Experimental observation on factors affecting intrusion volumes during low or negative pressure events

Tingchao Yu, Hanfeng Jin, Tuqiao Zhang, Yu Shao and Xiao Wu

ABSTRACT

External water intrusion during low or negative pressure transient events in urban water supply systems may cause pollution and health problems. The volume of intrusion pollutants is one of the significant indicators that can reflect the degree of health risks when a pollution incident occurs. A pilot-scale platform was constructed in this study to simulate intrusion events, which were caused by the sudden valve closure in a laboratorial water distribution system. The simulation aimed to determine the critical factors affecting the intrusion volume during low or negative pressure events and to present an intrusion volume model. Intrusion volumes were measured under different conditions with different flow velocities, internal and external pressures, and orifice diameters. The intrusion volume was considerably affected by the size of leakage points, initial flow velocity, and external pressure at leakage points. It also had a positive correlation with each of the three factors. Theoretical intrusion volumes were calculated with the orifice equation and compared with the measured intrusion volumes. A correction coefficient was introduced to improve the traditional equation of the intrusion flow rate.

Key words | correction coefficient, intrusion, low or negative pressure events, orifice equation, sensitivity analysis

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INTRODUCTION

Intrusion contamination from ground water and soil surrounding pipes is a less-visible and less-known pollutant pathway that may occur during short-time low or negative pressure events in a water distribution system (Karim *et al.* 2003; Gullick *et al.* 2005). Ground water, soil and water from air valve vaults may contain mixtures of microbial or chemical contaminants (Besner *et al.* 2010; Ebacher *et al.* 2013), and contaminated water may be intruded into water distribution systems when low or negative pressure events occur. Health risks associated with low or negative pressure events in water distribution systems have been observed. Hunter *et al.* (2005) conducted a case-control study of the relationship between intestinal diseases and low or negative pressure events. They concluded that up to 15% of intestinal diseases might be associated with water main burst and pressure loss events.

The occurrence of pressure drop or transient events, the presence of pathogens in the soil and water surrounding drinking water pipes, and the poor structural integrity of pipes are the three necessary components of intrusion contamination in water distribution systems (Hooper *et al.* 2006). Low or negative pressure events are commonly caused by sudden changes in water velocity, uncontrolled pump startup and shutdown, pump trip caused by power failure, water main break, sudden valve closure or opening, and sudden changes in demand (Kirmeyer *et al.* 2001; Boyd *et al.* 2004a). Once the internal pressure in pipelines drops and becomes lower than the pressure surrounding the water main, the water may intrude the pipes because of the poor structural integrity of such pipes evident in their leakage points, submerged air valves, and faulty seals.

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The volume of intrusion pollutants is one of the indicators that best reflect the degree of health risks involved. Boyd *et al.* (2004a, 2004b) provided evidence of intrusion caused by transient negative pressure events by using a pilot-scale experiment. Based on chemical tracer and volumetric methods, the intrusion volume was measured during the negative pressure events caused by sudden valve closure. LeChevallier *et al.* (2004) and Fleming & LeChevallier (2008) used an orifice equation to estimate intrusion volumes through leakage points under various scenarios. Ebacher *et al.* (2011) and Besner *et al.* (2011) simulated pressure transient events in a water distribution system and computed the intrusion volume with a commercial software program. Mora-Rodríguez *et al.* (2011) measured intrusion volume with experimental research, and they used computational fluid dynamics (CFD) to simulate the pressure variation in pipelines during pressure transient events. Ebacher *et al.* (2012) analyzed the effect of leakage rate and the head of the leakage orifice on intrusion volume. Collins & Boxall (2013) presented a new analytical expression to compute intrusion rates, which considered the influence of ground conditions and was validated by the results of CFD modeling and laboratory experiments. Yang *et al.* (2014) investigated the effect of porous media on intrusion flow rate and suggested a new expression to predict intrusion flow rate. The orifice equation is usually used to evaluate the intrusion volume. Because of the inconsistency between the theoretical and measured values, the non-0.5 exponential index of the head or the change of the leakage area is considered to calibrate the measured data. The experimental and numerical results (Van Zyl & Clayton 2007; Cassa *et al.* 2010, Cassa & Van Zyl 2011; Ferrante *et al.* 2011, 2013) indicate that the leakage points will expand or contract with the change of the pressure, and its effective size has a close relationship with the pipe material. The non-0.5 exponential index of head is used to cover the influence of the leakage shape change. However, the non-0.5 exponential index disagrees with the dimension concordant principle of the equation.

