Journal of Physics: Conference Series

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To cite this article: K Pérez-Carrascal and J García-Guarín 2021 *J. Phys.: Conf. Ser.* **1981** 012004

V International Meeting of Mathematical Education (IMME 2021) IOP Publishing
Journal of Physics: Conference Series **1981** (2021) 012004 doi:10.1088/1742-6596/1981/1/012004

Detection of water leaks with Dowsing technique and Reynold’s transport theorem

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Abstract. Zahorí techniques are traditionally used to detect water currents in land for subsequent extraction. On the other hand, water leaks represent economic losses in factories and residences. It is enough to survey a city and determine the exaggerated number of residential leaks. Once the leak appears, a corrective action must be taken, this action is founded in itself and in the problems derived from this failure; and it is that knowing the exact location of a leak is risky if strictly collateral damage appears in the property. This research proposes to complement two different techniques, the first detects the presence of water based on the Dowsing search, and the second uses the Reynolds Transport Theorem to detect the leak relying on numerical methods and computational simulation. The Dowsing search proved to be reliable to detect the presence of water, the Reynolds Transport Theorem, yields the location of the leak with an average relative error of 10.6727% and the computational simulation corroborates Darcy's Law. Therefore, the method proposed in this investigation is sufficient for the corrective management of leaks.

1. Introduction

Every hydraulic networks are prone to some type of leakage, however, these should not exist since they represent economic losses for companies [1]. Even if the leaks are small, in the long term they can become representative, for example in the Netherlands they reach between 3 to 7% of the water supply [1]. As pointed out by Colombo and Karney, leaks can cause electrical losses due to the waste of energy used by hydraulic machines to pump water, additionally in low pressure water distribution networks a leak can affect water quality by introducing these infections [2]. Likewise, large countries suffer from scarcity of water resources due to its high demand and in a Canadian study, it is said that, in the face of these challenges, the recovery of water loss due to leaks in transmission and distribution pipes can provide a solution, at least partially, to this problem [3]. The first methods that were developed for leak detection were based on Moyer's sonic signal devices [4], Cascetta noise correlators [5], Hessel acoustic devices [6] or O’Brien ground penetrating radar [7]. These are the so-called “hear-and repair” methods, referring to the fact that each pipe must be inspected to determine the existence of leaks in the network [8], However, there is something very important about the time factor, and that is that decisions about the presence or absence of water in a pipe are required before doing this exercise. Even after the presence of water has been detected, it is time consuming to carry out field trips until approaching the leak.

Dowsing is esoteric, generally involving the use of metal rods to find objects. More specifically, study objects that are not visible, such as water, metals, oil, and other objects. In fact, when looking for water in the field, most people turn to professional specialists who resort to two sets of theories and practices: on the one hand, geology and one of its specific subfields, hydrogeology, and, on the other, dowsing [9]. However, applications in water have not been extended to the study of hydraulic networks and leaks, but it may have promising results as found in other applications, for example, the Iraqi security forces even used a device similar to a dowsing rod to try to detect bombs and weapons during the war in Iraq [10].

Therefore, it is quite possible for someone to simultaneously rely on geology and dowsing to find groundwater, even though geologists express their forecasts as probabilities, never providing the client with a simple and detailed prediction in the way that dowsers do. Dig to this depth and you will hit the water with such flow and such qualities [9]. Therefore, dowsing alone cannot find leaks in hydraulic networks.

According to the bibliographic review, the investigations related to leaks have classified them into: a) methods for the evaluation of which quantify the amount of water that was lost; b) leak detection methods, which seek to identify the site where the leak occurred; c) models which focus on the effective control of leaks according to different levels [3]. Additionally, in the literature they have identified a gap in models for detecting leaks in real time [1]. Our research is framed in the second classification.

The method proposed in this research is based on the simultaneous use of two techniques, the Dowsing search with dowsing rods allows detecting the presence of water in real time, it has the characteristic that a field trip must be carried out. The second technique uses a mathematical method called the Reynolds transport theorem that is supported by computational simulation, this mathematical method does not require field displacement and can detect if there is a leak once the presence of water has been confirmed with the Dowsing search techniques. A hydraulic network prototype was used to validate the leakage distance predicted by the mathematical method, which yielded an average relative error of 10.6727%, which is acceptable for pipes with difficult access in which only two pressure gauges are installed, one at the inlet and another at the outlet, it was also shown that the pressure drops linearly according to Darcy's law for easily accessible pipes in which a greater number of pressure gauges can be installed. The contributions of this research are:

- The dowsing search method was effective in determining the presence of water in hydraulic networks.
- The Reynolds transport theorem allows to determine the location of the leak by measuring flow, pressure, and pipe diameter at the inlet and outlet, which is ideal for pipes that are difficult to access.
- Numerical methods, specifically the volume of fluid (VOF) method that performs a balance of continuity and momentum, which allows to visualize the leak and its spatiotemporal evolution.

