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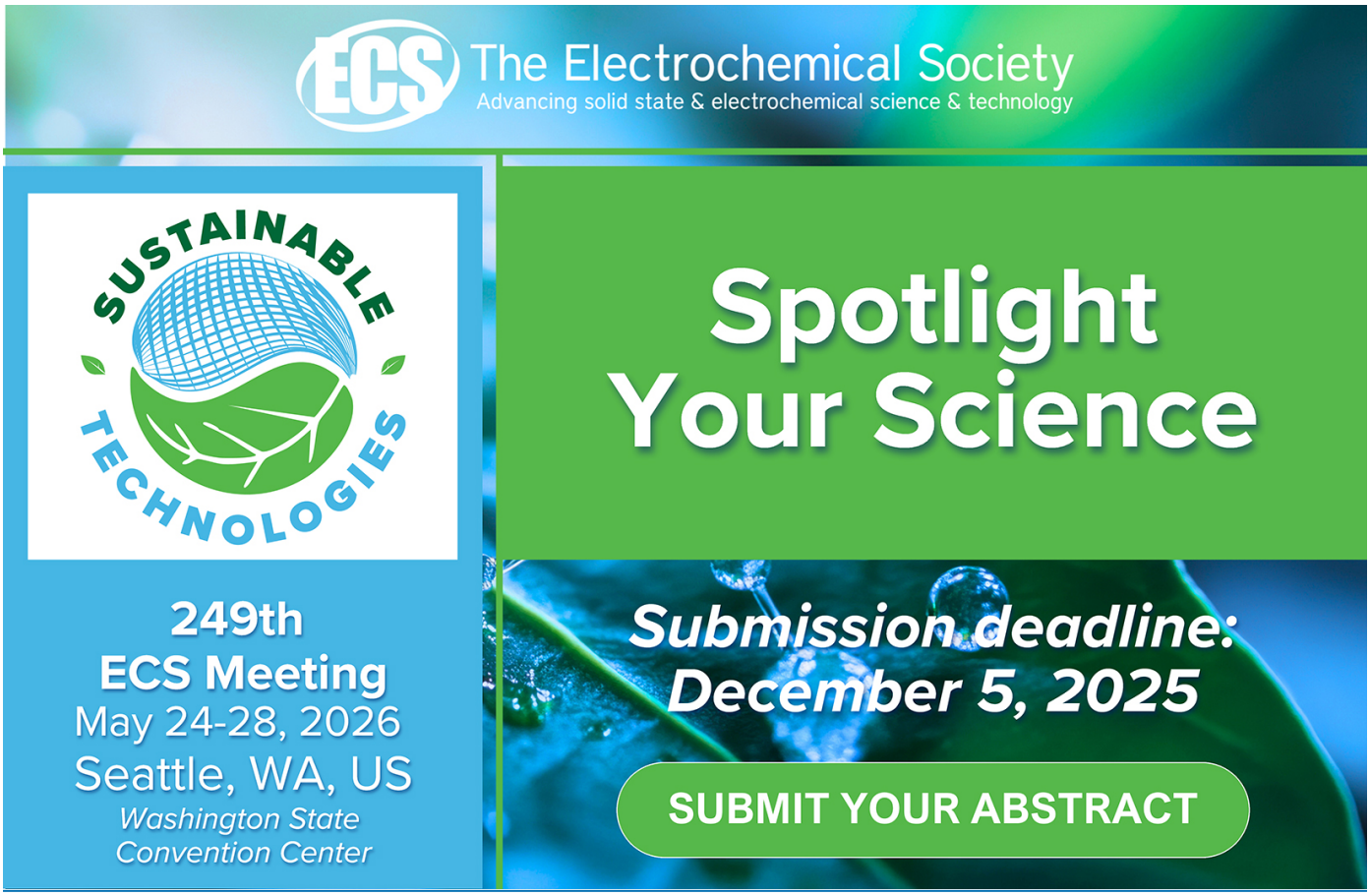
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Leakage diagnosis through experimental modeling and simulation

