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Effect of combination vacuum relief and air release valve on hydraulic transients during pipeline filling process

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Effect of combination vacuum relief and air release valve on hydraulic transients during pipeline filling process

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Abstract. Combination vacuum relief and air release valve is an air valve with considerably unbalanced admission and release capacity, which could suppress the column separation and rejoinder water hammer. In order to investigate the effect of combination vacuum relief and air release valve on hydraulic transients during filling process in a pipeline system, different diameter sizes and discharge coefficients of combination vacuum relief and air release valve are selected to prevent the column separation and rejoinder water hammer. The results show that both the air admission duration and air release duration are shorter and the air volume in the valve is larger with increasing in diameter sizes of combination vacuum relief and air release valve. Moreover, although the combination vacuum relief and air release valve with bigger diameter size could admit air fastly to prevent negative pressure, the air may also be released fastly which could result in secondary column rejoinder water hammer. The results also show that the air release discharge coefficient has a more obvious role in the water hammer protection than the air admission discharge coefficient. With increasing in air release discharge coefficient of combination vacuum relief and air release valve, the air release duration shortens and the column rejoinder water hammer becomes more serious. Therefore, the combination vacuum relief and air release valve with smaller diameter size and air release discharge is benefit for the water hammer protection during pipeline filling process.

1. Introduction

When filling process is conducted in a pipeline with undulating profile, the column separation phenomenon tends to occur at the local high point of pipeline. After that, the following column rejoinder would bring in serious pressure surge which threatens the safe operation of water supply system [1-2]. Therefore, it is necessary to install air valve along the pipeline to prevent negative pressure and extreme positive pressure. The role of air valve is that when the pressure drops to below atmospheric pressure, the air can be admitted to pipe through the air valve in order to suppress the negative pressure. And when the pressure rises to above atmospheric pressure, the remaining air in the pipe can be released to outside through the air valve [3]. According to the way of air admission and release, the category of air valve can be classified as air admission valve, air release valve, air admission and release valve with equal diameter, and combination vacuum relief and air release valve, etc. It should be noted that the combination vacuum relief and air release valve is an air valve with considerably unbalanced admission and release capacity, which could suppress the column separation and rejoinder water hammer. Due to its advantage, the combination vacuum relief and air release valve is gradually selected in the water conveyance projects.

In order to improve the performance of air valve, the characteristics of air admission and release are studied among many researchers. Lee and Leow confirmed that the negative pressure was suppressed by increasing the air admission discharge coefficient but the larger air release discharge coefficient could result in extreme positive pressure [4]. Lingireddy studied the diameter sizes of air valve and concluded that the secondary column rejoinder water hammer would be eliminated by air valve with larger air admission diameter and smaller air release diameter [5]. Carlos et al. investigated the characteristic of air release experimentally and tested the discharge coefficient of air valve [6]. Fontana et al. studied the location of air valve during pipeline filling process experimentally and found that when the air valve was located at the end of pipe, the pressure surge caused by water column impact was serious but when the air valve was located at middle point of pipeline, the pressure surge was mild [7]. Martino et al. used an orifice at the end of pipeline to represent an air valve and found that the maximum pressure head increased with the head of upstream reservoir and orifice size [8]. Similarly, Balacco et al. used an orifice at the middle of the pipeline to represent air valve and concluded that the pressure peak was affected by the opening of control valve at upstream or downstream of pipe only when the orifice size was small [9].

In this paper, the filling model combined with air valve model is built in order to investigate the effect of combination vacuum relief and air release valve on hydraulic transients during filling process in a pipeline system. Combined with a filling pipeline system, different diameter sizes and discharge coefficients of combination vacuum relief and air release valve are selected to prevent the column separation and rejoinder water hammer.

