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Experimental Quantification of Intrusion Volumes Due to Transients in Drinking Water Distribution Systems

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ABSTRACT

We are currently unable to fully assess the risks to human health and wellbeing from contaminant intrusion into drinking water distribution systems due to lack of understanding and accurate estimation of intrusion volumes during dynamic pressure events. This paper presents results quantifying such volumes from carefully controlled but representative physical three dimensional experiments. Results show how the volumes change as a function of the dynamics of the driving pressure and how these volumes can be estimated from the time integral of the measured driving head. Results also reveal the complex coupling of dynamic pressure behaviour interacting with the leak orifice and the exchanged volumes. The findings of this work can be integrated within assessment frameworks to enable better estimation of intrusion volumes and hence management of risk to public health.

INTRODUCTION

Water suppliers are legally and morally responsible for the quality of drinking water that issues from customers' taps, such as set out in drinking water quality standards (EU

Drinking Water Directive 98/83/EC). These standards and expectations are becoming increasingly more stringent and water quality failures are known to occur. Such failures occur for a number of reasons, such as discoloration of water caused by a change in hydraulic conditions and contamination of the source water. In many instances failures cannot be explained. A possible source of such failures is the contamination of drinking water due to the intrusion of pollutants into the distribution system from the surrounding soil and water. Leakage apertures provide a possible pathway for this. Leakage is an accepted feature of distribution systems. It is realised that, due to the ageing asset infrastructure, the elimination of all leakage is unlikely to be feasible or economically justifiable. In the UK, network utilities can lose up to 575 million litres per day through leakage (Brydon, 2013). Such leakage is considered to occur outwards due to the pressure differential between the water in the pipe and the lower pressure in the surrounding ground. Risks associated with long term depressurisation, such as to fix a pipe burst, should be mitigated with good working practices. However, distribution networks are dynamic systems with frequent changes in hydraulic conditions. Such changes induce transients in the form of pressure waves that move throughout the network. Transient events may induce low or even negative pressures over relatively short durations. Hence, the pressure of the water inside the pipe may briefly be lower than the pressure outside the pipe and there is potential for intrusion. Such intrusion volumes are likely to be small but may contain harmful contaminants. The smallest traces of certain contaminants may cause a water quality failure whilst others may seed bacterial growth, including within biofilms where they may be protected from disinfection residuals, ultimately impacting on public health.

LITERATURE REVIEW

Health Impacts

There is published evidence of water contamination as a possible cause of health issues. This includes epidemiology studies by Payment et al. (1991 and 1997) and randomised trials by Hellard et al. (2001). Craun and Calderon (2001) analysed waterborne disease outbreaks and their origins from 1971-1998 in the United States of America. They found that in this period 113 out of 619 disease outbreaks were caused by chemical and microbial contaminants entering public drinking water distribution systems (DWDS), although it is estimated that the true number might be much higher due to accuracy and reliability of data collection. From those 113 events, more than 21,000 cases of illness were reported mostly attributed to Giardia and bacterial pathogens, including 498 hospital and emergency room visits and 13 deaths. In the UK, Hunter et al. (2005) reported results from a postal questionnaire, finding a strong association between loss of water pressure at the home tap and the incidence of diarrhoea and estimated that the cost of such illness could exceed £100 million per annum in England and Wales (15% of the total estimated annual cost of diarrhoeal disease).

Intrusion Mechanisms

Research and evidence exists for the three components of contaminant intrusion risk as set out by Lindley and Buchberger (2002). Contaminants undesirable in drinking water have been shown to exist in the soil surrounding pipes (LeChevallier et al. (2003), Karim et al. (2003), Besner et al. (2006)). Pathways including leaks, cracks, submerged air valves, badly fitted joints/seals, and cross connections exist throughout distribution systems. Evidence is emerging which supports the dynamic nature of distribution systems and the widespread frequent occurrence of transient events (McInnis and Karney, 1995; Ebacher et al., 2011; Starczewska et al., 2013) while some research directly evidences the occurrence of low and negative pressure transients (Walski and Lutes 1994, Qaqish et al. 1995, Karim et al. 2003, Gullick et al., 2005, Fleming et al 2006 and Besner et al. 2007). Kirmeyer et al. (2001) performed transient modelling on the Montreal distribution system, where Payment conducted his epidemiology studies, and found that more than 90% of nodes would experience negative pressures under certain scenarios, such as power surges.

