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Interdependence of Hydraulic Parameters in Transient Induced Contaminant Intrusion in a Pipeline

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ABSTRACT: Contaminant intrusion during transients in pipelines is a remarkable mechanism which usually leads to declining the quality of the contained water. When rarefaction waves of water hammer reach a leakage, the negative pressure can suddenly suck pollution from surrounding area of leakage to the main pipe flow, thus deteriorating water quality. In this research, numerical and mathematical modeling of a reservoir-pipe-valve system with a leakage has been used to study the effect of hydraulic situations on the volume of contamination intruded into the pipeline during a waterhammer. Eulerian method of characteristics was employed to model the transient flow. The total Volume of Contaminant Parcel (VCPt) penetrating through the leakage is evaluated by Lagrangian solution of the advection equation and then it is established the criteria to compare various transient scenarios and the interconnection between key parameters. In order to elucidate this phenomenon in real pipe systems, the amount of contaminant intrusion is estimated for 72 different cases. They include two lengths of pipeline (say short and long), three different leakage locations, three different fluid velocities, two leak diameters and two pipeline materials (elastic and viscoelastic). The results indicate that the amount of intrusion in viscoelastic pipes is clearly less than that in elastic pipes especially in long pipelines: the ratio of intrusion in viscoelastic to elastic pipes on average is 0.027 and 0.496 in 2300m and 540m pipe, respectively. The critical zone of high intrusion risk is placed close to the downstream valve for small leak sizes, nevertheless, it is hard to estimate this zone in case of big leaks due to significant valve-leak-reservoir induced reflection waves.

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1. INTRODUCTION

Water quality changes through distribution networks due to complex physical, chemical and biological processes. It is highly probable that the water quality declines during water hammer since the negative pressure of the fluid is able to suck pollutants from possible leaks to the distribution network [1]. Fernandez and Karney (2004), were among the first who predicted the behavior of contamination intrusion from the leak point caused by water hammer [2]. Rezaei and Nasser (2012) studied the suction and release of leakage contamination during water hammer pressure oscillations. They employed the method of characteristic to solve the hydraulic equations and used Lagrangian method to model the emission of pollutants [3]. Jones *et al.* (2014), proved the contaminant intrusion in a large-scale laboratory model, and measured its rate under specified initial conditions in terms of discharge and steady-state pressure [4]. Laboratory results of Fontanazzaa *et al.* (2015) showed that the amount of contamination that entered from the leak point through the permeation mechanism in semi-filled pipes is relatively more than the contamination which enters by transient flows while the amount of contamination intrusion during a transient flow is directly dictated by magnitude and duration of the negative pressure at the leak position [5].

Fox et al. (2013 and 2016), experimentally revealed that when a waterhammer occurs in the network, the negative pressure wave sucks the contamination around the leakage site into the distribution network. Subsequently, the intruded volume travels toward the downstream of the leakage site [6, 7]. Payesteh and Keramat (2017), performed a sensitivity analysis on the hydraulic parameters affecting the amount of the contamination intrusion during water hammer in a reference reservoir-pipe-valve system with a leakage. They concluded that the magnitude of the negative pressure at the leak point is the most important factor. In the previous authors' research, the effect of each parameter on intrusion is separately studied thus making no conclusion regarding interconnection between parameters [8]. Therefore, in this research, simultaneous effect of two or more parameters are assessed by making several hypothetical waterhammer and transmission systems.

2. METHODOLOGY

Waterhammer modeling of elastic/viscoelastic pipes is

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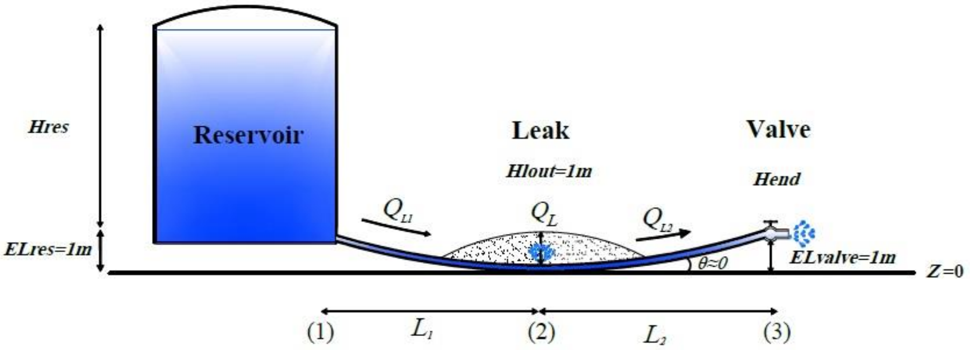

Fig. 1. Schematic of the reservoir-pipe-valve system with leakage to investigate the contamination intrusion into the pipeline.

Table 1. Reservoir and pipeline specifications.