This study is limited to elastic pipes. The results here reported are applicable only to these kinds of pipe while for plastic ones, because of their viscoelastic behavior (e.g. Evangelista *et al.* 2015), more analysis is required. We aim here to simulate intrusion events associated with low or negative pressure events to determine the intrusion volume under different conditions. Hydraulic transients were induced by the sudden closure of a discharge solenoid valve. Intrusion volumes were recorded with a video camera and determined with a volumetric method. The factors affecting intrusion volumes were analyzed under different conditions. A correction coefficient was also introduced to improve the traditional equation for intrusion flow rate.

MATERIALS AND METHODS

Experimental apparatus

An experimental installation, shown in Figure 1, was designed and constructed to determine the intrusion volume during low or negative pressure events. The design comprised experimental pipes, an electric ball valve, diaphragm valves, an upstream constant-pressure tank, a downstream overflow tank, an intrusion volume-measuring device, electromagnetic flow meters, a pressure measurement system, and other appurtenances used to control and measure the effects of low or negative pressure events. A steel pipe with a length of 50.3 m and a diameter of 50 mm was used to simulate the water transmission line, and the intrusion device was connected to the water main through a tee pipe. The electric ball valve situated upstream of the intrusion device can be closed in 1.0 s to cause low or negative pressure events within the experimental pipes. The upstream constant-pressure tank provided a stable pressure head to the transmission pipe, whereas the downstream overflow tank with constant overflow provided an additional pressure of approximately 1.2 m pressure head, which is larger than the maximal external pressure head (1 mH_2O).

The intrusion device (Figure 2) was used to simulate leakage in the pipes. The main part of the intrusion device was a Plexiglas water tank (0.4 m × 0.2 m × 0.5 m), which was closed and connected to the water main through a steel side pipe. The side pipe was fitted with a plate pre-drilled with a small hole in the center. A piece of scaled Plexiglas pipe, whose inner diameter was 34 mm, was mounted on the closed water tank to observe volumetric changes. The water level in the observation tube was

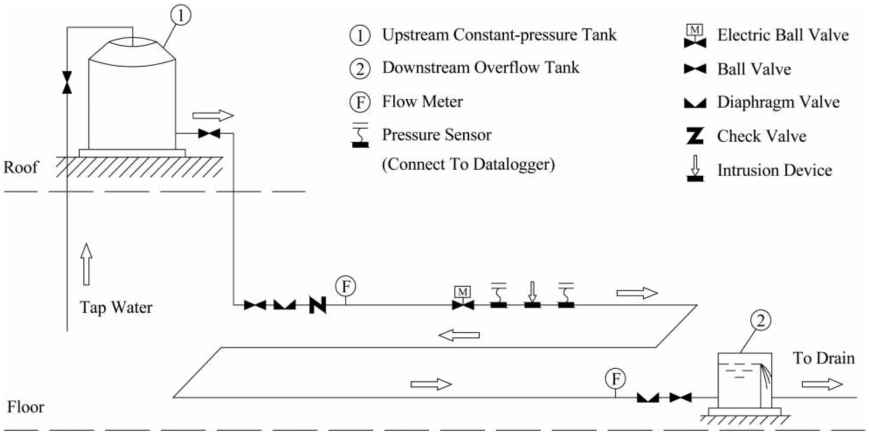

Figure 1 | Schematic of the experimental installation.

recorded with a video camera during the low or negative pressure events. The video recordings were converted into image files to determine the intrusion volumes after each experiment ended. The diameters of leakage points were changed by replacing the plates with holes of different diameters.

The pressure acquisition system consisted of three GE PTX-5032 pressure sensors. Two pressure sensors were installed on the water main, just 0.3 m upstream and downstream of the intrusion device, respectively. Another pressure sensor was installed on the intrusion water tank. They were used to measure the pressure changes associated with low or negative pressure events in the water main and in the intrusion water tank, respectively. These pressure sensors were connected to a data acquisition card. The data acquisition frequency of the pressure sensor was 1,000 Hz.

Experimental measure of the intrusion volume

The intrusion volume was affected by several factors, such as the sizes of leakage points, initial flow velocities, internal steady pressures before the low or negative pressure events, and external pressures at the leakage points. The initial flow velocities and internal pressures were changed by adjustment of the diaphragm valves upstream and downstream. The change in external pressures was achieved by installation of observation pipes of different lengths. The intrusion water tank was 0.5 m high, and the 0.2-, 0.3-, 0.4-, and 0.5 m-long observation pipes mounted on the tank could provide external heads of 6.86, 7.84, 8.82, and 9.80 kPa, respectively. The water overflowed the observation pipe before or after the negative pressure events. The dropping water level of the observation pipe indicated that external water intruded into the water pipe. This study used the single-factor method to investigate these factors affecting intrusion volume, and 64 experiments were performed, as shown in Table 1, involving different external pressures, initial flow velocities, and orifice diameters under a fixed initial internal pressure of 30 kPa.

