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Original Paper

Experimental Study of Check Valves in Pumping Systems with Air Entrainment

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Abstract

An experiment setup was introduced to study dynamic behaviour of different types of check valves and the effects of air entrainment on the check valve performance under pressure transient condition. The experiment results show that the check valves with low inertia, assisted by springs or small traveling distance/angle gave better performance under pressure transient condition than check valves without these features. Air entrainment was found to affect both wave speed and reverse velocity. With the increase of the initial air void fraction in pipeline, the experiment results show that the wave speed was reduced, the reverse velocity was increased. The first peak pressure increased initially and then decreased with the increase of the initial air void fraction, the pressure surge periods were increased proportionally with air void fraction due to the greatly reduced wave speed. The study can be applied to help choosing suitable check valves for a particular pumping system.

Keywords: air entrainment, pressure surges, pumping system, check valve.

1. Introduction

In pumping systems, check valves are fitted to pipelines in order to prevent the lines from draining backwards when pumps stop; sometimes check valves are also used to prevent the downstream reservoirs from emptying. In addition, check valves prevent the reverse rotation of pumps to protect pumps and other devices such as seals and brush gear (Thorley 1989). One of the most dangerous cases of pressure transients in a pumping system is the stop of pumps due to power failure. In this case, to prevent reverse flow through the pumps, when the flow reverses, check valves downstream the pumps are activated and closed. An ideal check valve closes at the instant of flow reversal. However, in practice, check valves seldom close precisely at zero reverse flow velocity; limited flow reversal will still occur due to the inertia and friction of check valve components. The sudden closure of check valves at a reverse velocity can cause large pressure surges downstream of the check valves and negative pressure surges upstream of the check valves. These pressure transients may cause the collapse of the pipeline or the damage of the hydraulic equipments in the pumping system. In order to minimize the pressure surges, the maximum reverse velocity Vr which occurs virtually at the instant of closure, should be reduced as near to zero as possible. Therefore, careful design and selection of check valves can help pumping systems limit excessive pressure transients followed by check valve closure.

From a general perspective, Megan (2006) and Ballun (2007) suggested that the best check valve need not necessarily be the one with the least potential to slam but the one that meet all relevant selection criteria: non slamming characteristics, head-loss characteristic, cost and application. Considering the non slamming characteristics, Thorley (1989) suggested few criteria to follow when selecting a check valve in order to avoid valve slamming. According to these suggestions, check valve should have low inertia of moving parts, small travel distance/angle and motion assisted by springs. The extend to which actual valves possess these features can be illustrated graphically in the form of Dynamic Performance Characteristics proposed by Provoost (1982) and in the form of Dimensionless Dynamic characteristics proposed by Koetzier et al. (1986). These check valve characteristics are usually produced from experiments or studies in which the fluid flow in pumping system is assumed to be without air entrainment. Few studies have been done on the effects of air entrainment in a pipeline system and its subsequent effects on check valve performance. Through the numerical studies, Lee (1995 & 2001) reported that the transient flow velocity near the check valve of a pumping system should be also dependent on the characteristics of the air entrained into the system. The present experimental study aims to investigate the effects of air entrainment on the pressure transient induced by check valve closure. The performance of five different self-actuating check valves is analyzed and compared in the event of a pump-trip. The focus would be mainly on the downstream pressure transient since in real-life pumping station, it is the water hammer effect downstream of the check valves rather than upstream which poses a greater danger to the whole piping system. This study may help modifying criteria of selecting a proper check valve for pumping systems with air entrainment.

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2. Test rig, instrumentation and test method

