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Experimental Quantification of Intrusion Due to Transients in Distribution Systems

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Abstract

In water distribution systems, rapid changes in flow can create short duration large magnitude pressure waves, known as transients. Previous research has linked extreme low-pressure transients with contaminant intrusion, which presents a risk to public health. Representative physical experiments have been undertaken at the University of Sheffield using a novel large-scale system. This has allowed for the quantification of the volume of intrusion drawn into the pipe for a range of initial system conditions. Analysis of the results demonstrates that the volume of intrusion is connected to the duration and magnitude of the negative pressure transient.

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Keywords: Contaminant Intrusion; Water distribution systems; Transients; Intrusion; Negative pressures

1. Introduction

Water distribution systems (WDS) are a foundation of modern society, transporting large pressurized volumes of drinking water which must be safe for customers to consume. The movement of an external contaminant into these systems is called intrusion and has been theoretically shown by Lindley and Buchberger [1] to occur when three requirements are met simultaneously: a contaminant externally adjacent to the system (physical, biological, or chemical agents), a pathway from this source into the flow (leak, badly fitted joint, air valve) and a driving force (pressure gradient). Having entered the system the contaminant would then be carried downstream to customers. Past literature has included WDS intrusion as a possible cause of water quality issues – Payment et al. (1991 & 1997, cited

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by LeChevallier et al. [2]) conducted two epidemiology studies, each suggesting that the distribution system was at least partially responsible for increased levels of gastrointestinal illnesses. Alternatively, the contaminant could be sheltered within biofilm or corrosion products with the pipes. September et al found that the presence of biofilms in the drinking water distribution system might play a role in the presence of potential pathogens [3], and therefore pose a water quality threat, even possibly an associated health risk.

Water distribution systems are often aged, for example, much of the UK's network is made of nineteenth century cast iron pipes that are deteriorating leading to large volumes of leakage. For example, Thames Water suffered a loss of 664.6m litres of water a day to leakage in 2010-11, which was 26% of the water supplied that year [4]. Similarly, in 2010-11, United Utilities Water lost 26% of the 1785.4m litres of water per day it supplies [5]. These levels of leakage highlight that numerous potential pathways exist for intrusion. The driving force is arguably the least well understood and quantified component of intrusion. Research by Collins and Boxall [6] has quantified intrusion under steady state conditions; however, intrusion under dynamic conditions is poorly understood.

In a water distribution system a rapid change in flow, caused by a pump trip or valve closure, can create a short duration large magnitude pressure wave. These waves are known as pressure transients and can reach extreme high and low pressures. Extreme low pressures could result in cavitation – the sudden formation and collapse of bubbles occurring when the pressure of the liquid falls below its vapor pressure. Transient pressure waves and longer duration depressurization events are known to occur in distribution systems [7, 8, 9, 10, 11] and could provide a driving force for contaminant intrusion through a leak into a potable water supply.

The purpose of this research is to quantify experimentally the volume of contaminant intrusion through a circular 2 mm orifice in a representative pipeline when it is subjected to low pressure transients. The Joukowski equation [12] states that the magnitude of pressure transients are related to amount and speed of velocity changes. Consequently, these experiments have been designed to independently test the impact of the two key initial conditions, flow rate and steady state pressure head, on the volume of intrusion following complete and rapid closure of a valve upstream of the orifice. Based on the principles of the Joukouwski equation it is believed that, as the flow rate increases with a set initial pressure head, the volume of intrusion will also increase due to a larger transient event; as the pressure head increases with a set flow rate, the volume of intrusion will decrease due to decreasing negative pressure. This research shows the relationship between the volume of intrusion and the duration and magnitude of the negative pressure transient.