The intrusion volume can be measured with the change in water level in the observation pipe. The procedure was organized as follows: first, the diaphragm valve was adjusted to establish the steady-flow conditions for 20–30 s; second, the electric ball valve was closed in 1.0 s to produce a low or negative pressure event; third, the pressure fluctuation within the pipes and the change in water level in the observation pipe during the pressure events were recorded. The dropping water level of the observation pipe was multiplied with the cross-sectional area of the observation pipe to obtain the intrusion volume for a single fluctuation in pressure. All intrusion volumes for each pressure fluctuation during the negative pressure event were accumulated to obtain the experimental measure of the intrusion volume.

Theoretical calculation of the intrusion volume

The orifice equation is commonly used to calculate the intrusion flow rate (Funk *et al.* 1999; Besner *et al.* 2011;

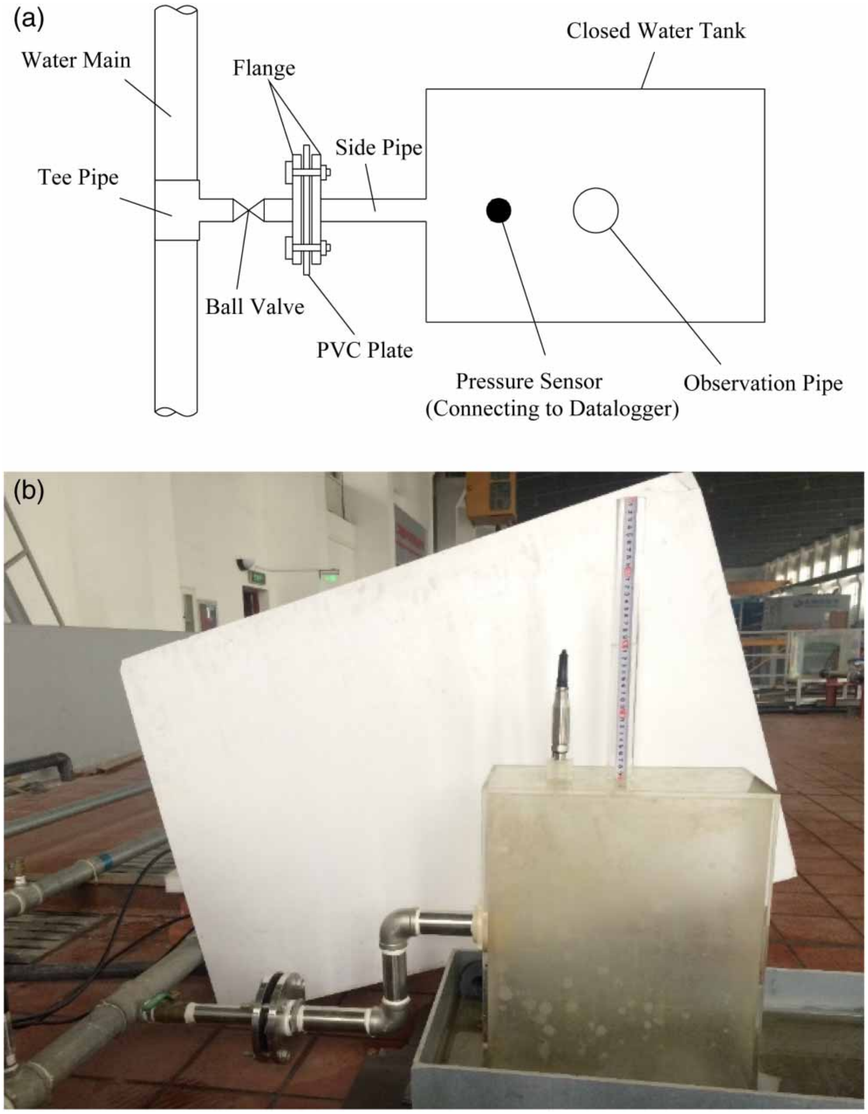

Figure 2 | Schematic diagram of the intrusion device (a) and photographs of the intrusion device (b).