2. Model for exact location of water leak

The model for the exact location of the water leak is based on using the dowsing technique in the initialization stage where the presence of water is identified. There are two pseudo-routines, in the case of absence of water what this indicates is that it is not possible to determine the leak by this method, since the hydraulic network does not contain water and therefore there is no possibility of finding leaks. In the opposite case that it is determined that there is water in the hydraulic network, first the location of the leak is determined using Reynolds' theorem, finally, the existence of the leak is corroborated with the rods and the results are verified as shown in the Figure 1.

3. Reynolds transport theorem and the volume of fluid numerical method

The leak location method is supported by the mathematical methods of the Reynolds transport theorem and the VOF numerical method.

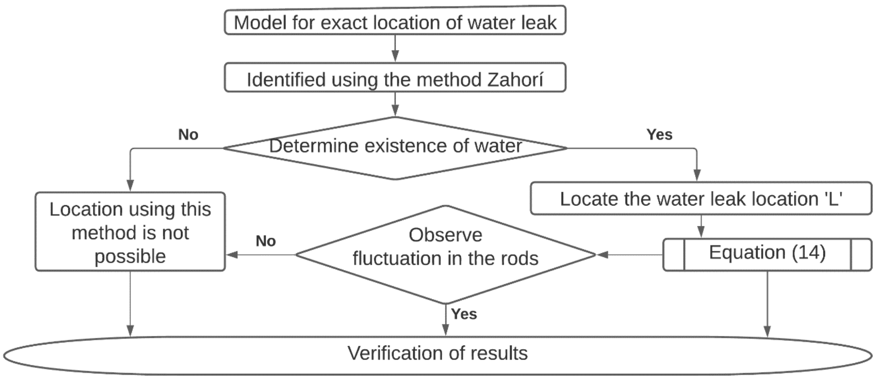


Figure 1. Leak location method.

3.1. Reynolds transport theorem

The equations of fluid mechanics come from applying the principles of conservation of mass, momentum and energy to fluid volumes. Since these volumes move with the fluid, it is convenient to express in an adequate way the variation of the fluid quantities within a fluid volume throughout its movement. This is what the Reynolds transport theorem provides, which can be considered as a three-dimensional extension of Leibnitz's equation [11]. The amount of water in the hydraulic network or piping system is quantified as the amount of water in 2 control volumes, one before the leak and the other after the leak, plus the amount of water that gains in the leak surface of the first control volume before the leak, plus the amount of water that is lost on the surface of the control volume of the leak, plus the amount of water that flows on the surface of the control volume at the outlet of the network hydraulic, as shown in the Equation (1).

$$\frac{dEsit}{dt} = \frac{d}{dt}\iiint_{vsc1}\left(\frac{v^2}{2}+gz+\frac{P}{\gamma}+h_Lg\right)\rho dv + \frac{d}{dt}\iiint_{vsc2}\left(\frac{v^2}{2}+gz+\frac{P}{\gamma}+h_Lg\right)\rho dv + \iint_{svc1}\left(\frac{v^2}{2}+gz+\frac{P}{\gamma}+h_Lg\right)\rho\vec{v}\hat{A}dA + \iint_{svc2}\left(\frac{v^2}{2}+gz+\frac{P}{\gamma}+h_Lg\right)\rho\vec{v}\hat{A}dA + \iint_{svcf}\left(\frac{v^2}{2}+gz+\frac{P}{\gamma}+h_Lg\right)\rho\vec{v}\hat{A}dA. \quad (1)$$

3.2. Volume of fluid method

In computational fluid dynamics (CFD) and more specifically in OpenFoam software, there is a two-phase fluid (air / water) algorithm that is used by the interFoam command, this is based on the VOF method in which a species transport equation is used to determine the relative volume fraction of the two phases, in each computational cell [12]. The VOF method used by interFoam solves the equations of quantity motion (Equation (2)) and continuity (Equation (3)) or the Navier-Stokes Equation (4) and continuity, expressed below.