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Abstract. The detection and location of leaks in water pipes is an important research topic, not only because of the waste of energy and material resources used in the extraction but also to avoid serious environmental, social and economic consequences. This paper describes experimental modeling and simulation of leaks using computational fluid dynamics software, and LabVIEW software where a virtual instrument was designed to test the simulation when detecting a leak in a pipeline. These techniques were tested on a piping bench carried out as an experiment in the automation laboratory of the Universidad Francisco de Paula Santander, Ocaña, Colombia. Simulations and experiments were carried out and it was discovered that using simulation techniques it is possible to obtain a result that detects the leak and shows its location.

1. Introduction

Pipeline leaks are the problem faced by water companies, because they use the pipelines as infrastructure for transporting their product. And it is a costly problem worldwide, strongly related to the waste of precious natural resources, environmental pollution and financial losses [1].

Over time, several solutions have been tried, ranging from manual inspection by trained operators to advanced satellite imaging. The methods are divided into two groups. They are based on specific hardware, such as acoustic reflectometry [2], optical fiber [3], etc. The software methods are based on estimation models [4], signal processing [5], and artificial intelligence algorithms [6], which take data from sensors for flow rate, pressure and temperature. In this group can be found methods such as simulations, negative pressure wave analysis [7], frequency response [8], but all procedures require expensive equipment, sensors and actuators with practical facilities. For example, the acoustic-based method requires high-precision sensors [9], which are expensive. The mass balance method can detect the occurrence of a leak but not the location of the leak [10]. The applicability of transient model-based detection methods to different situations is poor, and the response time of these methods is long.

Therefore, related to this, there is a need to build and study numerical models of the diagnostic processes of water pipe leaks. The detection and precise location of a leak can be investigated using computational fluid dynamics (CFD) software [11-13]. A simulation using CFD techniques can provide detailed data and analysis of non-dimensional variables to build the mathematical model that is used to detect the leak in the pipeline. The aim is to use flow parameters, such as pressure drop and location of the leak, to build a model to predict the leak.


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The paper is organized as follows. Section 2 presents computational fluid dynamics (CFD) software modeling; section 3 discusses the performance of the scheme with experimental data from a pilot pipeline. Finally, section 4 presents the conclusions

2. Modeling using computational fluid dynamics software

Equations that describe the transient response of a fluid through a pipeline are known in the literature as water hammer equations, among them are the motion equation (Equation (1)) and continuity equation (Equation (2)). To carry out the simulation of the pipe, Open FOAM software was used because it is free programming software, through the volume of fluid method (VOF), and the continuity equations and the pressure equation method.

2.1. Volume of fluid method

The volume of fluid method (VOF) method used by inter Foam solves the equations of motion (Equation (1)) and Continuity equation (Equation (2)) expressed below.

$$\frac{\partial \rho U}{\partial t} + \nabla \cdot (\rho U \cdot U) - \nabla \mu \cdot (\nabla) U - \rho g = -\nabla p - F_S, \tag{1}$$

$$\nabla \cdot U = 0, \tag{2}$$

where ρ is the average density of the fluid, U is the velocity, μ is the average dynamic viscosity, g is an acceleration vector, p is the pressure and F_S represents the surface tension force.

To determine the density and average viscosity, the method defines a function α (x, y, z, t) that represents the volumetric fraction of one of the materials in the finite volume, being α=1 a space completely occupied by that material (fluid) and α = 0 one completely occupied by the other phase (air). The differential equation that governs the function α is expressed in Equation (3).

$$\frac{\partial \alpha}{\partial t} + U \cdot \nabla \alpha = 0. \tag{3}$$

Weighted averages of densities and viscosities are defined in Equation (4) and Equation (5), respectively.