Table 1 | List of scenarios of the experiment

Variables	**Values**
External pressure (kPa)	6.86, 7.84, 8.82, 9.80
Orifice diameter (mm)	3.0, 4.5, 6.0, 7.5
Initial flow velocity (m/s)	0.25, 0.38, 0.51, 0.64
Initial internal pressure (kPa)	30

Mora-Rodríguez *et al.* 2012):

$$Q = C_d A \sqrt{2g\Delta H}, \tag{1}$$

where Q is the volumetric flow rate, C_d is the orifice discharge coefficient, A is the cross-sectional area of the orifice, g is the gravitational acceleration, and ΔH is the difference between the external and internal pressure heads. According to the orifice equation, the theoretical intrusion volume associated with low or negative pressure events can be computed with the following equation (Funk *et al.* 1999; Kirmeyer *et al.* 2001):

$$Q_i = C_d \frac{\pi d^2}{4} \sqrt{2g(H_{\text{ext}} - H_i)} \quad \text{when} \quad H_{\text{ext}} \geq H_i, \tag{2}$$

where Q_i is the volumetric flow rate at an instant of time, d is the orifice diameter, H_{ext} is the external pressure head, and H_i is the instantaneous internal pressure head at the leakage point. The total intrusion volume can be computed by integration of Q_i over the duration of the transient pressure.

Abdulrahman (2005) found that the simulation of the real-time unsteady leak rate for normal-sized leaks was achieved with sufficient accuracy through the steady-state discharge coefficient. Therefore, the orifice discharge coefficient C_d can be obtained from steady-state orifice discharge experiments. The experimental apparatus was operated under certain conditions with the flow discharged through the leakage points steadily. The discharge flow was measured with the flow meters upstream and downstream of the leak point. Then, the values of C_d under different conditions were calculated with the orifice equation. The average value 0.664 was used as the value of the discharge coefficient. From the pressure data collected in the experiments, the theoretical values of the intrusion volume were determined with Equation (2).

RESULTS AND DISCUSSION

Transient pressures caused by valve shutdown

The negative pressure within the pipeline may push the pollutants that existed in the external soil and water into the water distribution systems. Two pressure-measuring points are located respectively at 0.3 m upstream and downstream of the leakage point. The mean value of the pressure at the two measuring points is nearly the same as that at the leakage point. When the water hammer occurs, the internal pressure drops rapidly to the lowest point and rebounds to the highest point immediately. Then, it goes through a few cycles of fluctuation until the wave stops. The pressure change in the pipe is recorded in real time with the data acquisition system. The recorded steady-flow pressure data always have a slight fluctuation (± 2 kPa). Therefore, we consider that the transient pressure fluctuation starts when the valve is closed, and it ends when the amplitude of the pressure wave is lower than 2 kPa. The durations of the transient pressure and the maximal pressure drop caused by the valve shutdown, with an external pressure of 9.80 kPa, are presented in Table 2. The decreasing orifice diameter and the increasing initial flow velocity result in a large fluctuation and a long duration of the transient pressure. The video file has 25 frames per second, so the interval between two sequential images is 0.04 s. Every frame image of the video files is extracted to determine the water level in the observation tube every other 0.04 s. A typical fluctuation of the water level and a pressure change process in the main pipe during a complete shutdown event of the valve are shown in Figure 3. One cycle of water level fluctuation takes approximately 0.5 s. This observation indicates that the interval 0.04 s is sufficiently accurate to measure volume change.

Factors affecting intrusion volumes

The low or negative pressure events in this experiment are induced by the sudden closure of the electric ball valve, a condition leading to a sharp fluctuation of pressure in the pipe. Figure 4(a) shows the intrusion volume versus the initial flow velocity with four initial flow velocities of 0.25, 0.38, 0.51, and 0.64 m/s. The larger the initial flow velocity, the larger the pressure fluctuation caused by the rapid

Table 2 | Duration of transient pressure and the maximal pressure drop value to valve's shut-down when the external pressure is 9.80 kPa and the initial internal pressure is 30 kPa

	$d = 3.0$ mm		$d = 4.5$ mm		$d = 6.0$ mm		$d = 7.5$ mm	
Initial flow velocities (m/s)	**Duration (s)**	**Pressure drop (kPa)**	**Duration (s)**	**Pressure drop (kPa)**	**Duration (s)**	**Pressure drop (kPa)**	**Duration (s)**	**Pressure drop (kPa)**
0.25	1.60	67.54	1.15	61.47	0.85	57.41	0.64	47.84
0.38	1.73	84.50	1.45	77.45	1.08	74.91	0.82	64.16
0.51	1.98	95.47	1.60	87.54	1.18	90.14	1.02	78.08
0.64	2.40	103.23	1.74	96.71	1.35	99.88	1.16	89.37