$$\frac{\partial\rho U}{\partial t} + \nabla\cdot(\rho U\cdot U) - \nabla\cdot(\mu\nabla U) - \rho g = -\nabla_p - F_s, \quad (2)$$

$$\nabla\cdot U = 0, \quad (3)$$

$$\rho\left[\frac{\partial U_i}{\partial t} + U_i\cdot\left(\frac{\partial U_i}{\partial x_i}\right)\right] = -\frac{\partial p}{\partial x_i} + \mu\frac{\partial^2 U_j}{\partial x_j} - F_s + \rho g\mathbf{k}, \quad (4)$$

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 average density and viscosity, the method defines a function $\alpha(x, y, z, t)$ which represents the volume fraction of one of the materials in the finite volume, being $\alpha = 1$ a space completely occupied said material (fluid) and $\alpha = 0$ one completely occupied by the other phase (air). The differential Equation (5) governing function α is expressed as:

$$\frac{\partial \alpha}{\partial t} + U \cdot \nabla \alpha = 0. \tag{5}$$

The weighted averages of the densities Equation (6) and the viscosities Equation (7) are defined, respectively, as:

$$\rho = \alpha \rho_1 + (1 - \alpha)\rho_0, \tag{6}$$

$$\mu = \alpha \mu_1 + (1 - \alpha)\mu_0, \tag{7}$$

where the subscript 1 associates the property to the assigned material for $\alpha = 1$, and the subscript 0 to a property of the remaining material. The surface tension force is calculated by Equation (8):

$$F_s = \sigma k(x)\mathbf{n}, \tag{8}$$

where **n** is the unit vector normal to interface Equation (9) and k is the curvature of interface Equation (10):

$$\mathbf{n} = \frac{\nabla \alpha}{|\nabla \alpha|}, \tag{9}$$

$$k(x) = \nabla \cdot \mathbf{n}. \tag{10}$$

OpenFoam has a condition in the programming which is in charge of recognizing the process to be worked on, since there are two ways: when working with a single fluid, either liquid or gas, the software simply recognizes this condition and executes the equations. continuity and Navier-Stokes; When working with multiphase flow, the software recognizes this condition and adds one more equation to the solver. The pressure is solved by means of the Navier-Stokes equation and the continuity equation; but for multiphase cases the equation of the VOF method is added [13]. Equation (11) for the pressure in the solver is as follows:

$$P_{rgh} = p - \rho gh \ \therefore \ \rho = cte, \tag{11}$$

where P_{rgh} is the pressure generated by the solver; initial conditions are added to this pressure in the case containing folder Equation (12), p is the hydrostatic pressure; this pressure depends on the position where the particle is, in this case it depends on the height of the fluid on the z axis and it also depends on the density ρ, gh is the scalar product of the vector **g** and the position vector. Therefore:

$$P_{rgh} > p \Leftrightarrow h > 0. \tag{12}$$

4. Results and discussion

Below are presented one by one, the results obtained in this project to determine the approximate leakage distance, the digital and real models of a prototype for early leak detection, the visualization in the ParaView environment of a simulated model in OpenFoam, the comparison made from Darcy's Law and the proposals that were made from an approach that was given in the LabVIEW software.

4.1. Approximate leakage distance via L_I

In this section, Equation (1) was implemented, with the difference that the real case was analyzed for when there are three points (entry, exit and leakage). Starting from the continuity equation that says that the energy that enters must be equal to that which leaves, it is equalized and knowing the mass balance Equation (13), the entire energy equation was divided between obtaining as a result after a series of clearances and considerations the solution for L_1 Equation (14) that determines the distance from the inlet that the leak is located.

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_f, \tag{13}$$

$$L_1 = 12.1026 Hm_1 D^5 + Q_1{}^2 D - \frac{Q_f{}^2 D^5}{D_f{}^4 Q_1} - \frac{Q_2{}^2 D}{Q_1} - \frac{f_2 L_T Q_2{}^3}{Q_1} \Big/ f_1 Q_1{}^2 - \frac{f_2 Q_2{}^3}{Q_1}. \tag{14}$$