$$\rho = \alpha \rho_1 + (1 - \alpha) \rho_0, \tag{4}$$

$$\mu = \alpha \mu_1 + (1 - \alpha) \mu_0, \tag{5}$$

where subscript 1 associates the property to the material assigned for $\alpha = 1$ and subscript 0 to a property of the remaining material. The surface tension force is calculated using Equation (6).

$$F_s = \sigma k(x) n, \tag{6}$$

where n is the unit vector normal to the interface and k is the curvature of the interface, Equation (7) and Equation (8).

$$n = \frac{\nabla \alpha}{|\nabla \alpha|}, \tag{7}$$

$$k(x) = \nabla \cdot n. \tag{8}$$

2.2. Continuity equation

The continuity equation is easy to solve for compressible terms since the ideal gas equation is available, as shown in Equation (9).

$$PV = mRT. \tag{9}$$

Reducing Equation (9) gives Equation (10) and Equation (11).

$$P = \frac{m}{V}RT, \tag{10}$$

$$\rho = \frac{m}{V}. \tag{11}$$

Replacing Equation (10) in Equation (11) results in Equation (12).

$$\frac{P}{\rho} = RT \ \therefore \ T = CTE, \tag{12}$$

where ρ is the density, P is the pressure, R is universal gas constant, and T is the temperature; when working with incompressible flow it is somewhat tedious to evaluate the pressure, for this reason the following methods are used: Continuity method and mass conservation method.

2.3. Pressure equation

Open FOAM has a condition in the programming which is the one in charge of the recognition of the process that is going to work since there are two forms:

- When working with a single fluid, either liquid or gas, the software simply recognizes this condition and executes the continuity and Navier-Stokes equations.
- When working with multiphase flow the software recognizes this condition and adds one more equation to the solver.

The pressure is solved using the Navier-Stokes equation and the continuity equation; but for multiphase cases the VOF method equation is added. The equation for pressure in the solver is (Equation (13)):

$$P_{_rgh} = p - \rho gh \ \therefore \ \rho = CTE, \tag{13}$$

where $P_{_rgh}$ is pressure generated by the solver, to this pressure are added initial conditions in the case container; p is the hydrostatic pressure, this pressure depends on the position where the particle is located, in this case, it depends on the height of the fluid in the z axis and also depends on the density (ρ); gh is the scalar product of g-vector and position vector

2.4. Software configurations

CFD simulations can be divided into three main stages: pre-processing; simulation; and post-processing. Pre-processing includes geometry definition, mesh generation, boundary condition definition, and solver parameter setting. The simulation stage consists of using the built model to run the simulations. Post-processing is the analysis of the results [14].

2.5. Pilot pipe

A system for automatic leak detection was built in a pipe test bench. The prototype is located in the automation laboratory of Universidad Francisco de Paula Santander, Ocaña, Colombia, as shown in

Figure 1; the assembly consists of two glass containers of 0.4 m long, 0.3 m wide and 0.3 m high, with a thickness of 5 mm, two pumps that will transfer the fluid from one pond to the other, 4 supports to maintain a $\Delta z = 0$, and pipes and accessories of ½ inch necessary for the development of the project [15]. The prototype has a virtual instrument developed at National Instruments which was used to collect data for the simulation. Table 1 shows the data collected; with the data obtained, the behavior of the variables in six states was analyzed as shown in Table 1. This test helped to subsequently define the minimum and maximum thresholds of the signals.