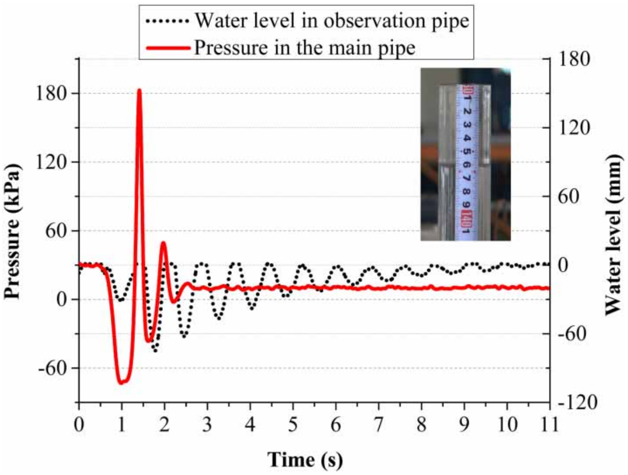

Figure 3 | Typical fluctuation of water level in observation pipe and the pressure change in the main pipe during a negative pressure event (the external pressure is 9.80 kPa, the initial internal pressure is 30 kPa, the initial flow velocity is 0.64 m/s and the orifice diameter is 3.0 mm).

change in flow velocity. The economic velocity of urban water distribution systems usually ranges from 0.5 to 1.5 m/s. The harm caused by intrusion events associated with low or negative pressure events can be effectively reduced through maintaining steady flow velocity in pipes.

The external water surrounding the pipeline can intrude into the pipe only with the existence of an intrusion pathway. The intrusion volume is associated with the size, shape, and location of leakage points. The effect of circular leaks with diameters of 3.0, 4.5, 6.0, and 7.5 mm is considered, as shown in Figure 4(b). The intrusion volume increases linearly with the increase in orifice diameter when the initial flow velocities are 0.25, 0.38, and 0.51 m/s. A large orifice diameter increases the intrusion volume in low or negative pressure events.

External pressure is an important factor that affects intrusion volume. The pressure inside a water pipe is usually higher than the pressure of groundwater outside the pipeline. However, the pressure inside the pipe decreases sharply when low or negative pressure events occur. Once the internal pressure becomes lower than the external pressure, the raw water outside the pipe may enter the pipe through leaks. Figure 4(c) shows that the intrusion volume increases almost linearly with the increase in external pressure. Therefore, the large depth and the high water table where the pipeline is buried can result in severe intrusion during low or negative pressure events.

Comparison of the measured volume with the theoretical volume

Figure 3 shows that during low or negative pressure events, the water level in the observation pipe has a fluctuation with an amplitude of approximately 0.08 mH_20 (0.78 kPa), which is only 0.3% of the amplitude of the pressure fluctuation in the main pipe (about 260 kPa). Therefore, the theoretical calculation method assumes that the external pressure is constant, i.e. the water level in the observation pipe maintains the maximum. According to this assumption, the theoretical intrusion volume may be slightly larger than the measured intrusion volume.

A comparison of the theoretical and measured intrusion volumes associated with low or negative pressure events is shown in Figure 5. Both the theoretical and measured values increase with the initial flow velocity. This phenomenon occurs because the intensity of water hammer in the pipe is affected by the initial flow velocity. The water pressure fluctuates severely, lasts long, and results in a large intrusion volume when a large initial flow velocity exists. The relative difference between the theoretical and measured values increases with the initial flow velocity, and decreases with the increasing diameter of the orifice. When the orifice diameter is 3.0 mm, with the initial flow velocity increasing, the relative difference between the theoretical and measured values varies from 44 to 55%. When the orifice diameter is 7.5 mm, the relative difference is small, with only a variation range of 22–37%. One reason is that when the orifice diameter increases, the water level in the observation pipe will have a larger decline during pressure fluctuation, and therefore, the theoretical intrusion volume will have a larger positive deviation and get closer to the measured value. Another possible reason is that the expansion effect of leakage area caused by pressure for the large leakage point becomes unremarkable compared with the small leakage point.

The theoretical calculation method assumes that the external pressure is constant, which may lead to a theoretical intrusion volume larger than the measured intrusion volume. However, Figure 5 shows a different result, that the measured value is greater than the theoretical value. Therefore, it is not entirely appropriate to describe the intrusion process with the traditional orifice equation.

