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# Sensitivity Analysis of Hydraulic Parameters on Contaminant Intrusion in Transient Conditions

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**ABSTRACT:** Water quality degrades due to the complex physical, chemical and biological processes passing through the transmission lines. One of these widely attracted processes is contaminant intrusion due to a transient event. When the negative pressure wave of water hammer reaches a structural deteriorations such as a leakage, it can suddenly sucks pollution from the surrounding area of leakage to the main pipe flow which can in turn endanger public health. The purpose of this study is to determine the effect of hydraulic parameters on the duration of negative pressure and the magnitude of the negative pressure and subsequently the volume of contaminant intrusion, in the case of a simple reservoir-pipe-valve system with a leakage. In this study, the Eulerian approach using method of characteristics was used to model the transient flow. The total volume of contaminant parcel (VCPt) passing through the leakage to the main pipe flow is obtained from the Lagrangian solution of the advection equation. The results indicate that the volume of intrusion is dominated by the magnitude and duration of negative pressure at the leak. The intruded parcel is considered as a decisive criterion to compare various transient scenarios. Reservoir pressure head, fluid velocity inside the pipe, wave speed, pipe diameter, leak diameter and leakage location are respectively the most effective pipe and flow parameters on contaminant intrusion which their specific significance is investigated in this research. Investigation of the interaction of these factors in the volume of contaminant intrusion can be considered as a subject for future research.

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## 1. INTRODUCTION

Water quality changes through the distribution network due to complex physical, chemical and biological processes. It is highly probable that the water quality changes during water hammer since the negative pressure in the pipe caused by the fluid transients can suck the pollutant from the leak to the distribution network [1].

Fernandez and Karney (2004), were among the first who predict the behavior of contamination intrusion in the leak point caused by water hammer [2]. Fox et al. (2013 and 2016), experimentally revealed that when a water hammer 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 [3, 4]. Rezaei and Nasser (2012) studied the suction and release of leakage contamination in water hammer conditions. They employed the method of characteristic to solve the hydraulic equations and used the Lagrangian method to model the emission of pollutants [5]. Jones *et al.* (2014), proved the contaminant intrusion in a large-scale laboratory model, and measured the rate of contaminant intrusion under specified initial conditions in terms of discharge and the steady-state pressure [6]. 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 [7].

The focus of this study is firstly on the investigation of the hydraulic factors affecting the driving forces of intrusion phenomenon, and then the determination of the effectiveness of each factor.

## 2. METHODOLOGY

### • Water hammer modeling

The pressure waves of water hammer in viscoelastic pipes are governed by two constitutive mass and momentum equations which according to Covas *et al.* (2005) are as follows [8]:

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

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

where, $x$ is distance along the tube, $t$ is time, $g$ is gravitational

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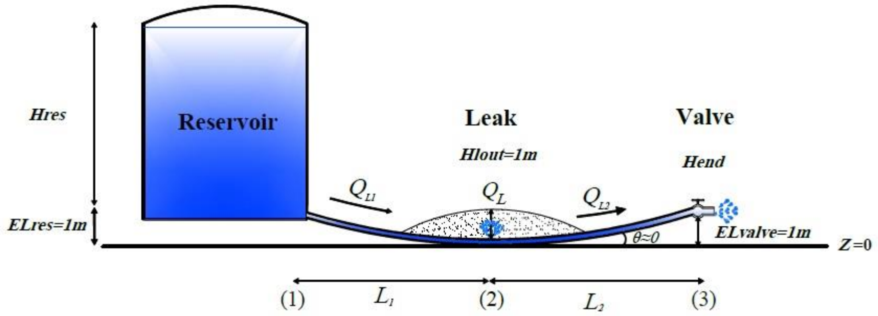


**Fig. 1. Schematic of the reservoir-pipe-valve system with leakage to investigate the contamination intrusion into the pipeline.**

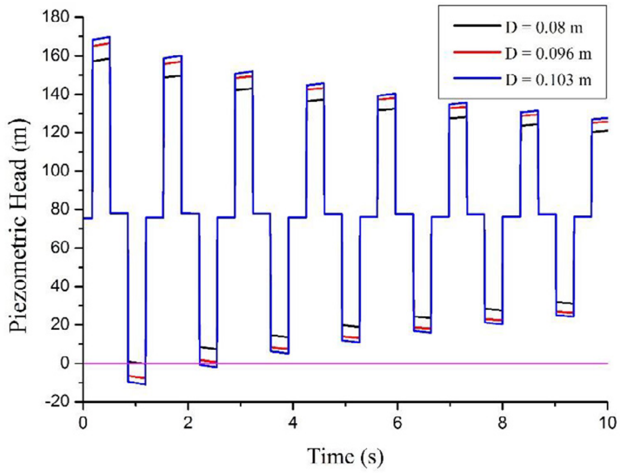


**Fig. 2. The pressure head at the leak location for three different pipe diameters**

acceleration, $D$ is diameter, $K$ is the bulk module, $A$ is the cross section of the pipe, $Q$ discharge, $H$ is the pressure equivalent height, $f$ is the friction coefficient and $\varepsilon_\phi$ 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. Besides, the intrusion occurs through the leakage to the pipeline during transients.

