboratory results to field installations.

Similarly, Lee [11] observed that the pressure surge in a rapidly filling pipe is quite sensitive to the orifice size. Experiments were carried out on a horizontal pipe equipped with an orifice at the end, with size ranging from zero (closed end) to half size of the pipe diameter. Lee concluded that, for very small orifices, entrapped air operates like a spring and reduces pressure surge. For an orifice with intermediate size, air is expelled quite readily and the water column can have a high velocity at the impact. For a large orifice, water following air expulsion can have high velocity, but the impact may be minimal due to non-significant flow deceleration.

The volume of entrapped air also influences the peak pressure, as pointed out by many researchers [8,11–13]. Among these, Zhou *et al.* [8] carried out experiments on a horizontal pipeline by varying the length of the initial air pocket, showing that the peak pressure increases with the decrease of the air pocket length. In the case of undulating pipeline under a high initial void fraction of the air pocket, Zhou *et al.* [13] showed that the increase of the maximum peak pressure obtains through the reduction of the void fraction, because of the decrease of the air cushioning effect. The highest pressure occurs at a certain small void fraction, whereas for smaller values, the smaller space for the water movement decreases the water impact force and thus the maximum pressure reduces as well.

Other relevant results were obtained by many researchers, who analyzed air release through both orifices [8,12–14] and air release valves [7,15,16]. In many cases, the valve (or the orifice) was located at the end of an ascending pipe [2,7,12,13,16] or at the end of a horizontal pipe [8,11,17].

Nevertheless, in field installations, supply pipes are almost never horizontal or vertical, since the pipe profile is a sequence of ascending and descending pipes, with air release/vacuum valves at high points. Consequently, Balacco *et al.* [9] developed an extensive experimental research to analyze pressure surges arising during the filling of an initially empty undulating pipeline. The pipeline was made of U-PVC with outside diameter OD = 75 mm (inner diameter D 67.8 mm) and was fitted with an orifice for air venting at the high point. The experiments were carried out by varying upstream and downstream valve opening degree, orifice diameter d and pipe sloping angle α (11°, 22° and 30°).

When the downstream valve was closed, the maximum pressure surge was achieved for a diameter of the orifice depending on the pipe sloping angle. The ratio d/D at which the pressure surge is maximum was found to reduce at increasing sloping angle, ranging between d/D = 0.19 for α = 11° and d/D = 0.08 for α = 30°.

When the downstream valve was partially opened, the size of the orifice poorly affected the maximum pressure surge. Experiments showed that the larger the orifice diameter, the smaller the opening degree of the upstream valve for which pressure surge achieves the maximum values. Finally, in the case of a fully open downstream valve, the maximum pressure surge was found fairly independent of the valve diameter.

Because of the large data collected during experiments, Balacco *et al.* [9] did not discuss in detail the pressure pattern and the transient characteristics at varying upstream and downstream opening degree and orifice diameter. In addition, the effect of the length of the descending pipe was not analyzed in the paper, although many authors pointed out the role of the size of the entrapped air pockets. To this aim, laboratory set up was modified and the length of the downstream pipe was doubled with respect to the first series. Pressure transients were recorded and pressure pattern was identified at varying system characteristics. Collected data were also analyzed in terms of maximum pressure surge at the air vent section to obtain a preliminary estimate of the peak pressure.

2. The Experimental Setup

An experimental facility (Figure 1) was made to collect transient pressure data at the Laboratorio di Idraulica e Costruzioni Idrauliche of DICATECh at Politecnico di Bari. In the experiments, an Unplasticized Polyvinyl Chloride (U-PVC) pipeline was used, with *OD* 75 and nominal pressure 10 bar (D = 67.8 mm, s = 3.6 mm). Two butterfly valves at the pipeline inlet and outlet allowed variance of filling velocity during the experiments. The pipeline slope used for the experimental tests was 30°.

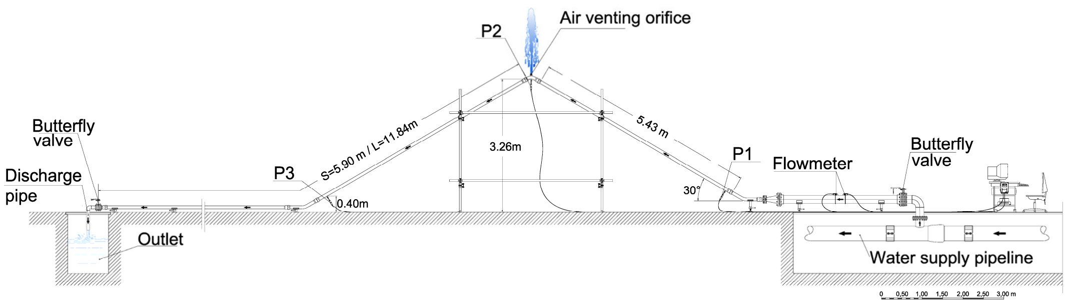

Figure 1. Experimental set-up.