2. Numerical model

2.1. Filling model

Before building the filling model, several assumptions are made [1-2]: (a) the water front is well-defined and vertical to the pipe axis; (b) the air pressure at the filling front remains atmospheric; (c) the steady friction coefficients are valid for transient flow; and (d) the water column is slightly compressible except in the immediate vicinity of water front. If these assumptions are invoked, the flow in the filled pipes can be described by method of characteristics with the C^+ and C^- equations [10]

$$C^+ : H_i^{t+\Delta t} = H_{i-1}^t + \frac{a}{gA} Q_{i-1}^t - \left(\frac{a}{gA} + \frac{f\Delta x}{2gDA^2} \left| Q_{i-1}^t \right| \right) Q_i^{t+\Delta t} \tag{1}$$

$$C^- : H_i^{t+\Delta t} = H_{i+1}^t - \frac{a}{gA} Q_{i+1}^t + \left(\frac{a}{gA} + \frac{f\Delta x}{2gDA^2} \left| Q_{i+1}^t \right| \right) Q_i^{t+\Delta t} \tag{2}$$

where H is piezometric head; Q is discharge; g is gravitational acceleration; a is elastic wave velocity; f is Darcy-Weisbach friction factor; D is diameter of pipe; A is area of pipe cross section; x, t are the variables of distance and time respectively; Δx, Δt are space and time increments respectively; the superscript t, $t+\Delta t$ are the previous and current time lines; and the subscript i-1, i, i+1 are any adjacent grid intersection point in x direction.

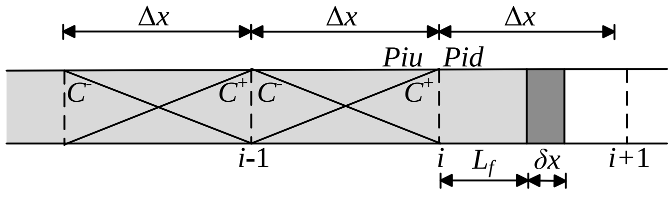

Figure 1. Water front during pipeline filling.

For the flow of the water front in figure 1, the finite difference equations are presented in the discrete form of continuity and momentum equations [1-2]

$$\left[\psi\left(Q_{Pid}\right)_{t+\Delta t}+\left(1-\psi\right)\left(Q_{Pid}\right)_{t}\right]-\frac{\delta x}{\Delta t}A=0 \tag{3}$$

$$\begin{aligned}&\frac{1}{A\Delta t}\left[\left(L_f+\delta x\right)\left(Q_{Pid}\right)_{t+\Delta t}-L_f\left(Q_{Pid}\right)_t\right]-\frac{1}{A^2}\left[\psi\left(Q_{Pid}\right)_{t+\Delta t}^2+\left(1-\psi\right)\left(Q_{Pid}\right)_t^2\right]\\&-gS_0\left(\psi\delta x+L_f\right)-g\psi\left(H_{Pid}-Z_{Pi}\right)_{t+\Delta t}-g\left(1-\psi\right)\left(H_{Pid}-Z_{Pi}\right)_t\\&+g\psi\left(L_f+\delta x\right)S_{t+\Delta t}+g\left(1-\psi\right)L_fS_t=0\end{aligned} \tag{4}$$

where energy grade line slope S is defined by $S = fQ_{Pid}^2/(2gDA^2)$; the subscript Piu, Pid are the upstream and downstream side of point Pi respectively; Z_{Pi} is pipe elevation of point Pi; L_f is water column length in the water front at the previous time line; δx is water column length during the current time step; ψ is time weighing factor; and S_0 is pipeline slope.

For the possible occurrence of column separation, the discrete gas cavity model (DGCM) is adapted here [11]

$$\left(V_g\right)_{t+\Delta t}=\frac{P_0^*\alpha_0V_R}{\rho g\left(H_{Pid}-Z_{Pi}-H_V\right)} \tag{5}$$

$$\left(V_g\right)_{t+\Delta t}=\left(V_g\right)_t+\left[\psi\left(Q_{Pid}-Q_{Piu}\right)_{t+\Delta t}+\left(1-\psi\right)\left(Q_{Pid}-Q_{Piu}\right)_t\right]\times\Delta t \tag{6}$$

where V_g is gas cavity volume; P_0^* is reference pressure; α_0 is initial void fraction; V_R is computational cell volume; ρ is water density; and H_V is gauge vapour pressure.