Laboratory Testing

Boyd et al. (2004a) provided the first experimental confirmation of the potential for contaminant intrusion into pressurised water mains during transient events, but under idealised conditions. Their configuration used an external column of water placed above a manually operated check valve and pre-drilled orifice mounted on the test pipeline. The transients were generated by a system valve closure, and required a manual synchronised valve opening on the external column. While this finding provided proof of intrusion for an idealised condition, their experiments were limited as *"neither the volumetric nor the* chemical tracer method provides an accurate estimate of the actual volume of contamination *associated with a specific event"*.

Research by Fox et al (2015) moved substantially closer to reality using a pipe with an orifice buried in a gravel media, to show that net intrusion and transport of material originating external to pipes can occur due to transient conditions. While this experiment did provide repeatable quantification of volume and estimation of the sphere of influence around the leak aperture, it did not allow for volume to be estimated across a range of transient conditions, which is essential for risk assessment.

Operational Systems

Research reported in Besner et al. (2007 and 2010) conducted experiments to determine if negative pressure caused by a transient resulted in contaminant intrusion in operational distribution systems. In the 2007 study a transmission main was rapidly closed and although sustained negative pressures were recorded, no significant water contamination was detected. The 2010 study investigated the same distribution system used by Payment et al (1991 and 1997) and Kirmeyer et al (2001). In the 2010 study, bacterial indicators of faecal contamination were found more frequently in the water found in flooded air-valve vaults than in the surrounding soil or water. This suggests that air-valve orifices can provide a critical pathway for contaminant intrusion. Although the paper does not provide direct evidence, the authors strongly suggest a link to the negative pressures shown during long-term pressure monitoring. While the risk for air-valves can be mitigated by good operational management, Besner et al. (2010) show that bacterial contamination has been found in soil and water surrounding pipes, hence leaks which cannot be easily managed could provide a pathway for contaminant intrusion.

Modelling

Any attempt to quantify the risks associated with contaminant intrusion requires the estimation of intrusion volumes. The most common method to do this is via some form of the Torricelli or orifice equation, Equation 1, such as in Funk et al., (1999); Kirmeyer et al., (2001); LeChevallier et al., (2003); Boyd et al (2004b); Fleming and LeChevallier, (2008); Ebacher et al. (2012).

$$Q = C_D \frac{\pi {d_o}^2}{4} \sqrt{2g}\, \sqrt{H_D} \qquad \text{Equ. 1}$$

Where Q is orifice flow rate, C_D is coefficient of discharge, d_0 the diameter of the leak orifice (assumed to be circular) and H_D the driving head.

While the orifice equation has been applied for estimation of intrusion volumes, its widest application to drinking water distribution systems is in the field of leakage. Farley and Trow (2003) demonstrated that the exponent for head can vary from 0.5 to 2.79; this was attributed by van Zyl and Clayton (2007) to the orifice expansion or contraction due to pressure, which strongly depends on its shape and the on pipe behaviour. However it is now suggested that a modified orifice equation using a 0.5 exponent is a more realistic description of leakage and intrusion flows for variable pressure (van Zyl et al., 2017). Cassa et al. (2010) showed that round holes present the smallest expansion with pressure – a maximum area increase of 1.4% for a 12 mm diameter hole in a 110 mm unplasticised Poly Vinyl Chloride (uPVC) pipe under a 60 m pressure head. The small change in area for an orifice under pressure corresponds to a pressure head exponent close to the historical value of 0.5. Fox et al (2016) explored pressure-area-flow rate effects in plastic pipes and concluded that the orifice equation, with a constant coefficient of discharge, is suitable for accurately estimating dynamic leakage flow rates from longitudinal slits, provided that the leak area is suitably incorporated.

The coefficient of discharge is also commonly found to vary as a function of resistance effects, including due to the orifice shape and local entry and exit conditions. Collins and Boxall (2013) developed and verified a modified coefficient of discharge for an orifice submerged in porous media experiencing steady state leakage or intrusion. The expression incorporated parameters capturing the effects of the surrounding porous media, including the inertial resistance, B, the orifice losses, k' and a geometric shape factor, G.

$$Q = \frac{1}{\sqrt{k' + \frac{d_o g\sqrt{G}B}{6}}}\frac{\pi {d_o}^2}{4}\sqrt{2g}\sqrt{dH}$$ Equ. 2

Besner et al (2011) provided a review of the components that should be considered and included in a quantitative microbial risk assessment (QMRA) framework for the public health risks associated with intrusion events. They conclude that while such risks can be estimated, they are based on several assumptions. They particularly note that population exposure is dependent upon both the quantity of pathogens entering the system and the duration of intrusion - both of which are time integral functions of the intrusion flow rate.