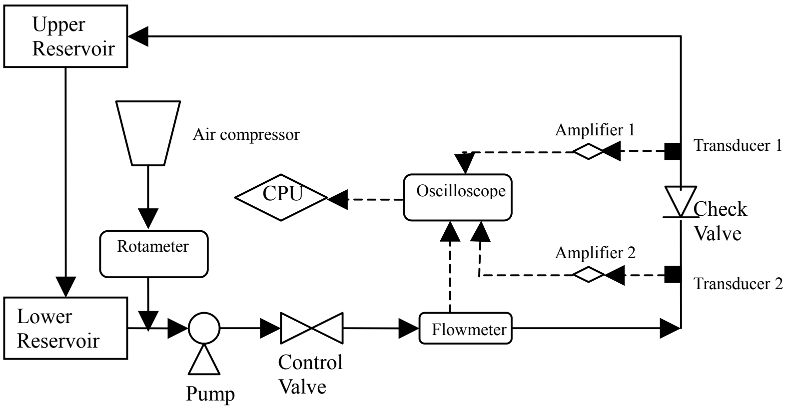
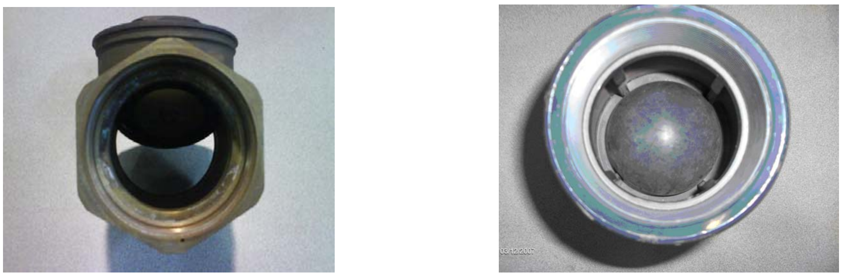


Fig. 1 Check valve test loop



a) Swing Check Valve

b) Ball Check Valve

c) Piston Check Valve

d) Double-Flap Check Valve

e) Nozzle Check Valve

f) Test Section

Fig. 2 Check valves used in the test and test section

The test rig for check valves is shown in Fig. 1. The test facility consists of a 2 HP single pump with speed 1450 rpm, a head tank with overflow located 8.0 m above sump level, a nominal 89 mm diameter PVC piping of 15.75 m length, test section, a control valve and an air compressor. The pump supplies water from the basement tank to the head tank. The water level in the head tank is constant by means of an overflow at a height of about 8.0 m above sump level. Excess water flows back into the supply reservoir. The air compressor is used to supply external air through a tube connected to the suction bell-mouth at the lower reservoir. The air supplied from the compressor is being controlled by a release valve and the amount of air introduced can be read through a rotameter. Check valves are installed at test section 5.75 m downstream of the pump. The steady flow conditions are controlled by a control valve. The hydraulic pressure transients are initiated by pump trip due to power failure. Pressure measurements are made using piezoresistive pressure sensor. An electromagnetic flow-meter is used to measure the flow velocity in the pipe. The key measurement location is at the check valve. Five difference types of check valve are used in the test as shown in Fig. 2 including swing check valve, ball check valve, piston check valve, double-flap check valve and nozzle check valve.

Because the installed flow-meter can not measure the reverse flow, the reverse flow velocity at the check valve is not measured; it is calculated from the measured pressure surge by use of the water hammer equation.

$$V_R = \frac{g\Delta H}{a} \tag{1}$$

Where V_R is the reverse velocity in m/s, ΔH is the transient pressure in meters of water, g is the gravitation constant 9.81 m/s2, and a is the wave speed in m/s.

Wave speed is a function of a number of different variables such as air content, pipe material, pipe connections, etc. Along the pipeline, the fraction of air content depends on the local pressure and local air volume. Therefore, wave speed is not constant and is calculated for each point i which has local pressure pi and air fraction content ε_i by the Eq. (2) (Lee 1994):

$$a_i^k = \left[\rho_w \left(1 - \varepsilon_i^k\right) \left(\frac{1}{K} + \frac{\varepsilon_i^k}{np_i^k} + \frac{c_l D}{eE} \right) \right]^{-\frac{1}{2}} \tag{2}$$

In this paper, the overall pressure wave speed may now be determined from the measured pressure transient period.

$$\Delta T = N \frac{2L}{a} \tag{3}$$

Where ΔT is the overall time, 2L/a is pressure transient period and N is the number of periods.

The dynamic characteristic graph of V_R vs dV/dt would be a useful chart to use for analyzing. The deceleration of flow is calculated from the pressure transient plot and Eq. (4), where V_O is the measured initial velocity in m/s.

$$\frac{dV}{dt} \approx \frac{V_O + V_R}{\Delta t} = \frac{V_O}{\Delta t} + \frac{a\Delta H}{g\Delta t} \tag{4}$$

Furthermore, the dimensionless dynamic characteristic for check valves can be shown by a plot of V_R/V_O versus $(D/V_O^2).(dV/dt)$.