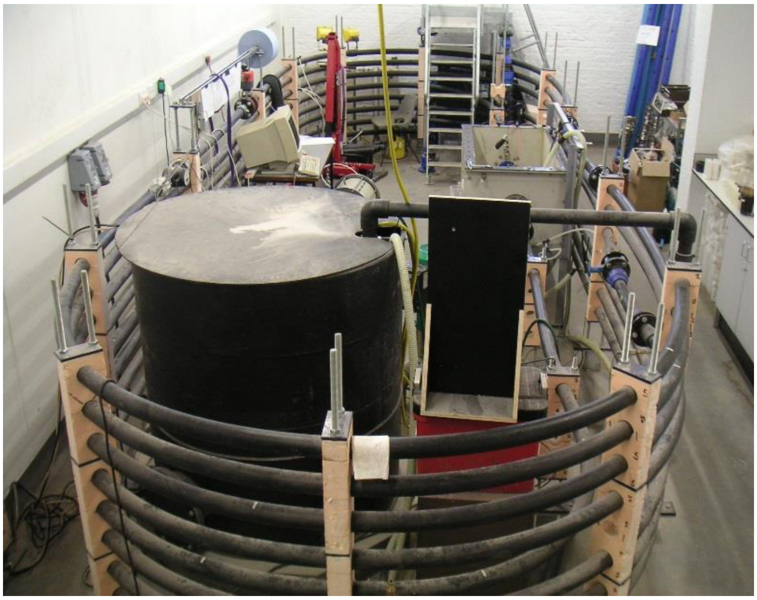

Fig. 1. Schematic Diagram and Photo of the Laboratory Facility [14]

2. Materials and Methods

A novel large scale, fully physically representative laboratory facility at the University of Sheffield has been built to study intrusion into distribution systems [6, 14]. The facility comprises of 150 m of 50 mm internal diameter medium-density polyethylene (MDPE) pipe configured as a recirculating system as shown in Fig. 1. A variable speed pump and a control valve control flow rate and pressure. The system is instrumented with up to four pressure transducers and two flow meters, four-quarter turn butterfly valves allow pressure transients to be created. This system is capable of producing flow up to 4 l/s and a steady state pressure head up to 40 m. The pipeline has a test section in the straight side 75 m from the reservoir tank; the intrusion element used in this paper is fitted into the test section.

2.1. Intrusion Element

An experimental intrusion element was designed to measure the intrusion volume for a range of initial pressure heads and flows. A 380 mm internal diameter outer cylinder of length 400 mm was capped at both ends by aluminum plates secured with bolts. This pipe has an 8 mm wall thickness and is made of acrylonitrile butadiene styrene (ABS). Running axially through this outer cylinder was a 50 mm internal diameter medium density polyethylene (MDPE) pipe with a 6 mm wall thickness, identical to the facility's pipeline. This inner pipe contained a 2 mm diameter circular leak orifice which was orientated so that the leak faced downwards in the middle of the element to minimize the direct relationship to the inlet/outlet point on the top of the cylinder. The benefit of a circular orifice as opposed to other types of leak, for example a crack, is that any variability attributable to pressure dependent area changes is negated. Figure 2 presents a schematic of this component. The volume between the two pipes was filled with water as steady state analysis by Collins and Boxall [6] showed that higher volumetric intrusion rates were observed when compared to other porous materials such as gravel, i.e. water was a 'worst case'. Computational fluid dynamics simulations undertaken by Collins et al. [15] determined that the external pipe was of sufficient size such that the steady state internal flow field in the water between the pipes was not significantly affected for the ranges of flow and pressure heads used in these tests.