AIMS

The main aim of this research was to experimentally quantify the volume of contaminant intrusion through an orifice in a representative physical system when subjected to hydraulic transients causing negative pressures. The work sought to investigate how the volume intruded changed with respect to the transient conditions as defined by the change in system pressure and flow rate and due to the presence of media external to the orifice. The work also aimed to explore the application of the orifice equation to quantify these volumes.

MATERIALS

The large scale laboratory facility at the University of Sheffield (Collins and Boxall, 2013; Fox et al., 2015) was used. The system comprises 140 m of 50 mm internal diameter medium-density polyethylene (MDPE) pipeline, configured as a recirculating system. Water is fed from an upstream reservoir through a 3.5 kW Wilo MVIE variable speed pump. System flow rate and pressure is controllable through this variable speed pump and a downstream control valve. Flow rate was measured with an Arkon Flow Systems Mag-900 electromagnetic flow meter. Pressure was measured by four Gems 2000 series Pressure Sensors, with a manufacturer stated accuracy of ± 0.16 m. Maximum conditions possible were 4 l/s and 40 m for flow rate and steady state pressure head respectively, providing conditions fully representative of operational drinking water distribution systems. Quarter turn butterfly valves are located throughout the pipeline capable of rapid manual closure to produce highly repeatable transients.

A circular orifice was installed in the pipe invert in a straight section of the pipeline, approximately 75 m from the reservoir tank using a 2 mm diameter drill bit. Due to residual stresses of the MDPE material, the actual diameter created was 1.55 mm. A circular hole was chosen to minimise pressure dependent area effects, as covered in the literature review (Fox et al, 2016). The size was chosen based on initial experiments to provide measurable intrusion volumes and to be representative of the type of background leakage that may be prevalent and go unrepaired within operational systems.

In order to measure the volumes exchanged through the leakage orifice the main pipe line was enclosed within a 400mm length of larger 380mm diameter outer pipe that had a single relatively unconstrained overflow (see Figure 1). The outer pipe was located centrally around the inner pipe. The outer pipe was made of stiff acrylonitrile butadiene styrene (ABS) with an 8 mm wall thickness. The outer pipe was capped at both ends by aluminium plates secured with bolts, creating a volume surrounding the orifice. This outer pipe and associated end plates were stiff such that any possible changes in volume due to dynamic pressures during experiments were minimised. While assumed small, any volume changes of the main MDPE pipeline due to dynamic pressures are a consistent effect across all tests. This would also be part of the mechanism driving intrusion in operational systems. The outer volume was sufficient such that the internal flow field within it was not affected for the ranges of flow and pressure available in the system, based on simulations in computational fluid dynamics (CFD) by Collins et al (2010).

To monitor the net movement from an external source into the system, a clear riser pipe was fitted above a secondary 12 mm orifice in the external pipe directly above the primary leakage orifice. This inlet/outlet point creates the sole pathway for fluid from the riser pipe into the pipeline system. The level in this riser pipe was monitored to quantify intrusion. The diameter of the riser pipe was designed such that its entry and exit losses were minimal compared to the primary leak orifice, but such that observable changes in level occurred in the riser pipe.

METHODS

Results are reported here for the intrusion volume measured as the result of complete instantaneous closure of a butterfly valve immediately upstream of the test section. This provided a range of transients in the test section each with an initial down surge. Initial conditions were varied independently to provide a range of transient conditions: for a set initial pressure of 20 m, flow rates in steps of 1 l/s from 1 l/s to 4 l/s; and for a set initial flow rate of 2 l/s, pressure heads in steps of 10 m from 10 m to 40 m. These values were chosen to give conditions representative of operational water distribution systems. Five repeats were carried out for each initial condition creating 35 experimental cases for two types of media in the external volume (see Table 1). The order of experiments was randomised and the system flushed between experiments including removal of any air. Once the desired initial conditions were set, the system was allowed to stabilise for at least 10 minutes before a transient was created. The two types of external media were water and pea gravel (diameter 3 to 8 mm and average porosity of 42 %). In order to ensure that the gravel media remained fully consolidated and minimise formation of voids, the gravel was rigorously compacted during filling and a water filled bladder pressurised to 32 m was installed behind one of the end plates to provide a compressive force on the solid particles. The gravel was periodically checked and maintained over the experimental period.