	Experiment 1	Experiment 2
Inner pipe diameter (mm)	600	10.8
Pipe length (m)	2300	540
H_{valve} (m)	40	14
Leak location (x_L/L)	0.33; 0.5; 0.66	0.33; 0.5; 0.66
Wave velocity (m/s)	c_{pvc}=390; c_{steel}=1000	c_{pvc}=390; c_{steel}=1000
Leakage Opening ratio (δ)	0.01; 0.001	0.01; 0.001
Fluid velocity (m/s)	0.5;1;2	0.5;1;2

governed by [9]:

$$\frac{1}{A}\frac{\partial Q}{\partial x}+\frac{\rho g}{K}\frac{\partial H}{\partial t}+2\frac{\partial \varepsilon_\phi}{\partial t}=0 \quad (1)$$

$$\frac{1}{A}\frac{\partial Q}{\partial t}+g\frac{\partial H}{\partial x}=\frac{-f\,Q|Q|}{2DA^2} \quad (2)$$

where x is distance along the tube, t is time, g is gravitational acceleration, D is diameter, K is the bulk module, A is the cross section of the pipe, Q discharge, H is the pressure head, f is the friction coefficient and ε_ϕ is hoop strain which accounts for the viscoelastic behavior of the pipe wall. These equations are solved using the Method of Characteristics (MOC).

Fig. 1 shows a schematic of a reservoir-pipe-valve system with a leakage. In this figure, H_{res} is the piezometric head of the reservoir, Z_{res} is the elevation of reservoir, L_1 and L_2 are the lengths of the pipes before and after the leak, Q_L is the leakage discharge, Q_{L1} and Q_{L2} are discharges before and after the leak, H_{Lout} is the piezometric head of the contaminated water outside the leakage site and Z_{valve} is valve elevation. The upstream reservoir transports water through the pipe to the valve. The extrusion of fresh water and intrusion of contaminated liquid occur through the leakage on the pipeline during transients.

The mathematical representation of the contaminant transport is provided by the advection-diffusion equation, which is based on Fick's and mass law. In the intrusion problem, the effect of diffusion is negligible compared to the convection [10] hence:

$$\frac{\partial \phi}{\partial t}+u\frac{\partial \phi}{\partial x}=0 \quad (3)$$

in which u is fluid velocity, and ϕ is the concentration of the contamination. To solve this equation, the Lagrangian method is used which calculates the volume of contaminant parcel $VCPt$ using [11]:

$$VCPt=\Delta t\sum_{j=0}^{N}\max(0,-Q_{L,j}) \quad (4)$$

in which Δt is the time step of the water hammer solution. In Eq. (4), non-zero terms in the summation correspond to the time steps which flow rate at the leak Q_L is negative meaning that contaminated water intrudes into the main pipe flow from the leakage.

3. DISCUSSION AND RESULTS

In order to provide a comprehensive cognition of the contamination intrusion phenomenon in various conditions, 72 different cases are studied. In each one, different leakage locations and sizes, different fluid velocities due to different reservoir pressures in an elastic and a viscoelastic pipe for a short and a long pipeline have been investigated (Table 1). In experiment 1, pipeline length L = 2300 m, D = 600 mm and valve pressure head H = 40m, which can be a typical model of suburban water transmission systems is considered. In experiment two, L = 540 m, D = 108mm and the rest as previous, are considered which can be a model of urban pipelines. Three positions for a leakage are separately considered: the

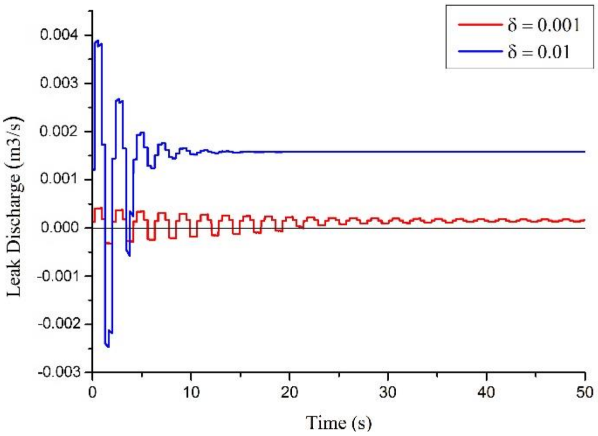

Fig. 2. Time histories of leakage inflow and outflow for δ = 0.001 and 0.01 in red and blue, respectively (x_L=360m).

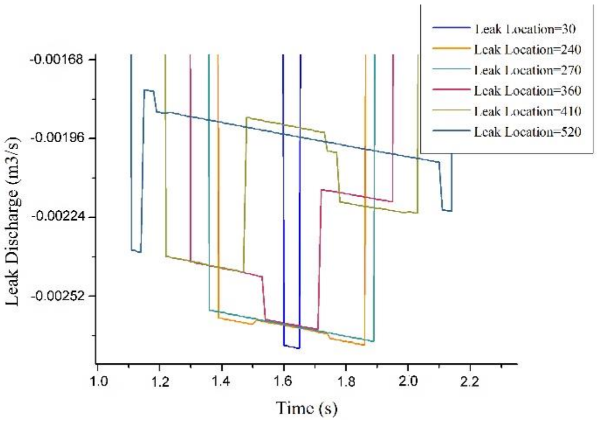

Fig. 3. Suction flow rate at the leak for different leak locations (*V* = 1 m/s and steel pipe).

middle, one third and two third from upstream. Two leakage size ratios being leak area over the cross-sectional area of flow δ = 0.01 and 0.001 are considered as a typical of small and large leaks. The fluid velocity is set to *V*= 0.5, 1 and 2m/s, which are conventional speeds in urban water transmission systems. Regarding viscoelasticity behavior, appropriate wave speeds in elastic models are adopted which provides an acceptable approximation of the dynamic behavior of viscoelastic materials [12]. As a result of smaller wave speed in viscoelastic pipes, the volume of contamination entered into these pipes is less than that entered into the elastic pipes.