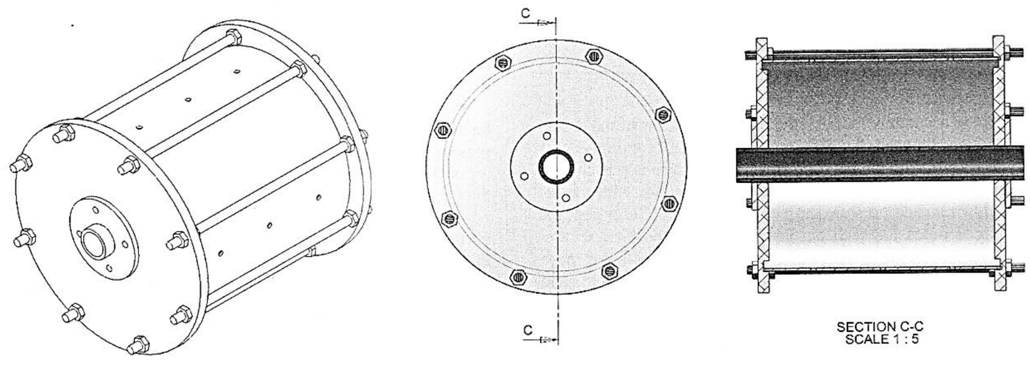

Fig. 2. Schematic of the Intrusion Element [6]

Two 0.25 inch British Standard Pipe (BSP) tappings were added at the mid-length of the intrusion element. The first tapping was created at the top of the outer pipe and fitted with a 12 mm push fit connection so that a clear plastic riser pipe could be attached. This vertical measuring tube created a column of water that served, as the only inlet/outlet for the intrusion element, thus by monitoring the level in this tube it was possible to quantify any intrusion. The second tapping point, approximately 150 mm around the circumference from this vertical point, served as a pressure measurement point, using a Gems 2000 series pressure transducer to measure the pressure in the external pipe. Two further pressure sensors logging at 300 Hz were added to the system upstream and downstream of the test section so that transients generated could be measured and checked for repeatability.

Fig. 3. Photo of Intrusion Element Showing Column of Water, Ruler and Gems 2000 Pressure Transducer

2.2. Experimental Method

Initial flow rates and external heads of pressure were established by altering the upstream pump speed and adjusting the pressure using a downstream control valve. Two sets of tests were run: a pressure of 20 m with flow rates of 1 l/s, 2 l/s, 3 l/s and 4 l/s; and a fixed flow rate of 2 l/s with pressure heads of 10 m, 20 m, 30 m and 40 m. These values were chosen to give conditions representative of live systems [16].

Table 1: Average Recorded Values of Initial Conditions

	Test Title	Desired Flow (l/s)	Desired Pressure Head (m)	Ave. Recorded Flow (l/s)	Ave. Recorded Head (m)	Standard Deviation in Recorded Flow	Standard Deviation in Recorded Head
Increasing Flow Rate	'Q1 H20'	1	20	1.03	20.05	0.03	0.25
	'Q2 H20'	2	20	1.76	20.04	0.06	0.50
	'Q3 H20'	3	20	2.75	20.04	0.09	0.46
	'Q4 H20'	4	20	3.51	20.06	0.03	0.33
Increasing Pressure Head	'Q2 H10'	2	10	1.84	10.04	0.02	0.53
	'Q2 H20'	2	20	1.76	20.04	0.06	0.50
	'Q2 H30'	2	30	1.83	30.07	0.04	0.39
	'Q2 H40'	2	40	1.72	40.05	0.10	0.40

Once the initial conditions were set, the system was allowed to stabilise before a transient was created by instantaneous closure of a valve upstream of the test section. Five repeats for each combination of flow and pressure head were carried out creating 35 test cases (seven combinations with five repeats each). The order of these tests was randomised and the system flushed between tests, so as ensure unbiased results and remove any air. For every test the water level in the riser pipe was recorded using a SVSi Gigaview High Speed video camera recording at 50 frames per second. The volume of intrusion was assessed by tracking the pixel locations of the meniscus in the tube; a ruler placed adjacent to the riser pipe was used for calibration. Repeated cycles of drops and rises in the meniscus were found, which were expected due to the dynamic nature of the transient. The drops indicated fluid flowing from the riser pipe into the system, i.e. intrusion, whereas the rises show leakage out from the system; only drops were considered. The total distance down the tube during the drops was calculated and then multiplied by the tube's internal area to produce the total volume of intrusion in millilitres.

3. Results

For each set of initial conditions (flow rate and pressure head), contamination intrusion was found to occur, i.e. there was a net movement of fluid into the pipeline. The average volume of intrusion for five repeated transient was calculated, as well as the standard deviation across the repeats to quantify repeatability.