Laboratory experiments aimed at simulating the filling of a pipe, initially dry at atmospheric pressure, through an air venting orifice. The pipeline has an undulating profile, with a high point in the middle, where an elbow and the orifice are installed, to simulate the intermediate high point of a conduit. The ascending pipeline, measured between the upstream valve and the air venting orifice, is 5.43 m long, whereas two configurations for the descending pipelines were considered in the experiments.

A first set of experiments was run with a shorter descending pipe, L_d = 5.90 m, measured again between the orifice and the downstream butterfly valve. The experiments were also run with a longer descending pipe (L_d = 11.84 m), aiming at analyzing the effects of the air volume downstream of the orifice on the pressure surge. For the sake of brevity, in the following, such configurations are referred to as S (configuration with shorter descending pipe) and L (configuration with longer descending pipe), respectively.

The pipeline is supplied by the laboratory hydraulic circuit, with a water tower ensuring a driving head of 16.3 m. An outlet pipe next to the downstream valve discharges water into a laboratory channel for recirculation.

Pressure and flow discharge were collected during experiments with a frequency of 300 Hz. Pressure was measured using pressure transducers ranging from 0 to 6 bar and collected using a National Instruments NI cDAQ-9174 analogue-digital converter. Three high-frequency response pressure transducers were installed along the pipeline, located at the beginning of the ascending pipe (P1); below the orifice (P2); and at the end of the descending pipe (P3). Flow discharge was measured using an ultrasonic flow meter, located upstream of the pipeline system. Pressure and flow transducers were calibrated in the laboratory and the accuracy and frequency response were verified before starting the experiments.

3. Results and Discussion

The experiments were carried out by manually turning the upstream butterfly valve and varying upstream (ψ_u) and downstream (ψ_d) valve opening degree, orifice size (d), length of descending pipe (L_d). For the sake of simplicity, the experimental variables used are summarized in Table 1. Orifice sizes were set according to commercial air vacuum valve sizes and to the need to preserve the ratio d/D between valve and pipe diameter suggested by manufactures (d/D = 0.094–0.375).

Table 1. Experimental variables used in the experiments.

Variable	*Value*
H_0 *(m)*	16.30
ψ_u (%)	25, 50, 100
ψ_d (%)	0, 25, 50,100
OD (mm)	75.0
D (mm)	67.8
d (mm)	6.4, 9.1, 12.7, 19.1, 25.4
L_d (m)	5.90, 11.84

A total of 120 configurations are analyzed. For each configuration, experiments were run at least five times to determine the consistency of results. In almost all cases, results show the repetitiveness of the transient under all the investigated configurations. For example, in Figure 2, the pressure surge at P2 following the opening of the upstream valve is plotted for S configuration and ψ_d = 100%, ψ_u = 50%, d = 6.4 mm. Data for all the five runs are plotted, exhibiting the same pressure pattern and small deviations from the average.

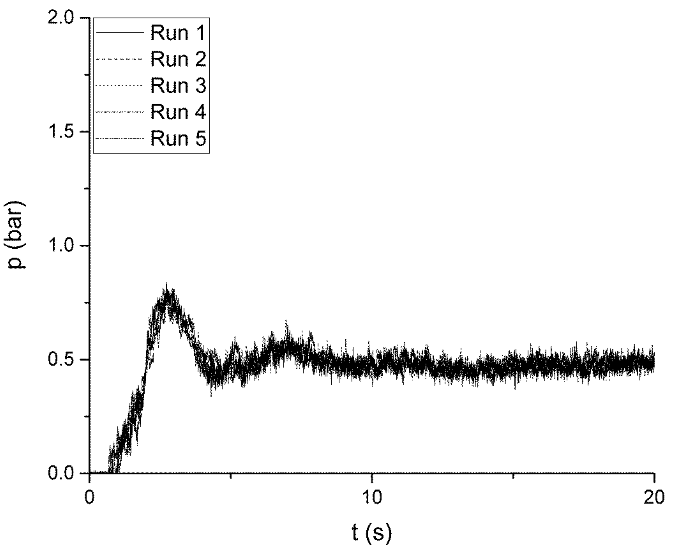

Figure 2. Pressure transients for all runs with ψ_d = 100%, ψ_u = 50%, d = 6.4 mm (S configuration).