2.2. Air valve model

Similarly, the air valve model is also built on some assumptions [10]: (a) air goes through the air valve under isentropic flow conditions; (b) the admitted air in the pipe remains near the air valve; (c) the air volume in the pipe is smaller than the pipe reach length. Thus, the state and continuity equations of air in the pipe can be described as

$$P_{air}\left(V_{air}\right)_{t+\Delta t}=\left[m_t+0.5\Delta t\left(\dot m_t+\dot m_{t+\Delta t}\right)\right]RT \tag{7}$$

$$\left(V_{air}\right)_{t+\Delta t}=\left(V_{air}\right)_t+0.5\Delta t\left[\left(Q_{Piu}-Q_{Pid}\right)_{t+\Delta t}+\left(Q_{Piu}-Q_{Pid}\right)_t\right] \tag{8}$$

where P_{air} is absolute pressure of air; V_{air} is air volume; m is air mass; $\dot m$ is mass flow discharge; R is gas constant; and T is absolute temperature.

The relationship between air pressure and piezometric head is

$$P_{air}=\rho g\left(H_{Pid}-Z_{Pid}+H_{atm}\right)=\rho g\left(H_{Piu}-Z_{Piu}+H_{atm}\right) \tag{9}$$

where H_{atm} is absolute atmosphere pressure head.

The air mass flow discharge depends on whether the air flow admitted or released is either sonic or subsonic [10]

(a) air admission in sonic flow

$$\dot m=C_{in}A_{in}\frac{0.686}{\sqrt{RT_0}}P_{air}\qquad P_{air}<0.528P_{atm} \tag{10}$$

(b) air admission in subsonic flow

$$\dot m=C_{in}A_{in}\sqrt{7P_{air}\rho_{air}\left[\left(\frac{P_{air}}{P_{atm}}\right)^{1.4286}-\left(\frac{P_{air}}{P_{atm}}\right)^{1.714}\right]}\qquad 0.528P_{atm}<P_{air}<P_{atm} \tag{11}$$

(c) air release in subsonic flow

$$\dot{m} = -C_{out} A_{out} P_{air} \sqrt{\frac{7}{RT}\left[\left(\frac{P_{atm}}{P_{air}}\right)^{1.4286} - \left(\frac{P_{atm}}{P_{air}}\right)^{1.714}\right]} \quad P_{atm} < P_{air} < 1.894 P_{atm} \tag{12}$$

(d) air release in sonic flow

$$\dot{m} = -C_{out} A_{out} \frac{0.686 P_{air}}{\sqrt{RT}} \quad P_{air} > 1.894 P_{atm} \tag{13}$$

where C_{in} is air admission discharge coefficient; C_{out} is air release discharge coefficient; A_{in} is air admission area; A_{out} is air release area; ρ_{air} is air density; and P_{atm} is absolute atmospheric pressure.

2.3. Model validation

The filling model combined with air valve model is validated by the test data of Apollonio et al. [12]. The test rig contains pressure tank with head of 16.3 m, ascending pipe with length of 5.43 m and slope of 30 °, descending pipe with length of 5.90 m and slope of 30 °, and an air valve located at the local high point with diameter of 6.4 mm. Figure 2 shows the test data and numerical result for the pressure at the air valve. It confirms that the overall trends of pressure surges by test data and numerical result are relatively similar. The only difference is that the maximum pressure by test data is larger than that by numerical result which may arise because the air compressibility is neglected by numerical model. Based on the overall results, the numerical model can be still as a tool to predict the filling transients in this paper.