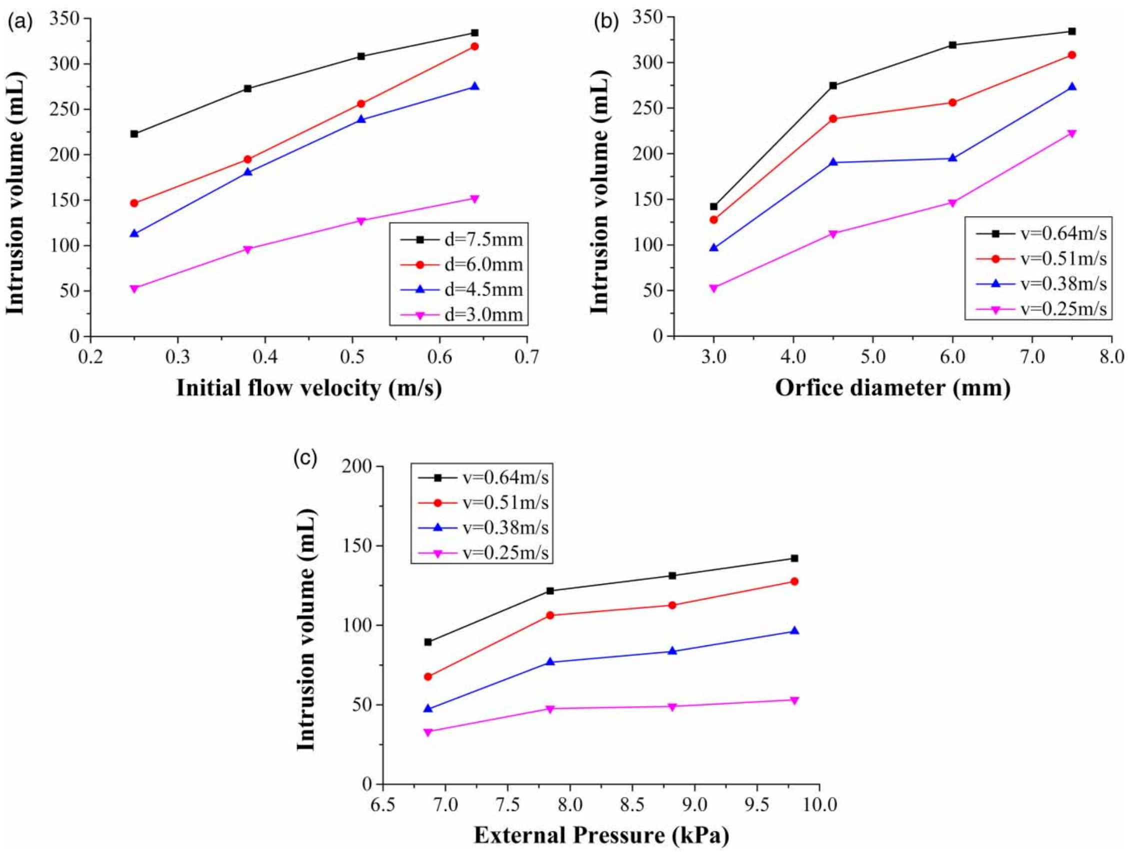

Figure 4 | Sensitivity analysis of three factors affecting intrusion volumes: (a) initial flow velocity with external pressure of 9.80 kPa; (b) orifice diameter with external pressure of 9.80 kPa; (c) external pressure with orifice diameter of 3.0 mm.

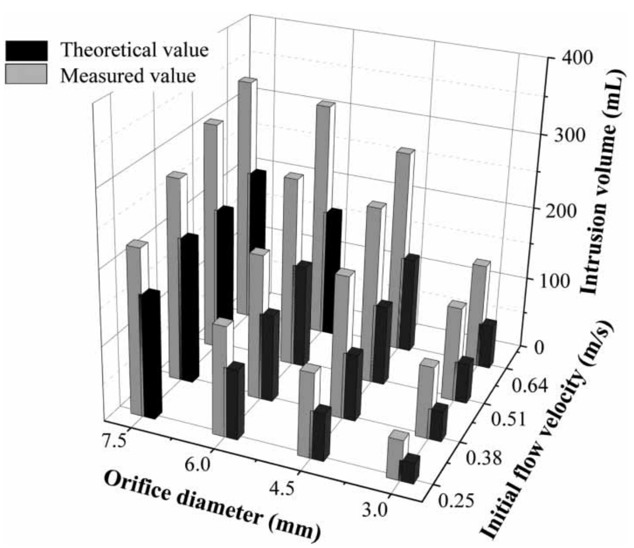

Figure 5 | Comparison of the theoretical value with the measured value of intrusion volume when the external pressure is 9.80 kPa and the initial internal pressure is 30 kPa.

The orifice equation is used to evaluate the intrusion volume in this paper. Because the non-0.5 exponential index does not obey the principle of homogeneity of dimensions. Therefore, the exponential index of the head is kept as a constant value (0.5) just like the traditional orifice equation used. A correction coefficient α is introduced to make the theoretical intrusion volume accurate through consideration of the change in the cross-sectional area of the orifice. The new expression of the intrusion flow rate equation is as follows:

$$Q = \alpha A C_d \sqrt{2g\Delta H}, \quad (3)$$

The correction coefficient satisfies the following relationship:

$$V_m = \alpha \cdot V_t, \quad (4)$$

where V_m and V_t are the measured and theoretical intrusion volumes, respectively. The target correction coefficients are calculated with Equation (4) based on the theoretical and measured intrusion volumes.