The consistency of the transients recorded at the three transducers is also preliminary assessed. For example, in Figure 3a, the whole transient recorded at the transducers is plotted for S configuration and $\psi_d = 0\%$, $\psi_u = 100\%$, $d = 6.4$ mm, whereas, in Figure 3b–d, details are given for better understanding. In Figure 3b, the initial phase of the transient is plotted. Transducer P1 exhibits a different pressure pattern with respect to the other ones. It is also confirmed for the final part of the experiment (Figure 3c) that pressure patterns for P2 and P3 are quite similar, whereas P1 exhibits smaller pressure surges, although the same period of pressure oscillation can be observed for all the transducers.

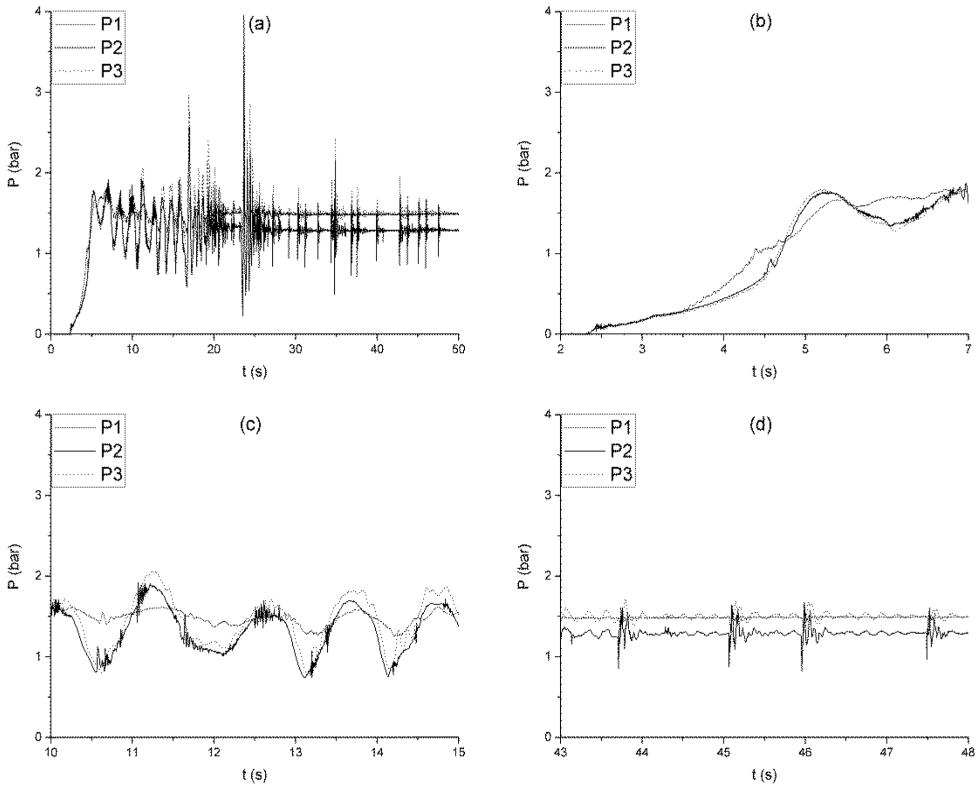

Figure 3. Pressure transient for $\psi_d = 0\%$, $\psi_u = 100\%$, $d = 6.4$ mm (S configuration).

In the last part of the transient (Figure 3d), a number of pressure surges can be identified, which are caused by the expulsion of air pockets entrapped in the water column coming from upstream. In addition, in this case, the pressures measured by P2 and P3 are slightly different, whereas P1 exhibits a much smoother pattern.

Finally, it can be noticed that the pressure recorded at P2 is lower than P1 and P3 when approaching steady state conditions. This is consistent with the experimental set-up, since the head over the pipeline is almost constant because of the very low discharge flowing when the downstream valve is closed, and the elevation of transducer P2 is around 3 m higher than P1 and P3 (Figure 1).

Plotted data also show that the pressure transient results from the superposition of mass oscillation transients and elastic transients. The former are characterized by low frequency and generally small peak pressure, and originate because of either the cushioning effect of the air during the filling of the pipeline or the movement of large air pockets during venting. Elastic transients are generated as a result of the impact of the water column on the orifice after an air pocket has been expelled. Such transients have high frequency and magnitude depending on the velocity of the water column at the impact.