An SVSi Gigaview high speed video camera was used to record the water level in the riser pipe at 50 frames per second. The volume of intrusion was assessed by tracking the locations of the meniscus in the riser pipe. Repeated cycles of drops and rises were found between maximum and minimum meniscus locations due to the dynamic cyclic nature of transients (see Figure 2). The drops in the meniscus level indicated fluid flowing from the outer pipe into the orifice through the surrounding media, these were considered as intrusion. The cumulative drop was calculated, calibrated from an adjacent graduated scale, and then multiplied by the internal area of the riser pipe to produce a total volume of intrusion in millilitres. Given the frame rate, image resolution and meniscus detection the average accuracy of volume estimate was ± 1.3 ml.

RESULTS

Figure 3 shows four examples of the transients created in the system across the various conditions set out in Table 1. The surrounding material is water in all cases. Each sub-figure includes five repeats evidencing the repeatability of the system. The time taken for the system to reach equilibrium after the valve closures ranged from approximately 6 s to 14 s as a function of the conditions being studied, but irrespective of the surrounding material. Figures 3 b) and d) show maximum negative pressures ‘flat lining’ at cavitation pressure around -10 m. Low or negative pressures sufficient to cause intrusion were generated for all the conditions reported here, i.e. a drop in meniscus level greater than experimental error indicating net movement of fluid into the main pipeline.

Figures 4 a) and b) present results of experimental intrusion volumes for both water and gravel media external to the leak orifice. Figure 4 a) shows results for an initial flow rate of 2 l/s and varying initial head. Figure 4 b) shows results for an initial head of 20 m and varying initial flow rate. For both water and gravel external to the leak orifice it can be seen that as the initial pressure head increases, the volume of intrusion into the system decreases; also as the flow rate increases, the volume of intrusion increases. The linear regression lines shown all demonstrate a good fit with R^2 values above 0.9. In both cases the gradient terms between water and gravel are similar.

Table 2 presents the average volumes of intrusion, from 5 repeats, for each of the hydraulic conditions set out in Table 1. The table includes direct comparison of how these volumes change as a function of the external water or gravel media. The results show that, under the same initial conditions for transient generation, the intrusion volumes are consistently lower when the orifice is surrounded by gravel rather than water, as also evident in Figure 4. Tentative trends can be seen in the difference between the two media as a percentage of the water intrusion volumes – as the flow rate increases, the percentage difference decreases; as the pressure head increases, the percentage difference increases.

ANALYSIS

An aim of this research was to explore the application of orifice equation based expressions to estimate intrusion volumes. The approach adopted was to assume that orifice flow could be estimated by applying Equation 1 at each instantaneous time when the driving head was negative and that these could be integrated over time to provide an estimate of the intrusion volume. The intrusion driving head, H_D, was defined as the external pressure indicated by the meniscus head in the riser pipe (measured from the meniscus to the point of intrusion, i.e. the orifice) minus the pressure in the pipeline. Only the negative driving head is considered for intrusion to occur.

Where

$$Q_O = C_D A_0 \sqrt{2g}\sqrt{H_D} \qquad \text{Equation 3}$$

And

$$H_D = H_M - H_S \qquad \text{Equation 4}$$

Thus

$$V_I = \int Q_O dt = C_d A_o \sqrt{2g} \int \sqrt{H_D} dt \qquad \text{Equation 5}$$

Where Q_O is the instantaneous intrusion flow rate, A_0 the orifice area, H_M is the external meniscus head, H_S the system head, and V_I the intrusion volume.

If the coefficient of discharge, area and acceleration due to gravity are constant, then from Equation 5 there should be a linear relationship between intrusion volume and the time integral of the square root of the negative driving head. The system head was measured by the pressure transducers; however, the meniscus head is a function of the fluid height in the riser pipe which changed over the duration of the intrusion events as recorded on the video images (Figure 2). Two methods were applied to assess the meniscus head to determine the driving head over time. The first using the average meniscus head over the transient duration. The second involved interpolation of the 50 Hz video data to the 300 Hz of the pressure data and calculating the driving head at every time point. The difference between the two method was found for a random sample of 6 transients (9 % of total tests) covering both gravel and water cases. The difference in calculated volumes was no greater than a maximum of ± 0.18

%. This can be explained by the variation in driving head being negligible compared to the driving head itself, therefore an approximately linear relationship exists between flow rate and pressure head. The simpler method was adopted for the complete data set.