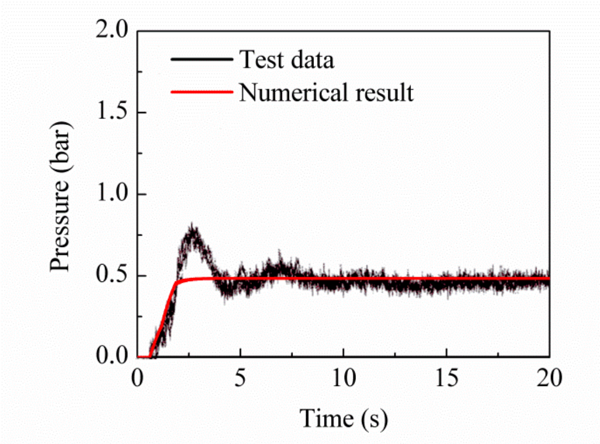

Figure 2. Comparison of test data and numerical result.

3. Results and discussion

A filling pipeline is shown in figure 3 [13]. The system consists a upstream reservoir with water level of 102.0 m, a control valve with head loss coefficient of 0.8 located at the inlet of pipeline, three pipes with diameter of 0.1 m, friction factor of 0.02, lengths of 300 m, 100 m, and 150 m. The elevation of pipeline is shown in figure 3. The filling process is initiated after the control valve opening suddenly. For the transient simulation, the wave speed is 1000 m/s.

Figure 4 gives the pressure surge and gas cavity volume time histories at local high point B during filling process. It shows that the column separation occurs at point B during filling process and the following column rejoinder water hammer is 27.1 m, which is 13.6 times of driving head. Figure 5 gives the pressure envelop and shows that the rejoinder water hammer can spread total pipeline, which threatens the safe operation of system. Therefore, a combination vacuum relief and air release valve is installed at the point B to prevent column separation and rejoinder water hammer.

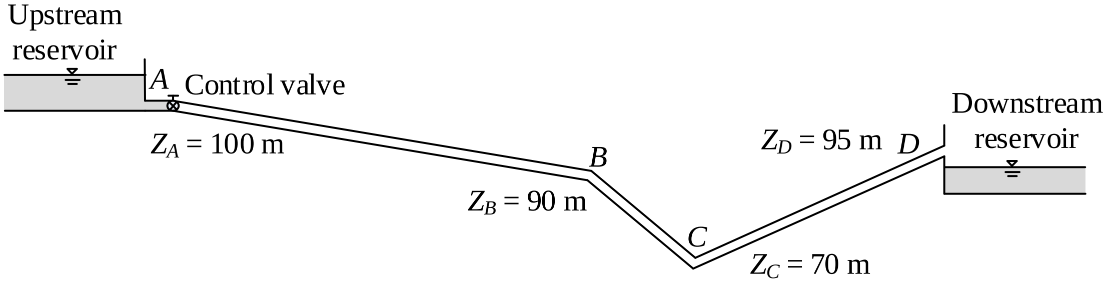

Figure 3. Sketch of a filling pipeline system.

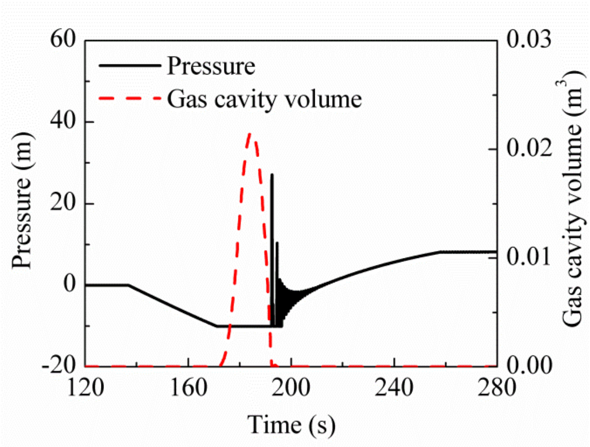

Figure 4. Pressure and gas cavity volume time history at point B without air valve.