In case the downstream valve is completely open ($\psi_d = 100\%$), experiments show a very small pressure increase, in the order of a few decimals of bar. As an example, in Figure 4, the pressure transients recorded for S configuration and ψ_u = 25%, d = 6.4 mm (a); ψ_u = 25%, d = 25.4 mm (b); ψ_u = 100%, d = 6.4 mm (c); ψ_u = 100%, and d = 25.4 mm (d) are plotted.

Because of the larger outlet area, the larger part of the initially entrapped air in the pipeline is expelled downstream and only a small part is expelled through the orifice at the highpoint. As a result, the elastic transients are negligible and the mass oscillation prevails in the resulting transient. The effects of both the orifice size and the length of the descending pipe are almost negligible. Consequently, collected data for this configuration are not further analyzed.

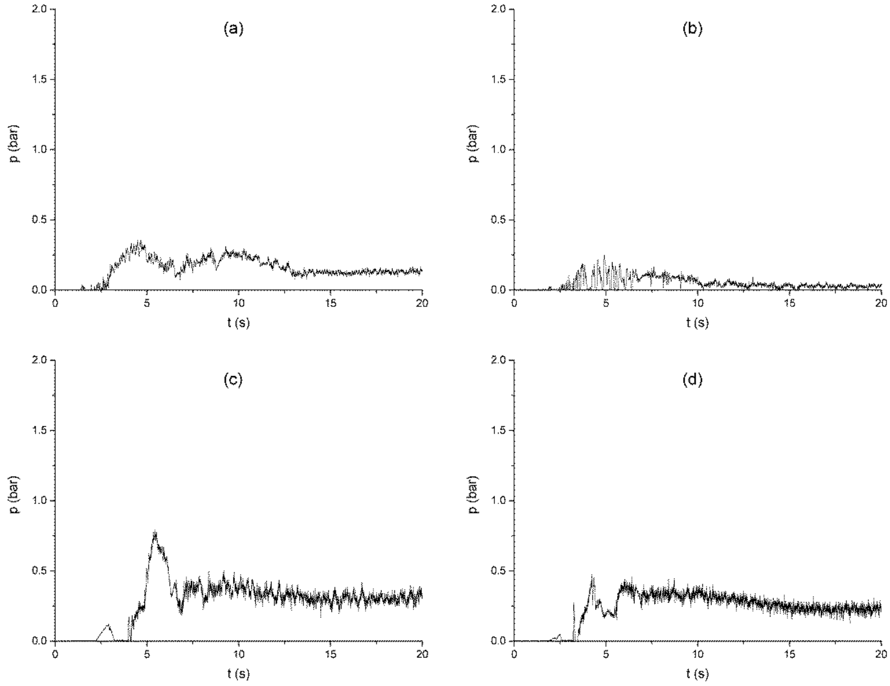

Figure 4. Pressure transients for ψ_d = 100% with S configuration and: (**a**) ψ_u = 25%, d = 6.4 mm; (**b**) ψ_u = 25%, d = 25.4 mm; (**c**) ψ_u = 100%, d = 6.4 mm; (**d**) ψ_u = 100%, d = 25.4 mm.

When the downstream area is partially (or totally) closed, transients show relevant pressure peaks instead. The greatest differences in the pressure transients were observed when the downstream valve is closed (ψ_d = 0%) because of the entrapment of a significant air volume, which can be expelled only by means of the air release valve. The air pockets assume different shapes and size according to the filling velocity and air discharge flowing through the orifice. In Figure 5, the pressure transients for S configuration and: ψ_u = 25%, d = 6.4 mm (a); ψ_u = 25%, d = 25.4 mm (b); ψ_u = 100%, d = 6.4 mm (c); ψ_u = 100%, d = 25.4 mm (d) are given.

Plotted data show that a number of high frequency pressure peaks occurs for ψ_u = 25% and d = 6.4 mm, whereas no peak is recorded for d = 25.4 mm. For smaller d, such pressure peaks also show a certain regularity during time, with a somewhat periodic behavior before all air is expelled.

Experiments with ψ_u = 100% exhibit a similar pressure pattern. A reduction in the number of pressure peaks is noticed while increasing the opening degree of the upstream valve, although the influence of ψ_u on the pressure pattern seems it smaller.

As mentioned above, the transient results from the superposition of high frequency pressure peaks and low frequency pressure oscillation. The former depends on the release of the air pockets moving upward with the flow, the latter depends instead on the expulsion of much larger air pockets coming back from downstream. The release of such larger air pockets causes a rigid column-like transient in the flow. The smaller the orifice diameter, the longer the time for release. The increase of the time required for full expulsion of the air pockets causes a greater acceleration of the water column. Consequently, smaller orifice diameters lead to a greater pressure peak. In the last part of the transient, when the pressure has achieved a steady state condition, small pressure peaks can be identified, which depend again on the expulsion of residual air pockets flowing with water from upstream.