The Equation (14) found that will work as long as it finds detected water, in this case, by Dowsing in the pipe, where Hm_1 is the pressure difference between inlet and outlet, D is the diameter of the pipe, f coefficients of friction, L_T the total size of the pipe and Q the flows, for which a certain amount of values were adapted to observe its behaviour. To determine the surface area of the leak Equation (15), a consideration was used that uses the subtraction of flows, said estimate is given as follows:

$$D_f = \sqrt{D^2 \times \text{Estimate}} \therefore \text{Estimate} = 1 - \left(\frac{Q_2}{Q_1}\right) \times 100\%, \tag{15}$$

where the area of a circle was chosen to perform the clearance of D_f since it does not matter whatever the geometry of the leakage area is if it is expressed in terms of leakage flow Equation (16).

$$Q_f = Q_1 - Q_2. \tag{16}$$

For the simulation presented in this investigation, a total distance was taken $L_T = 3$ m of pipe (14), and an average length of 2.7034 m was estimated for 10 flows extracted in the simulation time, then it was established that its relative error is 10.6727%.

4.2. Digital and real models of a prototype for early leak detection

A prototype was made to help with leak detection using only two flow sensors placed at the outlet of each branch of the network. The Figures of the digital prototype (Figure 2) and real (Figure 3) are shown below.

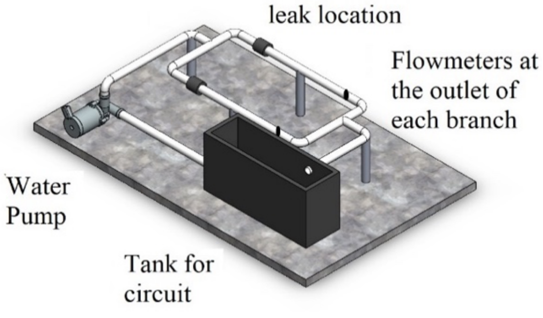


Figure 2. Digital prototype made in SolidWorks for early leak detection.

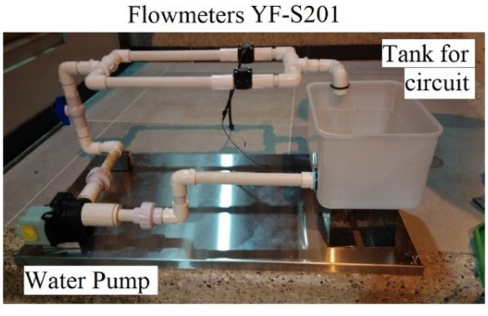


Figure 3. Real prototype that uses two YF-S201 flowmeters and a water pump (9 $^{L}/_{min}$).

4.3. Visualization in the ParaView environment and comparison with Darcy's Law

It was identified in the ParaView visualization of the simulation in OpenFoam (Figure 4) that a “pressure bubble” is generated near and shortly before the leak is generated, which is translated as an increase in pressure according to the color palette, and Darcy's law was ratified, which dictates that the pressure falls in a linear way, it was also seen that after the leak there is a small pressure jump that was verified by characterizing its slopes, which are respectively, $R^2 = 0.9995$ before the leak and $R^2 = 0.9982$ after the leak, as shown in Figure 5.

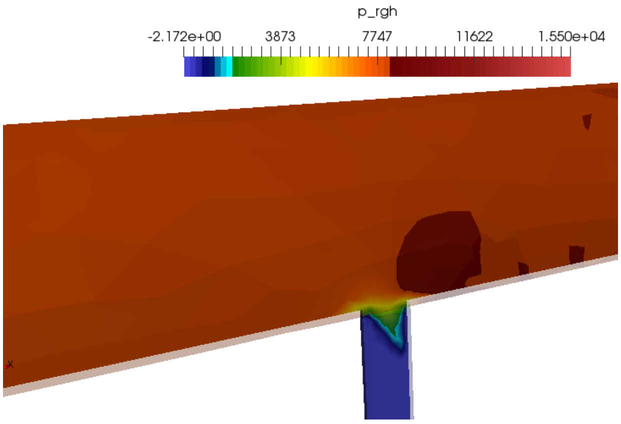


Figure 4. "Pressure Bubble" near the leak in ParaView.