Fig. 4 presents the average volume of intrusion over the repeated tests for initial flow rates of 1 to 4 l/s at a pressure head set at 20 m. It can be seen that as the flow rate increases, the volume of intrusion into the system increases. The regression was extended to show the continuous relationship between flow rate and intrusion volume. The coefficient of determination was 99.45% thus this regression describes the data well, i.e. the experimental results support the theory.

Fig. 5 presents the average volume of intrusion for pressure heads of 10 to 40 m at a fixed initial flow rate of 2 l/s. It can be seen that as the pressure head increases, the volume of intrusion into the system decreases. This appears to be a negative linear relationship with a high coefficient of determination of 96.36%.

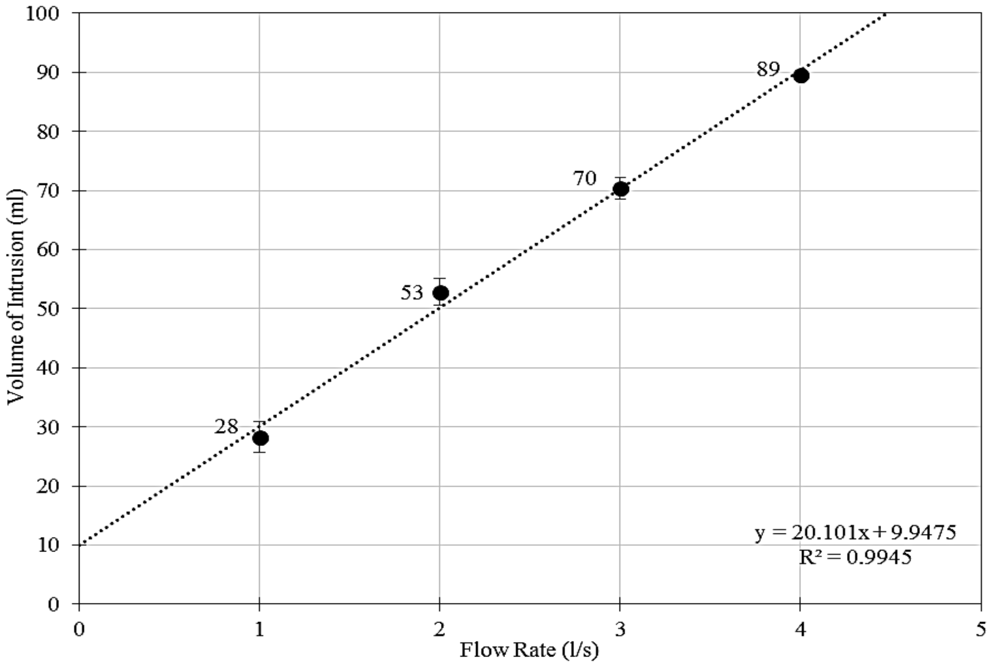

Fig. 4. Average Volume of Intrusion into the Distribution System for Different Initial Flow Rates, with standard deviation error bars.

4. Analysis and Discussion

The experiments conducted prove that when negative pressure is induced by extreme transients there is a net movement of fluid into the pipe system. Good quality, repeatable data has been obtained the standard deviation values for intrusion were small, ranging between 0.78 ml and 2.64 ml, equating to a maximum variation of 9.34%. The results show that there are clear relationships between the initial conditions of flow rate and pressure head, and the volume of intrusion into the system. For a set pressure of 20 m, as the flow rate increases the intrusion volume also increases as the size of a transient is linearly related to initial flow rate [13]. For a set flow rate of 2 l/s, as the pressure head increases the intrusion recorded decreases as the transient has a smaller magnitude negative. These results follow linear regressions, with high coefficients of determination.