Figure 5 shows that a linear trend is evident, for the data collected here, between the time integral of the square root of the negative driving head versus experimental intrusion volumes, with coefficients of determination, R^2, of 0.92 for the water and 0.87 for the gravel cases. Using the trendline gradients the C_d for water is calculated as 0.55, and for gravel as 0.57. This suggests that there is little difference in the combined coefficient of discharge, area and gravity effects between the two cases.

To further investigate the linear relationship shown in Figure 5, in particular if there was any association between the coefficient value and the different transient conditions, individual values of the coefficient of discharge were also calculated. No trend or pattern in these values could be found despite various ordering and replotting of the data.

DISCUSSION

Experimental Methodology and Method

The research reported here has shown that under idealised laboratory conditions pressure transients can lead to quantifiable intrusion of water through a leak orifice, aligning with previous literature (Boyd et al, 2004a and b; Fox et al, 2015). While the experimental configuration used here was full scale and fully three dimensional it required fluid exchange to occur through the pipe leakage orifice and through the outer pipe volume channelled to the single riser pipe. The internal diameter of the riser pipe was 12 mm, thus loss effects associated with this should have been small compared to the main leakage orifice of 1.5 mm diameter. The flow through the outer pipe was from the leakage orifice in the invert of the main pipe to the riser pipe at the top of the outer pipe. The outer pipe was sized to be large enough to avoid edge effects and to allow full three dimensional flow, based on CFD simulations (not shown). It is likely, however, that the flow paths in the external volume will have been different between test cases and in particular between cases with gravel and water media filling the outer volume. Arguably the overflow at the crown of the outer pipe is similar to leakage flow towards a ground surface, but this is not always the main route of leakage flows and concentration to a single point is unrealistic. This point overflow will have induced some additional resistance effects as the flow paths focus to this point, particularly so in the gravel cases, however due to the larger diameter of the external pipe and the riser pipe this will be substantially smaller than at the leaking orifice. While it is relevant to note these idealised factors of the experimental set up, they were constant across the experimental conditions and effects were small compared to the effects of interest.

It is possible that the transients could have been altered due to mechanical changes in the pipe material. Experimental data collected by Gally et al. (1979) shows strong effects of temperature on transient behaviour – an increase in temperature can decrease pressure fluctuations due to a lower propagation speed. Additionally, transient damping is affected by the stress-time history as the pressure waves result in retarded deformation of the pipe wall, Covas et al. (2004). Both of these effects were controlled and minimised here. The temperature difference within and between the experiments using different media was less than 2°C. The order of experiments with different initial conditions was randomised meaning that any such effects would manifest in scatter of the experimental data, which is low.

It is possible that there was movement of the gravel during and between experiments allowing the creation of a small void immediately external to the leak orifice, despite the use of a bladder to restrict this. However, experiments were randomised and the pressure in the bladder checked regularly, hence there should have been no consistent effect of this, with any impact manifesting as scatter in the data, Figure 3 b). But this scatter is comparable between media in Figure 4 suggesting any such effects were minimal.

Transient Intrusion Mechanisms

The data presented here provides definitive evidence that as the magnitude of the negative pressure increases so the intrusion volume increases. From Figure 4 a) it can be seen that for a given change in flow, and hence initial pressure surge, as the initial pressure in the system is increased the observed intrusion volume decreases. This is because the datum pressure is effectively increasing so the magnitude of negative pressure decreases, evident by comparing Figures 3 b) and c). Conversely Figure 4 b) shows that for a fixed initial pressure, increases in initial flowrate (equivalent to velocity for a fixed diameter) cause an increase in the observed intrusion volume. This change in pressure transient is evident by comparing Figures 3 b) and d), although manifest as greater period at cavitation pressure rather than a greater negative pressure.

Application of Orifice Equation

Linear correlations were observed between intrusion volumes and the time integral of the square root of measured negative head differential, Figure 5. From this is it evident that using a time integral form of the orifice equation it is possible to estimate intrusion volumes, supporting the use of an orifice theory based equation in this analysis and estimation of intrusion volumes through fixed area orifices. It should be noted that the calculation of the time integral of the square root of the measured negative head differential is very sensitive to the zero datum, i.e. the pressure at which the flow is being driven into or out of the pipe. It is possible that in particular the dynamic resistive effects in the external media, meant that the zero datum was not constant throughout a given transient tests. However, the intrusion volumes calculated here were not significantly different for the average and more detailed methods explored in Analysis.