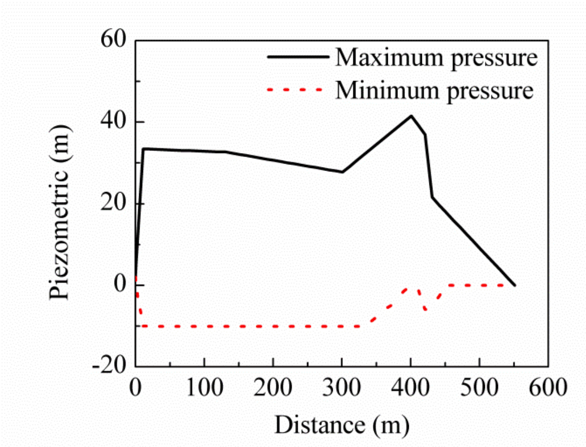

Figure 5. Pressure envelop without air valve.

3.1. *Effect of diameter size on filling transients*

In order to study the effect of diameter size of combination vacuum relief and air release valve on filling transients, both the air admission discharge coefficient and air release discharge coefficient are set as 0.65 and the air release diameter is a tenth of the air admission diameter. Three diameter sizes are shown in table 1.

Table 1. Three diameter sizes of combination vacuum relief and air release valve.

Diameter size	Air admission diameter (mm)	Air release diameter (mm)
I	20	2
II	30	3
III	40	4

Figure 6 gives the pressure surge and air volume time histories at local high point B and the extreme values for the system are included in table 2 when three diameter sizes of combination vacuum relief and air release valve are selected. The results show that the maximum pressure increases and the minimum pressure decreases with increasing in diameter size of combination vacuum relief and air release valve. Moreover, both the air admission duration and the air release duration are shorter and the maximum air volume becomes larger when the diameter size is increasing. This confirms that the large diameter size air valve is benefit to suppress negative pressure but also leads to fast air release which can result in secondary column rejoinder water hammer. Therefore, although the air release duration of air valve with smaller diameter size is longer, it is more efficient for the prevention of water hammer.