3. Results and discussion

Figure 3 shows the comparison of pressure-time histories immediately downstream of the check valves. The results show that when power failure occurred at flow rate 3.5 l/s and air entrainment 0.15%, the first pressure peak reaches 2.65 barg by using swing check valve. The first pressure peak is 2.34 barg, 1.65 barg, 1.60 barg, and 1.60 barg respectively when ball check valve, nozzle check valve, double flap check valve or piston check valve is used. From these results, five types of tested check valves can be divided into two groups. The first group includes swing check valve and ball check valve which gave high pressure transient. The second group includes nozzle check valve, double flap check valve and piston check valve which gave smaller pressure transient in comparison with the first group. The additional comparison of pressure-time histories immediately upstream of the check valves was shown in Fig. 4. When the check valves were closed, the upstream pressure transient gave a down-surge first; the minimum pressure value was lower when the check valves of the first group were used. Fig. 3 and Fig. 4 also shows that the damping of the pressure transient was slower for swing check valve and ball check valve in comparison with check valves of the second group. Generally, these findings indicate that the check valves in the second group are considered better pressure protection devices than the check valves in the first group.

To give a clearer investigation of pressure transient with different types of check valves, the dynamic performance characteristic of check valves is illustrated graphically in Fig. 5. The vertical axis is the maximum reverse velocity that occurs during valve closure. The base line is the mean deceleration of the liquid column as the flow is brought to rest. In this dynamic performance chart, the ideal curve would be coincident with the horizontal axis. Fig. 5 shows that swing check valve and ball check valve, which is the subject of the upper curves, would give high value of the first pressure peak. The dynamic characteristic of the check valves of the second group are lower curves. The lower curves implied that the check valves of the second group have a slower rate of deceleration, and these check valves come with low value of the first pressure peak. It is clear that the degree of amplification of the first pressure peak is dependent upon the rate of deceleration of the flow after pump trip. Generally, a slower rate of deceleration of the flow after pump trip leads to a smaller amplification of the first pressure peak. These findings are consistent with previous investigation (Lee 1995).

Figure 6 shows the dimensionless dynamic characteristic of different check valves. For a tested check valve, if the non-dimensional valve performance curve is below the operating point of the system, the selected check valve satisfied the requirement for the system. The operating point is determined as follow. From the predicted velocity-time history, the mean fluid deceleration dv/dt is obtained. Next step is normalizing this with Vo and D, and reading up on Fig. 6 to intersect with the corresponding Vr/Vo line. The operating point is the intersection point. The experiment results show that all the five types of used check valves are generally satisfy the non-slamming condition for the above pumping system.

The experiment results of the piston check valve were used to investigate further the effects of air entrainment. With air entrainment, wave speed at every point in systems depends on the local pressure and local air void fraction at that point. Therefore, the wave speed was no more constant like in systems with no air but varied along the pipeline and varied on time. The overall pressure wave speed may be determined from the measured pressure period. Figure 7 shows the variation of the overall wave speed with initial air void fractions. The calculated pressure wave speed for this PVC pipeline is about 400 m/s. However, the measured pressure wave speed in case of no air entrainment from the air compressor is about 310 m/s. The lower value of measured pressure wave speed is due to the present of dissolved gas and free air in the water. The experimental results show that by increasing value of the initial air void fraction, value of the wave speed was greatly reduced. This result is consistent with the experimental of observation of various earlier investigators such as Brown (1968) and with numerical results by Lee (1994). On the other hand, the experimental results show that by increasing value of the initial air void fraction, value of the reverse velocity was also increased as shown in Fig. 8. This may be a potential of high pressure surge when the check valve is closed.