Correction coefficient α

The correction coefficient α is affected by the external pressure, the initial internal pressure, orifice diameter, and initial flow velocity. The pressure fluctuation in the pipe is drastic when the orifice diameter is small or the initial flow velocity is large, and the leakage points usually undergo a considerable shape change, which means that the theoretical equation needs a correction. Figure 6 illustrates that the correction coefficient increases with the increase in the initial flow velocity, and decreases with the increase in the internal-external pressure difference and orifice diameter.

According to the preceding correlation analysis, we argue that the correction coefficient is a function of the internal-external pressure difference, orifice diameter, and initial flow velocity. The correction coefficient can be expressed as follows:

$$\alpha = \alpha(v_0, H_{ii} - H_{\text{ext}}, d), \tag{5}$$

where v_0 is the initial flow velocity, H_{ii} is the initial internal pressure, H_{ext} is the external pressure, and d is the orifice diameter.

Because the correction coefficient is dimensionless, three dimensionless parameters are introduced as follows:

$$k_1 = \frac{v_0}{c_0} \times 100; \quad k_2 = \frac{H_{ii} - H_{\text{ext}}}{H_a}; \quad k_3 = \frac{d}{D}, \tag{6}$$

where c_0 is the velocity of water sound waves, 1,482 m/s under 20 °C water temperature; H_a is the standard atmosphere pressure, 101.325 kPa; and D is the diameter of the main pipe. The correction coefficient can be fitted as the power exponent function of a single parameter from

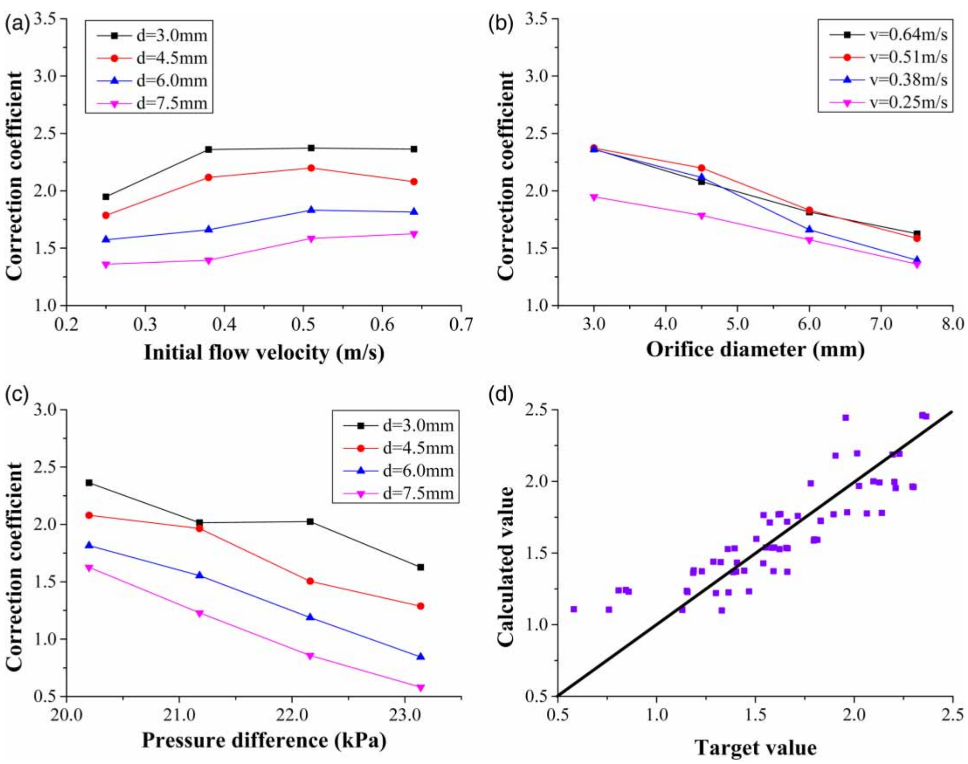

Figure 6 | Correction coefficient and its fitting results: (a) correction coefficient versus initial flow velocity under 9.80 kPa external pressure; (b) correction coefficient versus orifice diameter under 9.80 kPa external pressure; (c) correction coefficient versus internal-external pressure difference under 0.64 m/s initial flow velocity; (d) fitting results of the calculation equation of the correction coefficient.