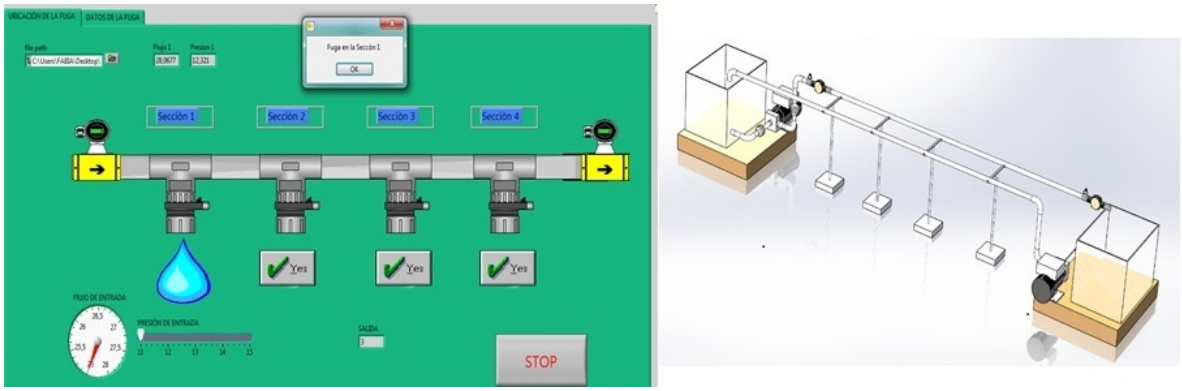


Figure 1. Prototype.

Table 1. Data of the input variables.

Variable	Low	Leakage section				Work
		1	2	3	4	
Inlet pressure (psi)	11-12.20	12.20-12.60	12.61-12.8	12.81-13.2	13.21 -14	14.4-14.97
Outlet pressure (psi)	2-4	4.85-4.40	4.82-4.63	4.98-4.6	4.80-5.034	6.3-6.0
Outlet flow (L/min)	10-17.60	19.15-18.02	18.76-17.64	18.69-18.35	18.17-17.94	24.7-24.6
Inlet flow (L/min)	25-25.9	28.1-27.7	27.41-27.7	27.41-26.6	26.22-26.14	26.6-26.22

3. Results

Figure 2 shows the bubble caused by the increase in pressure due to the simulated leak 3 meters from the initial pipe.

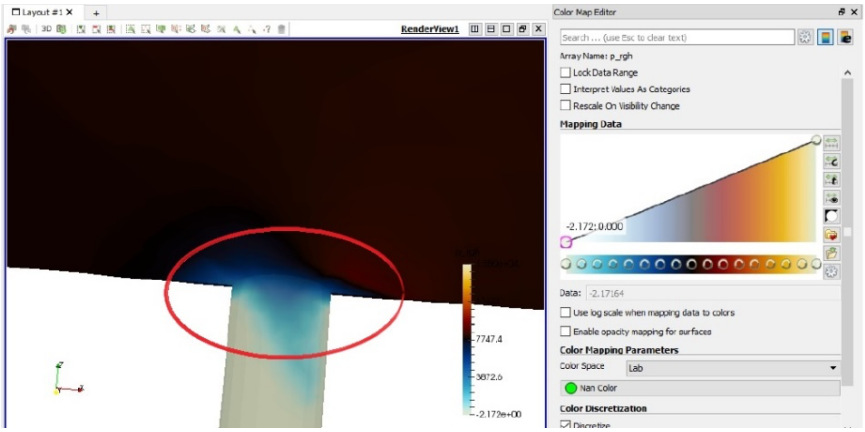


Figure 2. Increasing pressure bubble due to leakage.

When the leakage point is three meters away from the pipe, it can be seen in Figure 3. The two curves show a jump in its slopes for the length of 3 meters (place of the leakage) and they remain constant, thus proving Darcy's law that says that the pressure behavior in a pipe should be a linear drop by means of Equation (14).

$$q = -k\left(\frac{dh}{dl}\right), \tag{14}$$

where $-k$ is a constant known as the coefficient of permeability and determines the geometry of the pipe; when comparing the friction factors before and after the failure, it is found that these two would be different if found by means of the equations for Reynolds numbers in the turbulent state.