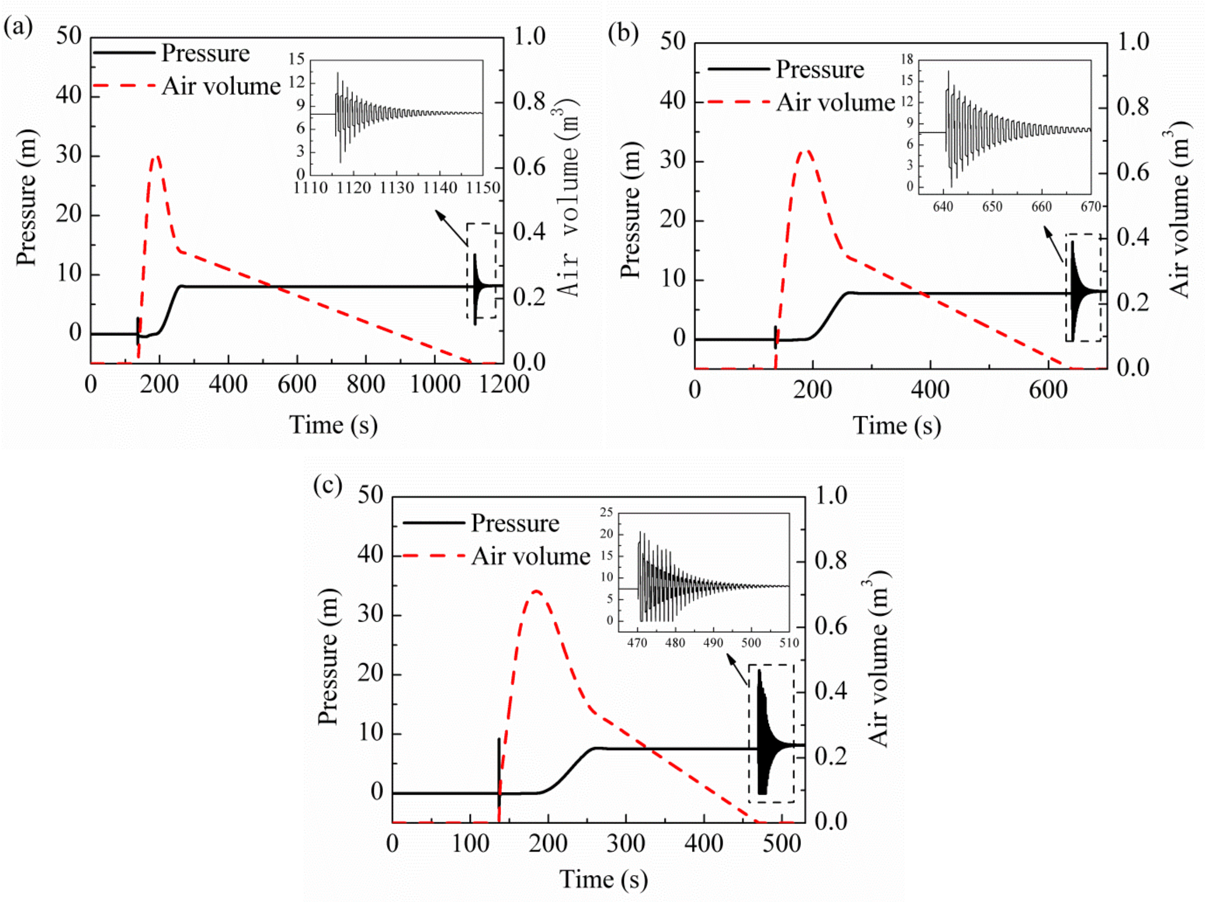

Figure 6. Pressure and air volume time history at point B with air valve (a) diameter size I; (b) diameter size II; (c) diameter size III.

Table 2. Statistics of system extreme values for three diameter sizes of air valve.

Diameter size	Maximum pressure (m)	Minimum pressure (m)	Air admission duration (s)	Air release duration (s)	Maximum air volume (m^3)
I	32.2	-2.6	51	928	0.65
II	35.2	-5.3	50	453	0.68
III	39.5	-9.8	48	285	0.71

3.2. *Effects of discharge coefficient on filling transients*

Similarly, in order to study the effect of discharge coefficient of combination vacuum relief and air release valve on filling transients, the air admission diameter is set as 20 mm and the air release diameter is set as 2 mm. Three discharge coefficients are shown in table 3.

Table 3. Three discharge coefficients of combination vacuum relief and air release valve.

Discharge coefficients	Air admission discharge coefficient	Air release discharge coefficient
I	0.65	0.65
II	0.95	0.65
III	0.65	0.95

Figure 7 gives the pressure surge and air volume time histories at local high point B and the extreme values for the system are included in table 4 when three discharge coefficients of combination vacuum relief and air release valve are selected. The results show that the air admission duration is shorter and the maximum air volume becomes larger, thus the air release duration becomes longer when the air admission discharge coefficient is increasing. But the maximum and minimum pressures are not affected by the air admission discharge coefficient. However, when the air release discharge coefficient increases, the air release duration becomes shorter and the minimum and maximum pressures caused by column separation and rejoinder are getting worse. Therefore, the combination vacuum relief and air release valve with smaller air release discharge coefficient is suited for the prevention of water hammer.