Initial conditions of flow rate and pressure head have been varied independently for this experimental study in order to show individual effects, however they form a coupled system – both contribute to the characteristics of a transient. Another parameter is needed that captures their combined contributions. When the transient is generated upstream of the intrusion element, the consequential periods of negative pressure draw in fluid. These periods of negative pressure can be quantified by integrating the upstream pressure trace where its values are less than zero, see Fig. 6. This integration gives a value quantifying the magnitude and length of time below zero for an upstream transient pressure trace with units of metre seconds. As an example for transients generated with initial conditions of 3 l/s flow rate and a steady state pressure head of 20 m, integrating the negative pressure components gives five values (for each repeat) that average at 8828 s m. For a set pressure of 20 m, as the flow rate increases the integral also increases; for a set flow rate of 2 l/s, as the pressure head increases the integral recorded decreases.

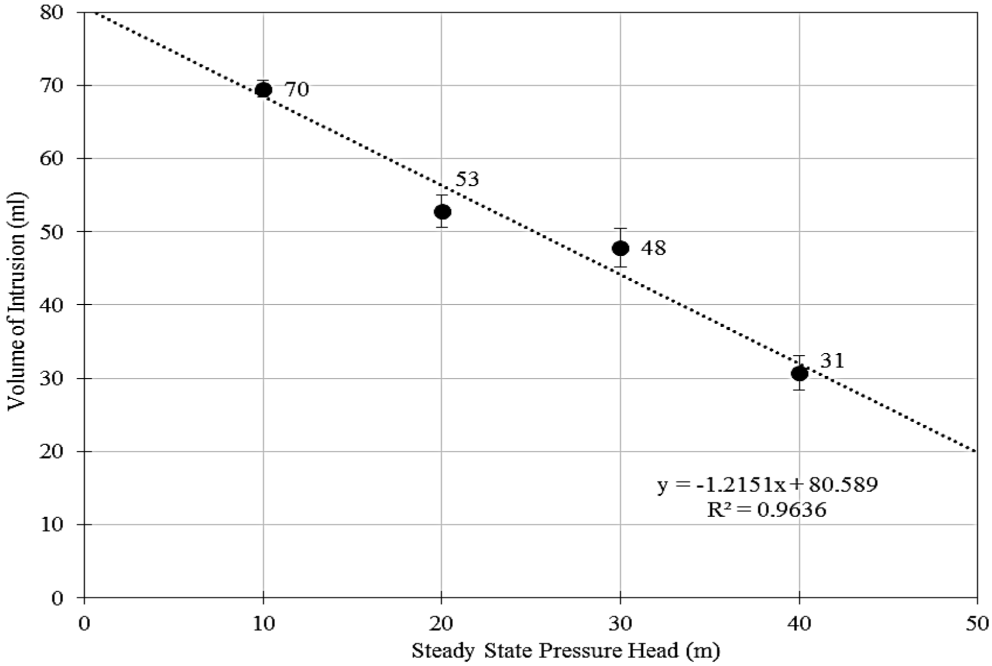

Fig. 5. Average Volume of Intrusion into the Distribution System for Different Initial Pressure Heads, with standard deviation error bars.