Figure 6. With the data on the target value of correction coefficient α and the three factors, the proposed equation of correction coefficient α can be fitted as follows:

$$\alpha = 0.012\frac{k_1^{0.008}}{k_2^{2.422}k_3^{0.513}}, \quad (7)$$

The square of the correlation coefficient (R^2) is 0.76. The fitting results are shown in Figure 6(d). The slash represents the condition in which the calculated value is the same as the target value. Each point denotes the target and calculated values of the correction coefficient for each condition. The calculated value is close to the target value when the point becomes close to the slash. Figure 6(d) depicts that the majority of the data points are located near the slash, so this means that the target and calculated values are close to each other under most conditions. Calculating the correction coefficient with Equation (7) is therefore reliable.

DISCUSSION

The experiment provides evidence that contaminated water will enter into the pipe due to low or negative pressure events. The result is consistent with previous studies (Boyd *et al.* 2004a, 2004b; Mora-Rodríguez *et al.* 2011). Ebacher *et al.* (2012) studied the intrusion problem with the real network investigation and CFD modeling. Compared with Ebacher *et al.* (2012), the comprehensive factors that influence the intrusion volume are investigated in this paper. However, the real components of water distribution systems, such as submerged air vacuum valves, are not considered. The experiment is carried out without considering the ground conditions. Therefore, the soil's influence is not considered in the derived intrusion equation.

The experiment uses a tank to simulate the ground water surrounding the buried pipe. A hole of a certain size may exist around the leakage point of the buried pipe, according to the soil parameter, leakage degree, and time of the leakage. We therefore use a tank to simulate the ground water in the hole near the leakage point. However, the soil affects the intrusion volume. The water near the leakage point intrudes into the pipe when low or negative pressure events occur. Then, the other water that percolates out from the surrounding soil supplements the deficiency of water in the hole. If an intrusion occurs quickly, and a large amount of water enters the leakage point, the seepage water becomes inadequate and the soil hole loses pressure. Therefore, the soil attempts to prevent the ground water from intruding into the pipe. This perspective indicates that the real intrusion volume in the experiment should be larger than that in the real situation.

For the convenience of changing the size of the leakage point, a tee joint and the plate with a small orifice in its branch pipe are used to replace the leakage point within the pipe. The branch pipe may affect the water hammer and transient pressure. The pressure difference can change the area of the leakage point because of the elasticity of the pipe material. The pressure difference always expands the leakage point area regardless of whether the water intrudes into the pipe or leaks out from the pipe because the experimental leakage point is in the flat plate. However, the real leakage point is in the convex surface of the pipe. The leakage area can be expanded easily when the water leaks out from the pipe. It tends to shrink when the water intrudes into the pipe because of the arch effect of the pipe wall. Therefore, the intrusion volume may be affected regardless of whether the leakage point is in the pipe. An experiment on the leakage point within the pipe should be conducted in the future.

The measured intrusion volume is evaluated in this study through the volumetric method. We only consider the dropping water level in the observation tube to calculate the intrusion volume. However, a part of the intruded external water may be pressed out instantly by the positive pressure when this water is intruded into the pipe because of the negative pressure, and the volume of this part is not considered in the volumetric method. Therefore, the measured intrusion volume should be larger than the real intrusion volume. The theoretical orifice equation also considers the intrusion volume only when $H_{ext} > H_i$, and the possible outflow of this part of the intrusion volume is ignored. CFD simulation should be an appropriate choice to trace the intruded water continuously in the future.

The shutdown event of the valve affects the transient pressure, which is the main impetus that changes the intrusion volume. The pressure and water level in the observation tube determined in the experiment are both time-related. The electric ball valve used in this experiment has an adjustable shutdown time and it was set for 1.0 s in the test. For further study on the effect of valve shutdown time, various scenarios with different valve shutdown times should be carried out in the next experiment.

CONCLUSIONS

An experimental installation was designed and constructed to determine intrusion volumes associated with low or negative pressure events. Intrusion volumes were determined through a volumetric method. Based on the intrusion volumes measured under various conditions, the sensitivity of the factors affecting the intrusion volume was analyzed. The theoretical intrusion volumes were calculated with the orifice equation and then compared with the measured intrusion volumes to propose a correction coefficient.

The intrusion volume was considerably affected by the size of leakage points, initial flow velocity, and external pressure at leakage points. It also had a positive correlation with each of the three factors. The cross-sectional area of the leakage point underwent a shape change during negative pressure events, which probably resulted in theoretical intrusion volumes that are less than the measured intrusion volumes. A correction coefficient was introduced to improve the traditional orifice equation. The correction coefficient had a positive correlation with the initial flow velocity, whereas it had a negative correlation with the orifice diameter and the internal-external pressure difference.

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