Since several scenarios are simulated, an experimental quantification regarding the effect of pipe material on the amount of intrusion can be made. For example, in the first experiment, among the whole 36 cases, half are run for elastic and half for viscoelastic pipe. The average of *VCPt* for each pipe material can be defined by

$$VCPt_m = \frac{\sum_{i=1}^{N\exp} VCPt_i}{N_{\exp}} \tag{5}$$

where $N_{\exp}$ denotes the number of experiments whose average are computed for each material; $N_{\exp}$=18 herein. The following index defined by the ratio of mean intrusion in viscoelastic pipes to that in elastic pipes

$$\alpha = \frac{VCPt_{m,VE}}{VCPt_{m,E}} \tag{6}$$

illustrates the reduced extent of intrusion in viscoelastic materials. In experiment 1 which corresponds to a long pipeline, the role of viscoelasticity in declining intrusion is prominent, making $\alpha = 0.027$ which represents a very small amount of contaminant intrusion. In the second experiment however, this ratio reaches to $\alpha = 0.496$ meaning that in short pipes, viscoelastic property of the pipe wall is less effective on intrusion reduction or cessation.

The general trend regarding the amount of intrusion is expected to be according to Joukowsky's pressure rise, so that higher wave speed and initial velocity bring about higher intrusions. However, several counterexamples have been found among the 72 cases. For instance, in the second experiment, for $\delta = 0.001$ and viscoelastic pipe, the intrusion of the case *V*= 2 m/s is less than that of *V*= 1 m/s. Another example of unusual interdependence among affecting parameters is observed with changing reservoir pressure (for the same pressure at valve). In a velocity range from 0.5 to 1m/s, increasing reservoir pressure leads to rising contaminant intrusion while for velocities higher than 2m/s, the pressure of the reservoir has its suppressing effect on negative pressure at the leak and intrusion. These findings are in agreement with the laboratory results of Jones *et al.* (2014) [4].

Considering Eq. (4), two aspects clearly contribute to increase *VCPt*: the magnitude of negative leakage discharge and the duration (denoted by *d*) for which negative discharge at leak occur. These two agents are evident in Fig. 2 which shows how they are altered by the leak size variation (*V*=2m/s, x_L=360m , *L*= 540m, *c*= 1000 m/s). Regarding the inflow duration *d* to the main pipe flow, the role of leakage size ratio δ is of great significance. As seen in Fig. 2, for δ = 0.001 (red curve) *d* is the summation of a number of inflows occurring at several water hammer periods, while for δ = 0.01 (blue curve) only two rarefaction waves at the leak location determines *d*.

Big leaks can produce significant waves to change the main transient flow of valve maneuver. According to Fig. 3, for δ = 0.01, *V*=1m/s, *L*= 540m, *c*= 1000 m/s, long durations are accompanied by lower magnitudes of negative discharge and short durations correspond to higher magnitudes (blue line). The opposite interdependence of these two key quantities reveals an extremum at which highest amount of intrusion occurs. This pattern is in fact due to the interaction of the main water hammer wave (generated by the valve) and leak induced waves which is also affected by the pressure reflections from upstream reservoir. This complicated interaction eventually leads to the maximum intrusion to be formed at the middle of the pipeline in this leak case (Table 3). For the other leak case with δ = 0.001, the interactions between the valve and leak waves are less dominant in *d* that is to say wave reflections from the leak are negligible so that the amount of intrusion is simply dictated by the main water hammer waves which is mainly governed by the leak distance from upstream reservoir: the more distant leak from reservoir, the higher *d* and hence more intrusion. This is valid for both experiments.

4. CONCLUSIONS

Contaminant intrusion is likely to happen due to water hammer in drinking water pipelines. In this study, Eulerian method of characteristics was employed to model transient flow in conjunction with Lagrangian solution of the advection equation to determine total Volume of Contaminant Parcel (*VCPt*) entering from the leakage site. 72 different hypothetical transient scenarios are considered to study the amount of intrusion due to negative pressure wave at the leak point. The following are key findings from running the scenarios:

- Viscoelastic pipes are greatly advantageous in intrusion reduction, especially in long transmission lines.
- Large leak sizes are prone to significant leak induced wave reflections, thus making the leak position zone of high intrusions quite unpredictable (case dependent).
- Small leaks do not generate significant waves so that the duration for which negative pressure induced by valve maneuver maintains is the decisive parameter. This means that the amount of intrusion is only dominated by valve maneuver so that high intrusions are more likely when leak is close to the downstream valve.

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