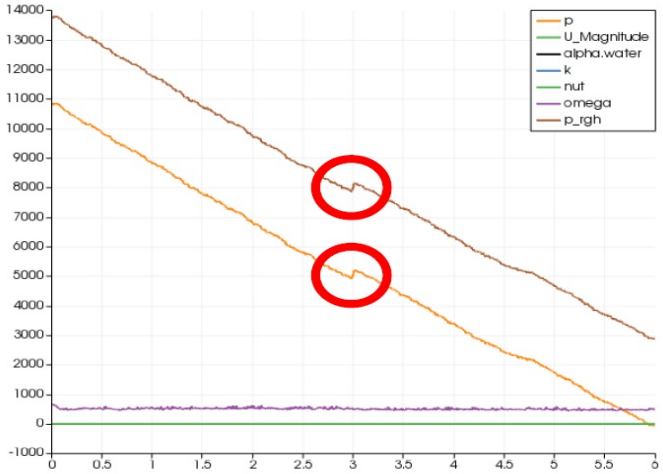


Figure 3. Fluid conditions.

In the experiment described in section 2.4 different leakage points were taken, in four sections, as shown in Table 1. The variables that provide significant information to the system according to where the leak is located is the inlet pressure that increases as the leak is located further away from the inlet pressure sensor. And the inlet flow that decreases as the leak moves away from the inlet pressure sensor. Figure 4 shows the pressure and flow drop when a leak occurs in real time in the virtual instrument created for system validation.

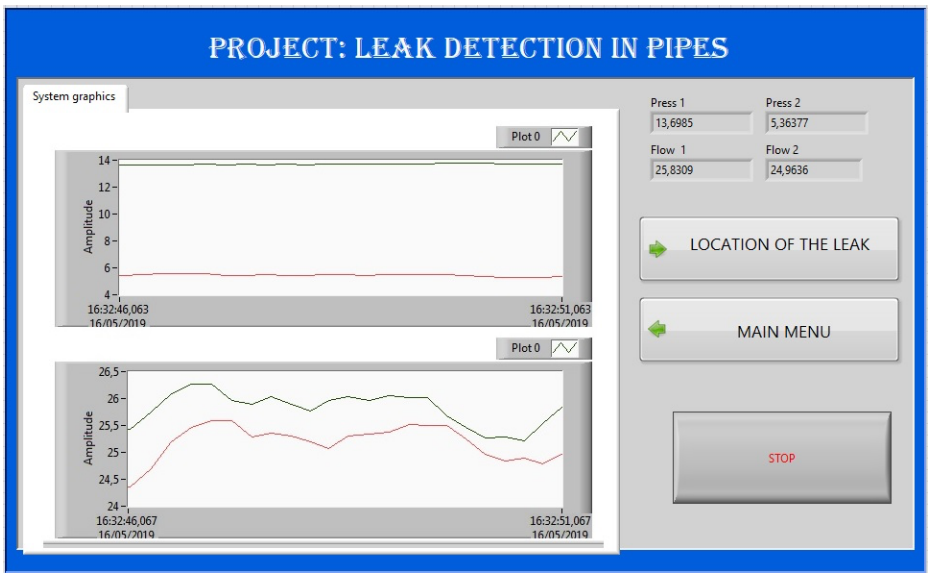


Figure 4. Pressure and flow drop when a leak occurs in the experimental pipe.

4. Conclusions

This research proposes a simple method based on the analysis of non-dimensional variables. When the pressure drops between the inlet and outlet of the pipe, the inlet and outlet flow rates are measured; this prediction model can detect the location of the leak: the pressure drop is greater when the location of the leak is farther away from the inlet. This phenomenon can be used to locate the leakage point in the pipeline according to the relationship between the location of the leak and the pressure drop; if we observe the two graphs both the simulated CFD response and the experimental response we have that the inlet pressure with a leak at 3 meters is between 13.21 psi to 14 psi, and the outlet pressure between 4.80 psi to 5.034 psi.

Therefore, the pressure drops in the CFD simulation pipe are generally consistent with the data obtained in the experiment, which indicates the reliability of the CFD models. The simulated method presented in this document is limited to detecting a single leak in the fluid pipe, while the experimental method involved mixing these equations together with designing a fuzzy controller to locate multiple leaks.

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