Similarly, in Figures 6 and 7 the pressure transients for ψ_d = 25% and ψ_d = 50% are plotted. Unlike the case ψ_d = 0%, data show a smaller influence of the orifice size on the pressure pattern, whereas the pressure transient significantly changes by varying the upstream valve opening degree.

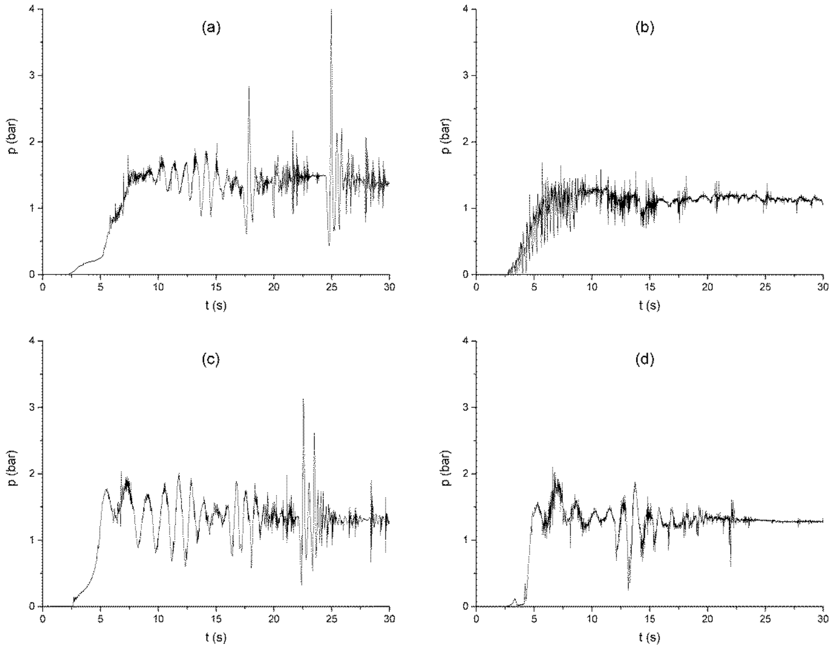

Figure 5. Pressure transients for ψ_d = 0% with S configuration and: (**a**) ψ_u = 25%, *d* = 6.4 mm; (**b**) ψ_u = 25%, *d* = 25.4 mm; (**c**) ψ_u = 100%, *d* = 6.4 mm; (**d**) ψ_u = 100%, *d* = 25.4 mm.

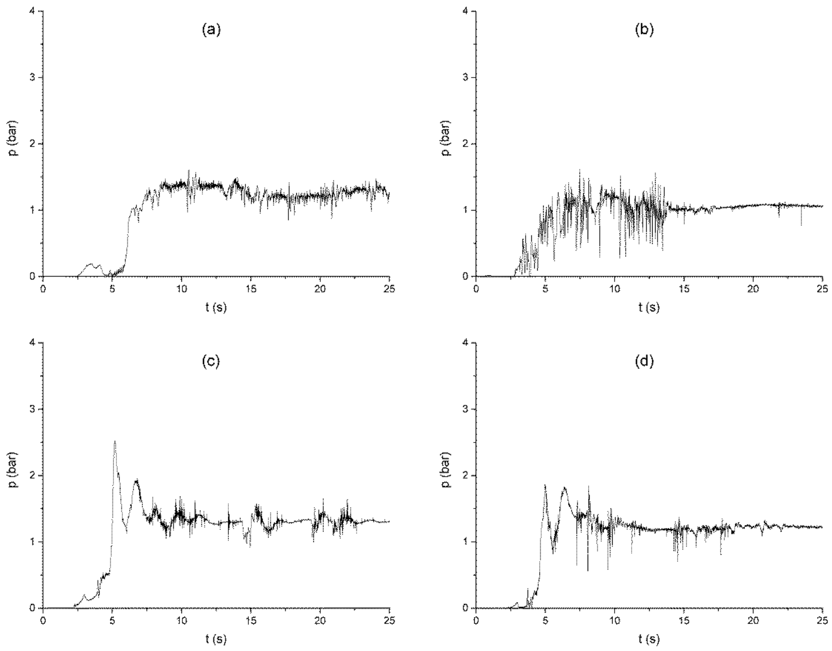

Figure 6. Pressure transients for ψ_d = 25% with S configuration and: (**a**) ψ_u = 25%, *d* = 6.4 mm; (**b**) ψ_u = 25%, *d* = 25.4 mm; (**c**) ψ_u = 100%, *d* = 6.4 mm; (**d**) ψ_u = 100%, *d* = 25.4 mm.