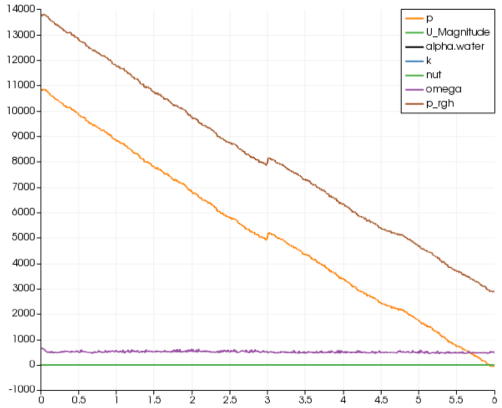
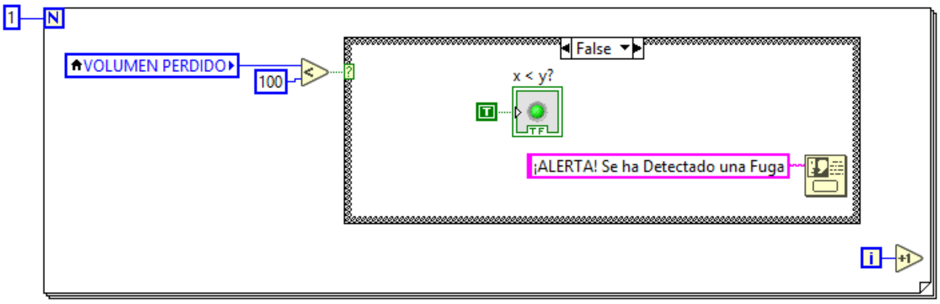


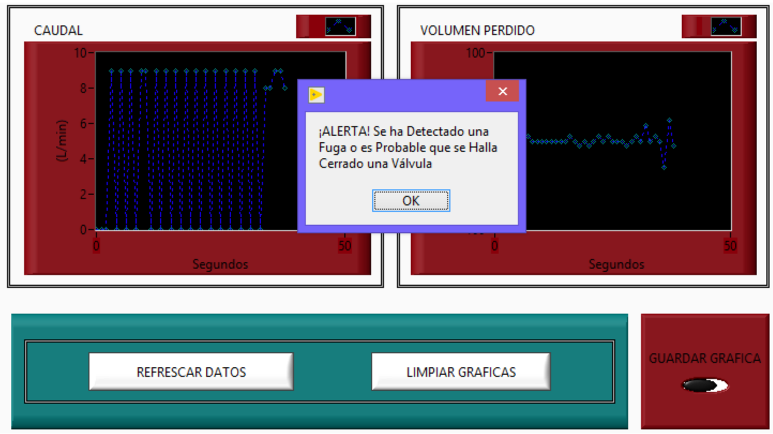
Figure 5. Pressure drop along the pipeline.

4.4. Proposal for the most complete elaboration of a virtual instrument in LabVIEW
An interface was developed in LabVIEW as shown in Figure 6, to monitor in real time (exactly in microseconds) the prototype shown in Figure 3, and which the YF-S201 sensors were connected through an Arduino board, using only an algorithm of difference in the flow Equation (16) with respect to the time reflected in the block diagram (Figure 7) of said program. The function of this algorithm is to check if flow is lost at the end of the pipe. For purposes of an improvement in this virtual instrument, it is proposed to develop a block diagram that includes the equation for the approximate location of the leak L_1 (14), and thus have not only an alert that indicates that a leak has been detected, but also indicates the distance at which the leak is located in the section of the hydraulic network that is being monitored.



¡ALERTA! Se ha Detectado una Fuga

Figure 6. Conditional (Case) used in the Block Diagram in LabVIEW.



¡ALERTA! Se ha Detectado una Fuga o es Probable que se Halla Cerrado una Válvula

Figure 7. Leak Control Panel with message on screen warning possible leak.

5. Conclusions

In this research, the dowsing technique was proposed to detect the presence of water in hydraulic networks, which was coupled with the Reynolds Transport Theorem to detect the distance in which the leak was located, the results were thrown as a function of the flow rate, which is ideal for hidden leaks where the geometry of the leak is unknown, and the experimental data corroborated the predictions with an additional relative error percentage of 10.6727%. It was proposed to use numerical methods; to inspect the spatiotemporal evolution of the leak, so a pressure drop bubble was determined near the leak. In addition, the pressure drop along the simulated pipeline was inspected, thereby ratifying Darcy's Law and identifying a sudden pressure drop over the leak. Evaluating the two slopes, it was obtained for the first section that its slope was 2024 (before the leak) with an adjustment $\mathrm{R}^2 = 0.9995$, and for the second section that its slope was 1769 (after the leak) with an adjustment $\mathrm{R}^2 = 0.9982$ which are excellent.

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