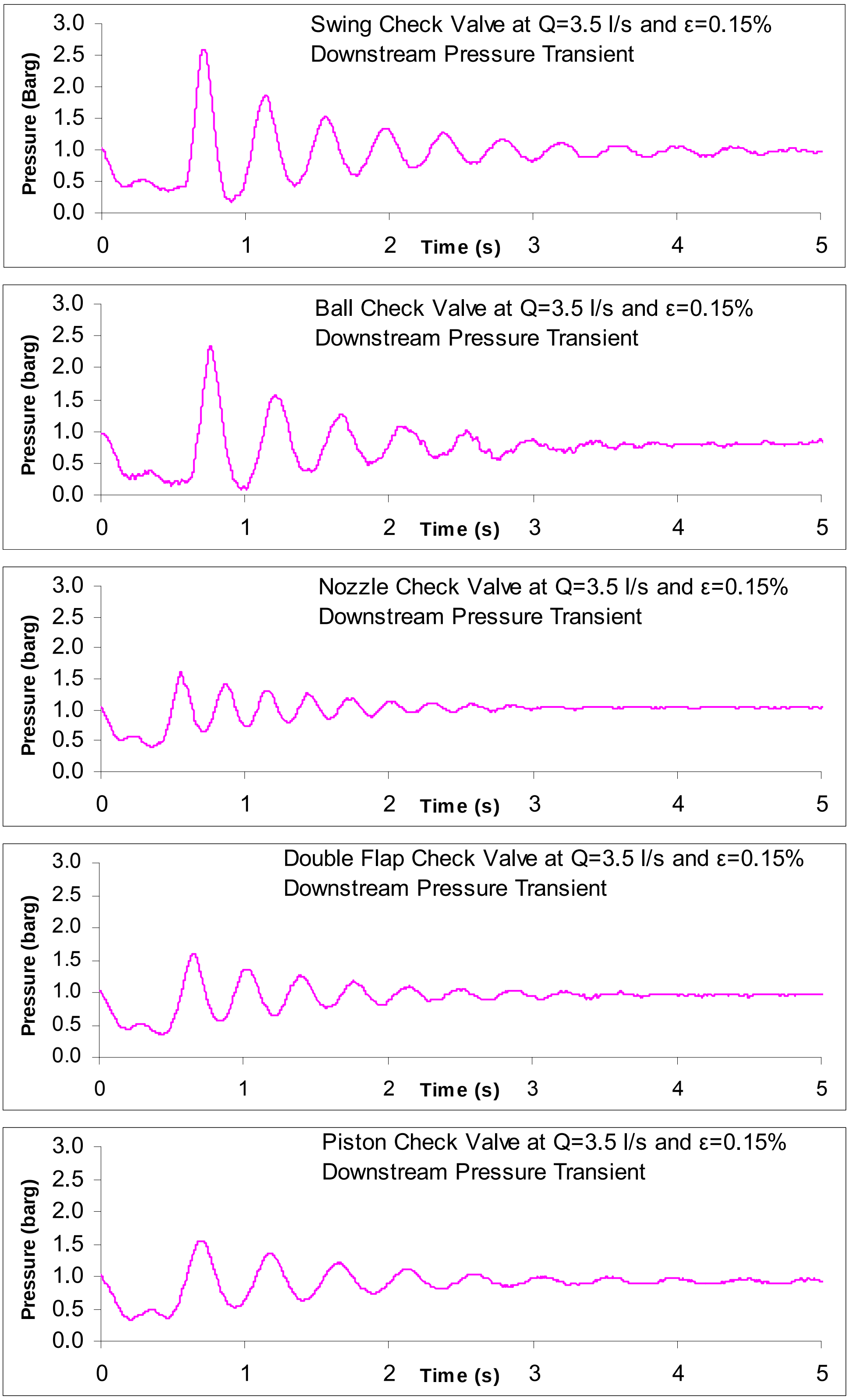


Fig. 3 Pressure-time histories immediately downstream of check valve

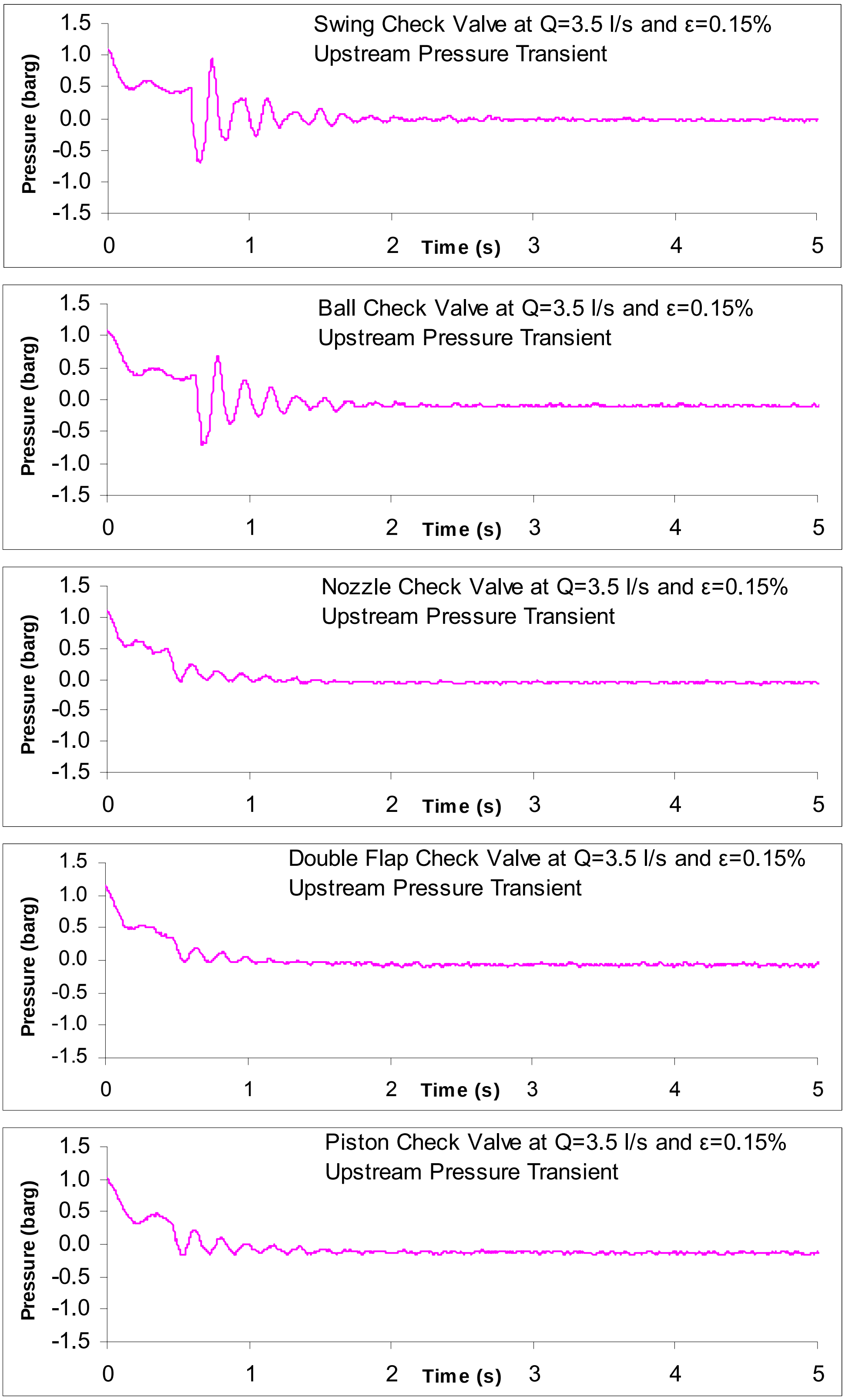


Fig. 4 Pressure-time histories immediately upstream of check valve

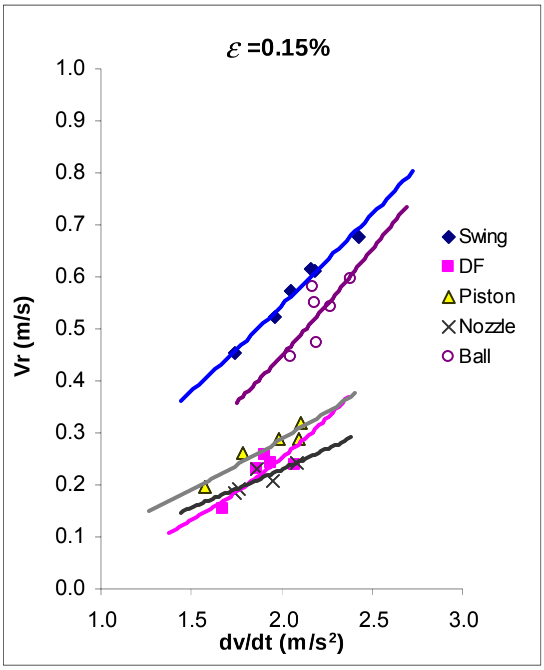


Fig. 5 Dynamic performance characteristic of Check Valves

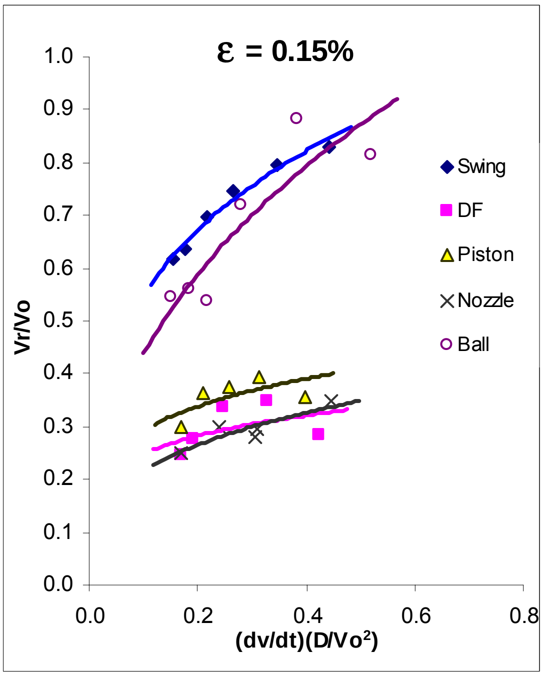


Fig. 6 Dimensionless dynamic charactersictic of Check valves

Further comparison of transient pressure with different amount of air void fraction was shown in Fig. 9. The results show the decrease of measured pressure magnitude with higher air content. The numerical computation (Lee 1995) permitting the investigation with very small amount of air content shows that when the initial air void fraction was increased, the pressure head of the first pressure peak grossly increased to a maximum value then slightly decreased as shown in Fig. 10. The lower average wave speed by the present of air entrainment delays the wave reflection at the reservoir and thus allows a more complex variation in pressure interaction to occur in the system, culminating in a peak at a specific transient interval (Lee 1994). In these experiments, the positive effect of air entrainment to pressure peak was indicated by the increase of reverse velocity when initial air void fraction was increased. On the other hand, the increase of initial air void fraction leads to the decrease of the wave speed. The reduction of the wave speed of the mixture directly causes changes in the strength of pressure oscillations. When the positive effect from the delayed wave reflection couldn’t compensate for or exceed the negative effect from the reduction of wave speed, a suppressed pressure peak happens. This may explain why the first peak pressure increased initially and then decreased with the increase of the initial air void fraction. In addition, the pressure surge periods were increased proportionally with air void fraction due to the greatly reduce of wave speed. These characteristics are also observed by previous investigators.