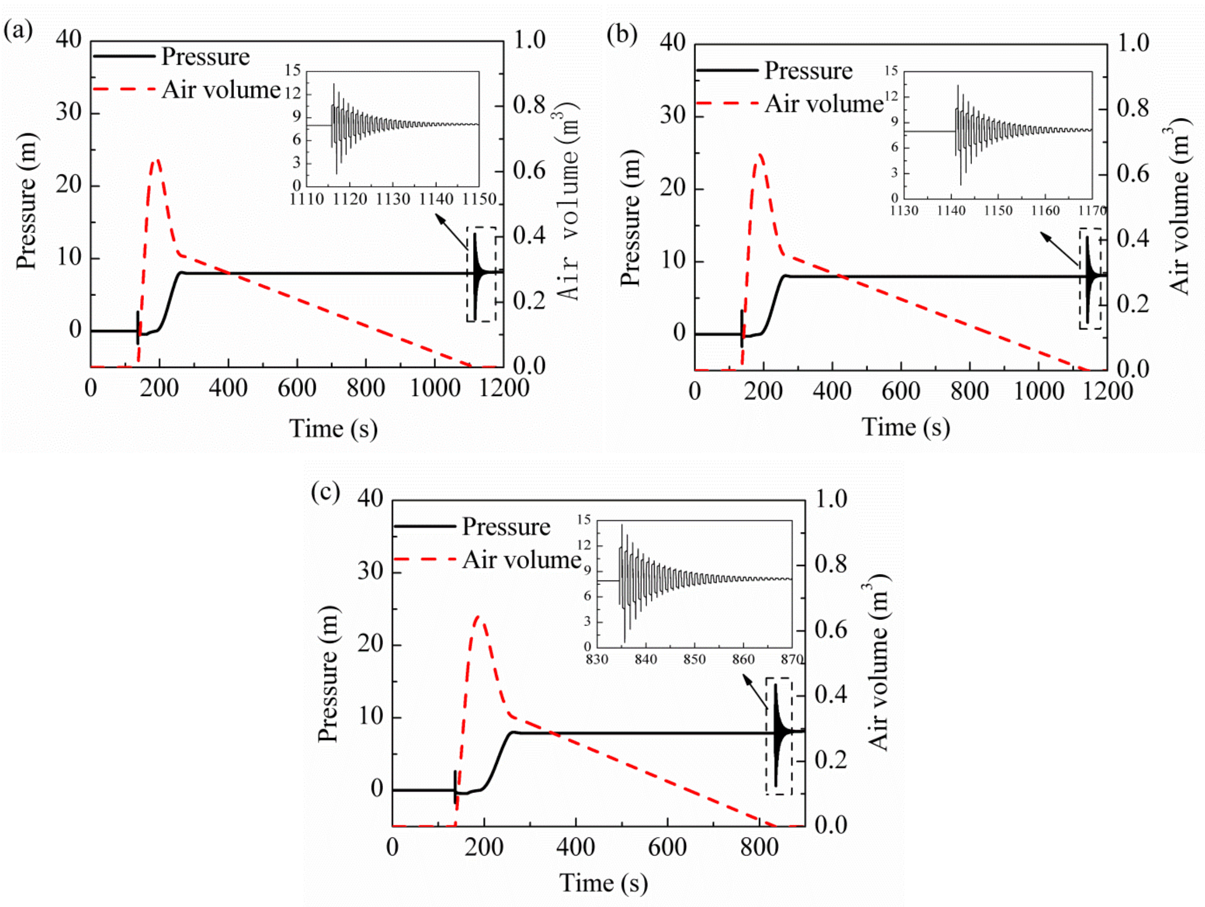

Figure 7. Pressure and air volume time history at point B with air valve (a) discharge coefficient I; (b) discharge coefficient II; (c) discharge coefficient III.

Table 4. Statistics of system extreme values for three discharge coefficients of air valve.

Discharge coefficient	Maximum pressure (m)	Minimum pressure (m)	Air admission duration (s)	Air release duration (s)	Maximum air volume (m^3)
I	32.2	-2.6	51	928	0.64
II	32.2	-2.8	50	954	0.66
III	33.3	-3.6	51	646	0.64

4. Conclusions

The parameters of combination vacuum relief and air release valve including diameter size and discharge coefficient are investigated to prevent the column separation and rejoinder water hammer during filling process in a pipeline system with undulating profile. To this end, a filling model

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combined with air valve model is proposed and validated. The results show that the combination vacuum relief and air release valve is efficient to prevent column separation and rejoinder water hammer. Moreover, when the diameter size or the air release discharge coefficient of combination vacuum relief and air release valve is smaller, the maximum and minimum pressures during filling process can be both improved. Therefore, in order to prevent the column separation and rejoinder water hammer during filling process in a pipeline with undulating profile, the selection of air valve is suggested as the combination vacuum relief and air release valve with smaller diameter and smaller air release discharge coefficient.

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