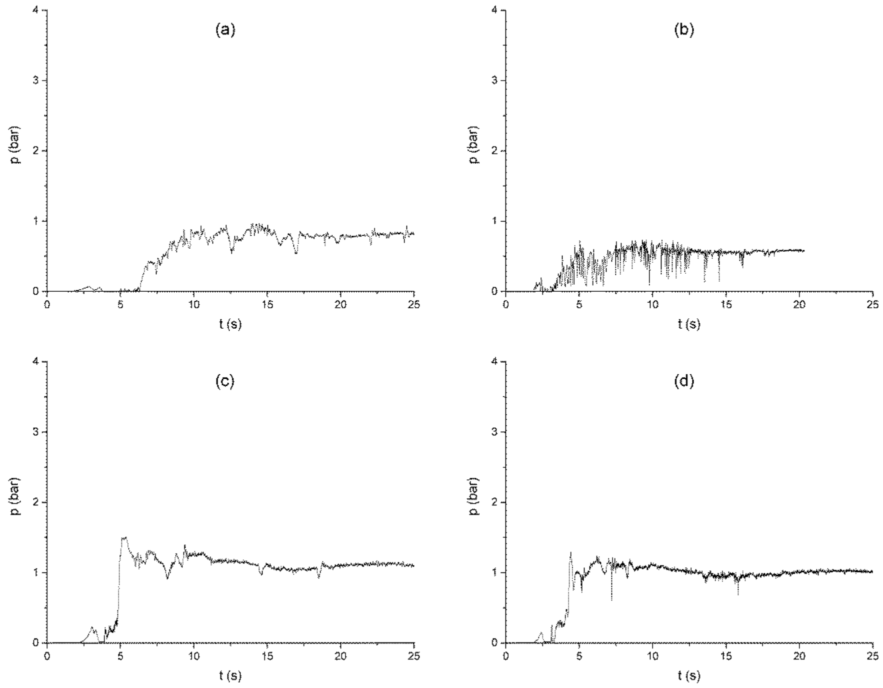

Figure 7. Pressure transients for ψ_d = 50% with S configuration and: (**a**) ψ_u = 25%, d = 6.4 mm; (**b**) ψ_u = 25%, d = 25.4 mm; (**c**) ψ_u = 100%, d = 6.4 mm; (**d**) ψ_u = 100%, d = 25.4 mm.

Only few configurations show a pressure peak during the transient, and no periodic regularity as for ψ_d = 0% was identified. Pressure transients for L configuration show a similar pattern and are not analyzed for the sake of brevity.

A comprehensive analysis of experiments, summarized in Tables 2 and 3 is plotted in Figures 8 and 9 for the *S* and L configuration, respectively. In this paper, only the maximum pressure surge is analyzed at varying system configurations. The ratio between peak pressure $p_{\max}$ and steady state pressure p_0 at transducer P2 is given, in order to compare results from different configurations.

Table 2. Values of $p_{\max}/p_0$ at varying ψ_u, ψ_d, d/D (*S* configuration, L_d = 5.90 m).

ψ_d (%)	d/D	ψ_u (%)		
		25	**50**	**100**
0	0.09	3.41	2.31	2.82
	0.13	2.39	2.22	2.18
	0.19	1.98	1.91	1.95
	0.28	1.73	1.72	1.59
	0.37	1.49	1.51	1.64
25	0.09	1.35	1.94	2.15
	0.13	1.44	2.10	1.97
	0.19	1.84	2.01	1.81
	0.28	1.85	1.66	1.40
	0.37	1.93	1.54	1.68
50	0.09	1.29	1.42	1.45
	0.13	1.39	1.48	1.49
	0.19	1.42	1.49	1.56
	0.28	1.46	1.40	1.48
	0.37	1.48	1.28	1.28

Table 3. Values of p_{max}/p_0 at varying ψ_u, ψ_d, *d/D* (L configuration, L_d = 11.84 m).