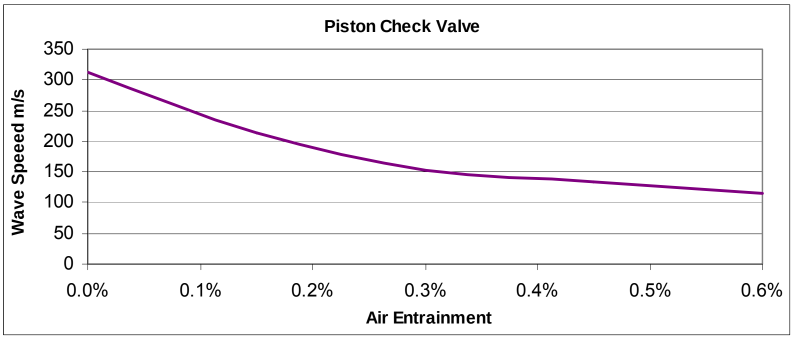


Fig. 7 Sample plot showing wave speed variation

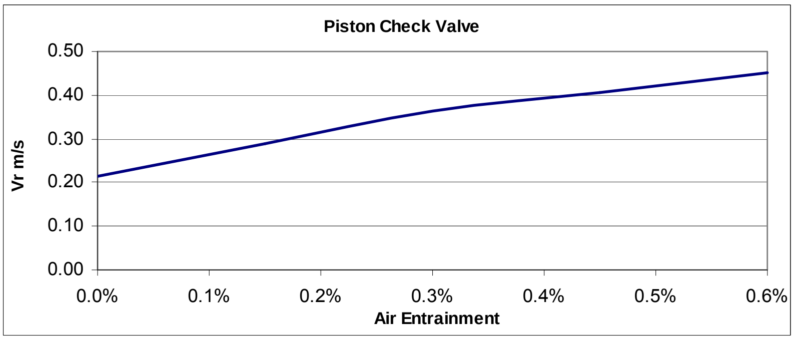


Fig. 8 Sample plot showing reverse velocity variation

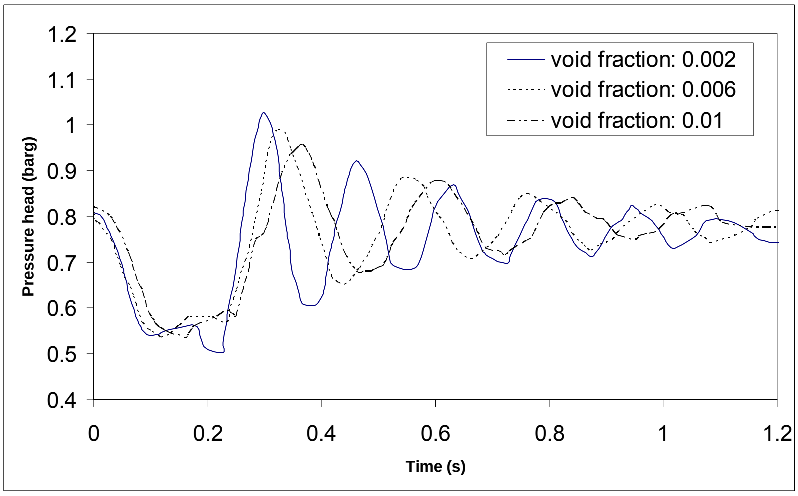


Fig. 9 Transient pressure measured from the experiment at check valve

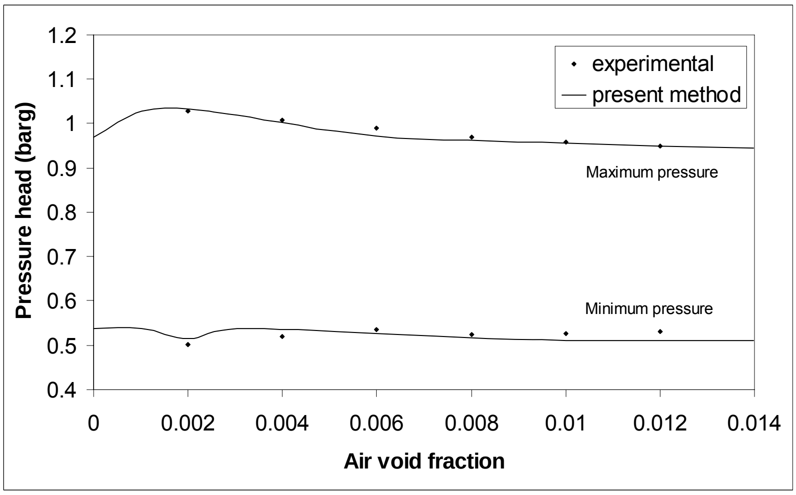


Fig. 10 Maximum and minimum first pressure peak

4. Conclusions

An experiment setup was introduced to study dynamic behaviour of different types of check valves and the effects of air entrainment on the check valve performance under pressure transient condition. The experiment results show that the check valves with low inertia, assisted by springs or small traveling distance/angle such as piston check valve, nozzle check valve and double flap check valve gave better performance under pressure transient condition than the check valves without these features such as swing check valve and ball check valve. Air entrainment was found to affect both wave speed and reverse velocity. With the increase of the initial air void fraction in pipeline, the experiment results show that the wave speed was reduced, and the reverse velocity was increased. In combination with numerical studies, the results show that the first pressure peak increased initially and then decreased with the increase of the initial air void fraction, the pressure surge periods were increased proportionally with air void fraction due to the greatly reduce of wave speed. This is the reason why although selected check valve is satisfied for no air entrained system, valve slamming problem may still occur at a particular air entrainment level. These findings can be applied to help choosing suitable check valves for a particular pumping system. However, the accuracy of experiment results may be affected by using water hammer equation to calculate reverse velocity in case of air entrainment. The future work should measure the reverse velocity directly from the experiment. A more accurate air void fraction measurement should be employed to count on the free air and gas dissolved in the fluid. The future experiment should be done for a large range of the flow deceleration.

Nomenclature

a	Wave speed	n	The polytropic index
c_l	Parameter describing pipe constraint	p	Pressure inside the pipe
D	Mean diameter of pipe	Q	Fluid flow rate
E	Modulus of elasticity	t	Time
e	Local pipe wall thickness	V	Flow velocity
f	Friction factor	V_O	Initial flow velocity
g	Gravitational acceleration	V_R	Reverse velocity
H	Gauge piezometric pressure head	ε	Fraction of gas in liquid
k	Time level	ε_0	Initial air void fraction
K	Bulk modulus of elasticity	ε_g	Fraction of dissolved gas in liquid
L	Length of downstream pipeline	ρ	ρ density of fluid
N	Number of periods		

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