· The modelling of the contaminant transport

The mathematical representation of the mass 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 [9], hence:

$$\frac{\partial \phi}{\partial t} + u\frac{\partial \phi}{\partial x} = 0 \tag{3}$$

in which $u$ is fluid velocity, and $\phi$ is the concentration of the contamination. To solve this equation, the Lagrangian method is used which calculates the volume of contaminant parcel $VCPt$ using [10]:

$$VCPt = \Delta t \sum_{j=Nin}^{n} Q_{L(j)} \tag{4}$$

in which $\Delta t$ is the time step of the water hammer solution. In Equation 4, the summation is over 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. RESULTS AND DISCUSSION

The effect of main hydraulic and pipe parameters on the amount of contamination intrusion in a typical reservoir-pipe-valve model with a leakage (Fig. 1) is studied.

Among several alternatives for the effective parameters, the significance of the pipe diameter is discussed herein. If all other parameters are kept constant (e.g. wave speed, reservoir head), a higher diameter corresponds to less friction (Darcy-Weisbach equation), so that an increased velocity establishes in the pipe during the steady state. During transient state, this velocity rise results in higher Joukowsky and hence larger negative pressure as depicted in Fig. 2. The pink line displays the one-meter pressure head and assists to identify when contaminations enter the main flow. The number of crosses of this line with the pressure diagram indicates how many

**Table 1. Evaluation of the sensitivity of each parameter on the volume of contaminant intrusion in the pipe**

| | Upper reservoir pressure (m) | Fluid velocity (m / sec) | Wave speed (m / s) | Pipe diameter (mm) | Leak diameter (mm) | Leakage location (m) |
|---|---|---|---|---|---|---|
| $VCPt = 0.01 lit$ | 76.77 | 0.85 | 963.64 | 85.073 | 1.8799 | 116.1 |
| $VCPt = 0.015 lit$ | 77.017 | 0.89 | 1002.6 | 90.441 | 2.8963 | 185.51 |
| Amount of changes | 0.2463 | 0.0342 | 38.983 | 5.3672 | 1.0164 | 69.407 |
| Percent change | 0.3208 | 3.9855 | 4.0454 | 6.3089 | 54.065 | 59.781 |
| $VCPt$ chart gradient due to change of each parameter | 155.86 | 12.54 | 12.36 | 7.92 | 0.92 | 0.83 |

times the intrusion to the main flow occurred. According to Fig. 2, in the case of larger pipe diameter (blue line), the contaminant intrusion occurs in two cycles. The whole trend of change of VCPt with internal pipe diameter is depicted in Fig. 3. According to the results of Table 1, volume of the contamination intrusion has the highest sensitivity to the pressure of the upper reservoir. The velocity of the fluid inside the pipe, the wave speed of water hammer, and the diameter of the pipe, are the priorities of the next three influential factors, respectively. The leakage diameter and leakage location are also two factors in which the volume of contamination intrusion is about one degree sensitive to them.

## 4. CONCLUSIONS

Contaminant intrusion to pipelines is an important mechanism which usually leads to deteriorate the quality of drinking water. The amount of penetration during a transient flow directly depends on the magnitude and duration of the negative pressure at the leakage location. This research conducts numerical simulations for fluid transients in conjunction with intrusion into the pipeline from a leak. The purpose of this study is to determine the effect of several parameters on the magnitude and duration of negative pressure and consequently, the volume of contaminant intrusion.

The results showed that according to the model presented in this study, the volume of the contamination intrusion has the highest sensitivity to the pressure of the upstream reservoir. The velocity of the fluid inside the pipe, the water hammer wave speed, the pipe diameter, the leak diameter and the leakage location are respectively the next effective factors. The volume of contaminant parcel has the maximum for leak diameter and leakage location, in fact, the volume of contamination inlet to the pipe increases due to the leakage in certain locations of the pipe and for the specific leakage diameters. In the model presented in this study, for the leakage establishment, 82.3% of the length of the pipe was observed with the highest volume of contamination, and the diameter of the leakage pipe was equal to 3.9% of the maximum inflow pipe.

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