ψ_d (%)	d/D	ψ_u (%)		
		25	**50**	**100**
0	0.09	1.63	1.60	1.58
	0.13	1.44	1.42	1.50
	0.19	1.58	1.47	1.70
	0.28	1.49	1.61	1.72
	0.37	1.59	1.69	1.83
25	0.09	1.40	1.87	1.66
	0.13	1.46	1.58	1.62
	0.19	1.54	1.68	1.76
	0.28	1.93	1.32	1.43
	0.37	1.76	2.05	2.23
50	0.09	1.42	1.50	1.77
	0.13	1.35	1.52	1.57
	0.19	1.39	1.60	1.45
	0.28	1.36	1.60	1.45
	0.37	1.37	1.56	1.65

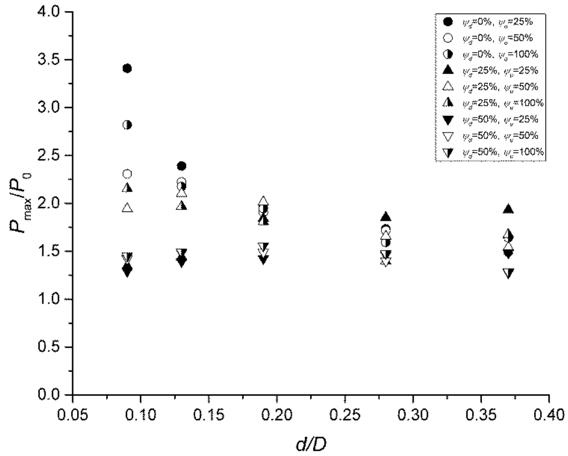

Figure 8. Values of p_{max}/p_0 at varying ψ_d, ψ_u, *d/D* (*S* configuration, L_d = 5.90 m).

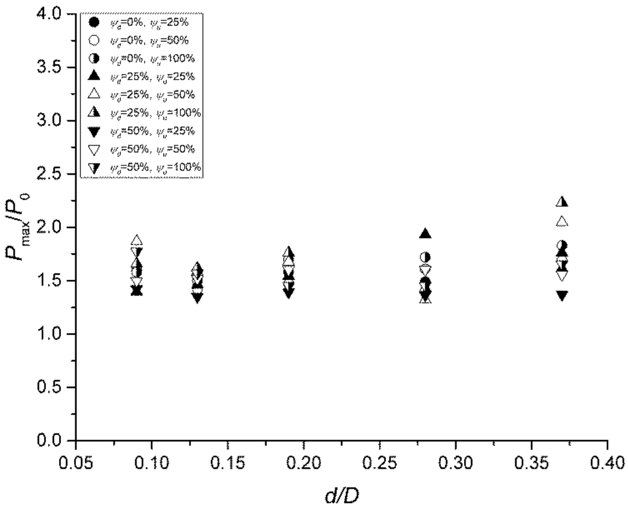

Figure 9. Values of p_{max}/p_0 at varying ψ_d, ψ_u, *d/D* (*L* configuration, L_d = 11.84 m).

Data show that the opening degree of the upstream valve has a small influence on the maximum pressure. For S configuration, a greater dispersion can be observed only for the smaller values of d/D and ψ_d. For the other configurations, deviations at varying ψ_u are always within (0.40–0.50)$\cdot p_0$. The maximum pressure surges for this configuration range between 1.3$\cdot p_0$ and 3.5$\cdot p_0$, as already pointed out by Balacco *et al.* [9]

In case of L configuration, much smaller deviations are observed. Unlike the S configuration, the greatest scattering generally occurs for the greatest ratios d/D. Maximum pressure surges are also fairly independent of d/D, with values of p_{max}/p_0 generally within 1.3–2.0.

Due to the limited influence of the opening degree of the upstream valve, in Figure 10, the average peak pressure at varying ψ_u is plotted for both S and L configurations as a function of ψ_d and d/D.

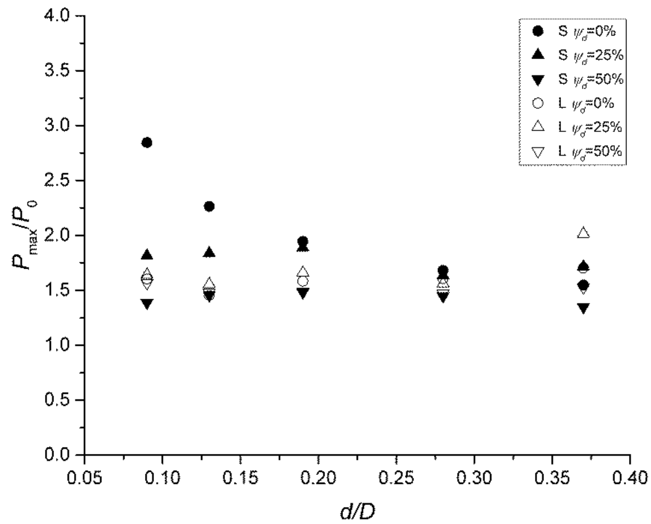

Figure 10. Average pressure surges for S and L configurations at varying ψ_d, *d/D*.