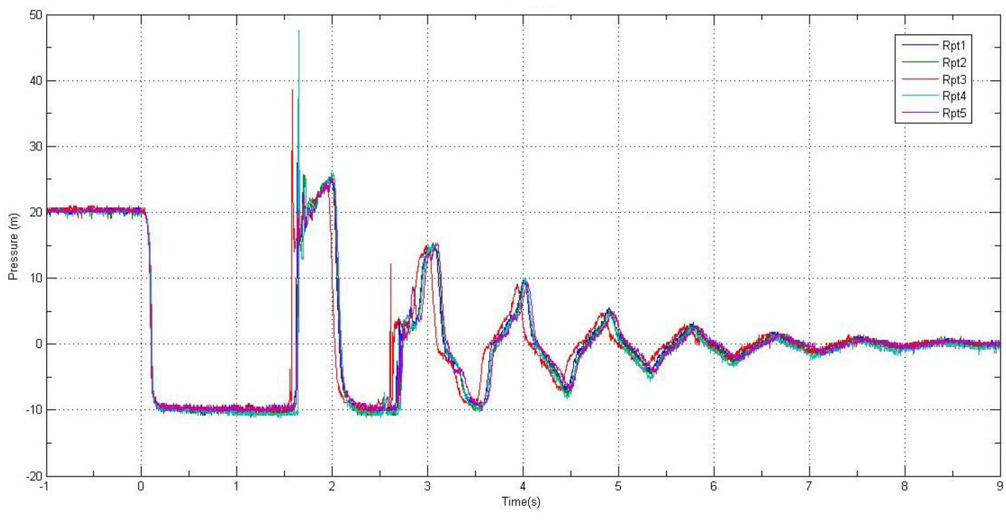

Fig. 6. Upstream Pressure Traces for Transients Generated with Initial Conditions of 3 l/s Flow Rate and a Pressure Head of 20 m (‘Q3 H20’)

Fig. 7 plots all 35 repeat tests, showing volume of intrusion against the time integral of the negative sections of the pressure transient. A logarithmic trend line is shown with a coefficient of determination of 93.70%, which as we expect shows that the more negative the transient, the larger the volume of intrusion into the system. Transients with a duration negative integral less than 3800 s m, and thus a relatively small volume of intrusion, have low initial flow rates or high initial steady state pressure heads e.g. ‘Q1 H20’, ‘Q2 H30’ and ‘Q2 H40’. Conversely, high initial flow rates or low initial steady state pressure heads, e.g. ‘Q2 H20’, ‘Q2 H10’, ‘Q3 H20’ and ‘Q4 H20’ have negative integral values greater than 3800 s m and intrusion volume greater than 60 ml. The latter mentioned transients reach cavitation pressures, which decreases the transient wave speed. This causes the system to spend more time at lower pressures; the coupled system becomes ‘self-aggravating’ thus there is not a linear relationship between duration negative integral and volume of intrusion. Additional work is needed to further understand the effects of cavitation on transients and contamination intrusion.

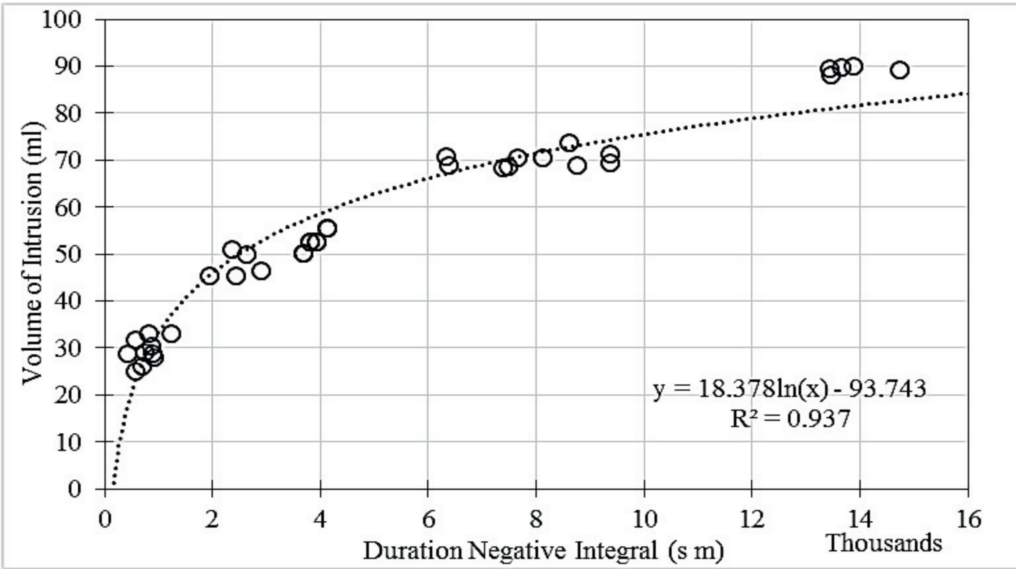

Fig. 7. Upstream Pressure Traces for Transients Generated with Initial Conditions of 3 l/s Flow Rate and a Pressure Head of 20 m (‘Q3 H20’)