Collins and Boxall (2013) developed and validated for low (up to +/-10m) head steady state conditions an equation that accounted for gravel media effects external to a leak orifice. The gravel was expected to impart additional resistance effects immediately outside the leakage orifice, which were expected to be made apparent through a reduction in the coefficient of discharge. Application of this using the properties of the gravel used here yield a modified coefficient of discharge of 0.56. This value agrees with the average fitted values calculated from Figure 5 between the gravel and water cases, 0.55 and 0.57, respectively. From the data presented by Collins and Boxall (2013) it is apparent that the orifice effects associated with a 1.5 mm orifice are dominant over gravel media effects so this result is perhaps not surprising.

From Figure 4 and Table 2 it can be seen that for transients generated with the same initial system conditions the volumes of intrusion are consistently lower when there is gravel surrounding the orifice rather than water. Under steady state conditions the effect of gravel media external to an orifice is known to reduce the orifice flow rate. Thus the presence of the gravel media could be expected to reduce the intrusion volume. Under transient conditions there is a complex coupling of the driving head due to the transient, exchange of volume through the orifice (both leakage and intrusion) and the dissipation of the transient in the pipe system. Lower resistance to exchange through an orifice should result in greater intrusion volumes, but dissipates the transient faster resulting in less overall driving force and hence lower volumes. Conversely increasing the resistance to flow through an orifice (adding gravel media externally) should decrease the volume, but it also decreases the dissipation effects and hence increases the overall driving force.

Figure 6 shows a comparison between transients generated by valve closures from initial conditions of 4 l/s and 20 m for water and gravel. The initial waves in both cases are very similar, suggesting that the changes due to the external conditions were not very significant, similar to the repeatability evident in Figure 3. Thus there is no significant change in driving transients, but due to the sensitivity of the calculation of the intrusion volume to the time integral of the square root of measured negative head differential this could still be sufficient to explain the change in volumes observed and calculated here.

Practical Implications

Overall the research presented here provides physical evidence from controlled but realistic experiments of how intrusion volumes change as a function of transient conditions, within the limits of the experimental setup. The work also shows that the time integral of the square root of the negative driving head can be used to estimate intrusion volumes, but only if the driving transient pressure profile is well quantified. This indicates a need to radically improve our ability to model the propagation of pressure transients in operational systems, including accounting for all damping / dissipation effects and network uncertainty; from friction and viscoelastic material effects to network uncertainties such as pipe material, diameter, connectivity etc. and uncertainties of leakage (location, size, orifice shape, external media etc.). The research reported has particularly highlighted the complex coupling of the driving head due to the transient, exchange of volume through the orifice and the dissipation of the transient.

It should be noted that the intrusion volumes reported and estimated here are worst cases, no consideration is given to push-pull exchange through the orifice; it is simply assumed that any volume that has been external to the pipe, even if only for a short period, is a contamination risk. This work better informs the volume estimations integrated into QMRA frameworks and hence enhances understanding of contamination risks.

CONCLUSIONS

The work presented here supports previous research providing physical evidence that contaminant intrusion can occur due to dynamic pressure transient events within water distribution systems. Specifically, the work shows how intrusion volumes change as a function of the hydraulic conditions within in a full scale laboratory pipeline that replicates operational environments. Expected underlying trends have been clearly evidenced: as the change in velocity increases (increasing initial pressure surge) the volumes of intrusion increase; and as the change in pressure increases (increasing the initial pressure offset) the volumes of intrusion decrease. Analysis has demonstrated that the time integral of the square root of the negative driving head can be used in an integral form of the orifice equation to predict observed intrusion volumes. However, the required orifice discharge coefficient is found to be consistent across cases with gravel and water media surrounding the leak orifice. This is despite smaller volumes being measured and estimated for the gravel cases. Further analysis reveals that this is due to the complex coupling between the dynamic pressures and exchange through the orifice. This paper has improved the understanding of intrusion volumes. However, in order to make accurate estimates of intrusion volumes and fully assess the risks of contaminant intrusion, a step change improvement in our ability to model transients across complex pipe systems is required.

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