All the values fall in a fairly narrow interval, except for the S configuration with ψ_d = 0% and the smaller ratios of d/D, which exhibit greater pressure peaks.

Although the large number of configurations analyzed in the experiments provides a preliminary framework of the phenomenon, the interpretation of the results by means of the models available in the literature proves much more difficult. Because of the entrapped air pockets within the water column, such models are not able to reliably predict the pressure surge resulting from expulsion.

For the rigid column transient, the models (e.g., [2,8,16]) assume a sharp interface between the air pocket and the water column. The air pocket is progressively expelled from the pipeline through the orifice (or the air vent). On the contrary, in the analyzed configurations, especially for lower values of ψ_d, a number of (more or less) large air pockets are entrapped within the water column, similar to the ones identified by Zhou *et al.* [10] in the "Zero or Minimal Air Release-Waterhammer Effects Negligible" pressure oscillation pattern.

Consequently, a more complex model should be developed, which accounts for the forces acting on the air pocket. The reliability of one-dimensional governing equations should be also carefully verified.

The maximum pressure surge due to the elastic transient arising from the expulsion of small air pockets from upstream could be calculated using the well-known relationship of Allievi–Joukowsky (e.g., [12]). Nevertheless, the deceleration of the water column consequent to the impact on the orifice after air expulsion is very hard to estimate. Preliminary calculation carried out by Balacco *et al.* [9] showed calculated values to be always greater than measured values. For the greater opening degree of the downstream valve, calculated maximum pressure surges were one order of magnitude greater than the measured values.

As for the rigid column model, the available models refer to a sharp interface between air and water, and not to a small air pocket entrapped within the water column. It is also difficult to estimate the water hammer celerity because of the entrapped air, although some models are available to this aim in the literature. The elastic pressure surge is also independent of the length of the downstream pipe.

The experiments show that the elastic pressure peaks are generally negligible because of the small size of the air pockets moving with the flow. In addition, the pressure surges due to the mass oscillation resulting from the pressurization of the initially empty pipeline are quite small. The maximum pressure peaks occur instead as result of the mass oscillation caused by the release of the large air pockets moving upward because of the buoyancy force.

4. Conclusions

Pressure surges following air expulsion during the rapid filling of a pipeline can cause severe damage to water systems. Although many theoretical and experimental studies are available in the literature, a detailed knowledge of the pressure transients resulting from the air expulsion at the high points of undulating pipelines is still lacking. To this aim, extensive laboratory experiments were carried out. An undulating pipeline was investigated, by varying the diameter of the air venting orifice and both upstream and downstream valve settings. The pressure patterns and the maximum pressure surges at varying system characteristics were analyzed.

For the configuration with a shorter downstream pipe, experiments showed significant variability of peak pressure for smaller orifice diameters at varying settings of upstream and downstream valves. The smaller the orifice diameter, the greater the variability in peak pressure, whereas for larger diameters, the peak pressure is almost independent of the valve regulation. The maximum peak pressure was recorded for the smallest diameter and the closed downstream valve. The ratio between the peak pressure and the steady state pressure was around 1.5–2.0 for large orifice diameters, whereas values up to 3.5 were recorded for smaller diameters.

When the downstream valve was fully open, a very low peak pressure was instead recorded, regardless of the upstream valve regulation and the orifice diameter.

The effect of the volume of entrapped air downstream of the high point was analyzed by doubling the length of the descending pipe. Results showed that the peak pressure substantially coincided with the short configuration at larger orifice diameter, whereas for smaller diameters the peak pressure was found to vary in a narrower range. Consequently, the larger air volume reduced the variability of the peak pressure, which was found almost independent of valves regulation and orifice diameters. The greatest peak pressure arises when the valve downstream of the air vent orifice is closed and a small volume of air is entrapped. Such a configuration also shows the greatest variability with respect to the size of the orifice.

In conclusion, experiments suggested criteria for predicting the maximum pressure surge during the rapid filling of a pipeline. Further analysis and experiments are required for the definitive assessment of the possibility of generalizing these results.

Acknowledgments: The writers gratefully acknowledge the support received for this research from Faraplan and BM Idrodata.

Author Contributions: Ciro Apollonio, Gabriella Balacco and Alberto Ferruccio Piccinni conceived and designed the experiments; Ciro Apollonio performed the experiments; Gabriella Balacco, Nicola Fontana and Gustavo Marini did the computation and analysed the results. Gustavo Marini drafted the manuscript. Alberto Ferruccio Piccinni and Maurizio Giugni revised the manuscript. All authors read and approved the final manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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