5. Conclusions

The work presented has proved that in a large-scale experiment contaminant intrusion can occur and has quantified an intrusion volume based on initial conditions of flow rate and steady state pressure head. Clear trends can be seen: for a set pressure head of 20 m, the volume of intrusion increases as the flow rate increases; for a set flow rate of 2 l/s, the volume of intrusion decreases as the pressure head increases. Furthermore an analysis of the transient pressure trace concluded that the greater the magnitude and longer duration negative, the larger the contaminant volume intruded. This is not a linear relationship as there is a has been found between those extreme transients (high initial flow rate or low initial steady state pressure heads) that reach cavitation and those that do not (low initial flow rate or high initial steady state pressure heads).

Acknowledgements

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References

[1] T.R. Lindley, S.G. Buchberger, Assessing Intrusion Susceptibility in Distribution Systems, Journal of American Water Works Association. 94 (2002) 66-79.
[2] M.W. LeChevallier, R.W. Gullick, R.K. Mohammad, M. Friedman, J.E. Funk, The Potential for Health Risks From Intrusion of Contaminants Into the Distribution System From Pressure Transients. Journal of Water and Health. 1 (2003), 3-14.
[3] S.M. September, F.A. Els, S.N. Venter, V.S. Brozel, V.S., Prevalence of Bacterial Pathogens in Biofilms of Drinking Water Distribution Systems. Journal of Water and Health. 5 (2007), 219-227.
[4] Thames Water Utilities Limited. Reducing Leakage. Available at: http://www.thameswater.co.uk/cr/Preciousresource/Reducingleakage/index.html.
[5] United Utilities Group PLC. Corporate Responsibility Report 2011.Available at: http://corporateresponsibility2011.unitedutilities.com/documents/leakage.pdf.
[6] R. Collins. J.B. Boxall, Influence of Ground Conditions on Intrusion Flows through Apertures in Distribution Pipes, Journal of Hydraulic Engineering. 139 (2013), 1052-1061
[7] T. Walski, T. Lutes, Hydraulic transients cause low-pressure problems, Journal of American Water Works Association. 86 (1994), 24-32.
[8] G. Kirmeyer, M. Friedman, K. Martel, Pathogen intrusion into the distribution system. American Water Works Association, Denver, 2001
[9] R. Gullick, M.W. LeChevallier, R. Svindland, M. Friedman, Occurrence of Transient Low and Negative Pressures in Distribution Systems, Journal of American Water Works Association. 96 (2004), 52-66.
[10] K. Fleming, J. Dugandzik, M.W. LeChevallier, Susceptability of Distribution Systems to Negative Pressure Transients. American Water Works Association, Denver, 2007
[11] M. Besner, G. Ebacher, J. Lavoie, M. Prévost, Low and Negative Pressures in Distribution Systems: Do They Actually Result in Intrusion? Proc., World Environmental Resources Congress, ASCE, Reston, VA, 2007
[12] A.S. Tijsseling, A. Anderson, The Joukowsky Equation for Fluids and Solids. Available: http://www.win.tue.nl/analysis/reports/rana06-08.pdf.
[13] B.E. Wylie, V.L. Streeter, Fluid Transients. United States of America: McGraw-Hill, Inc., 1978.
[14] S. Fox, W. Shepherd, R. Collins, J. Boxall. Experimental Proof of Contaminant Intrusion into a Leaking Pipe During a Transient Event. Computing and Control for the Water Industry, 2013
[15] R. Collins, J. Boxall, M. Besner, S. Beck, S., B. Karney, Intrusion Modelling and the Effect of Ground Water Conditions. Proc., Water Distibution System Analysis, ASCE, Reston, VA (2010). 585-594
[16] Ofwat. Levels of Service. Available: http://www.ofwat.gov.uk/regulating/aboutconsumers/levelsofservice.