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On the initial investigation of the use of temperature gradient measurements to estimate the presence of leaks

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Abstract. Leakage in water pipes is of great concern, so that techniques for its detection have been widely studied over the years. In this scenario, vibro-acoustics techniques are the most used ones because they can be no intrusive, can provide information on the amplitude (severity) and location (time delay) of leaks in buried pipes with reasonable precision, however, requiring the use of equipment and instrumentation of high cost in addition to the training of specialized labor workers. The latter may restrict the application of this kind of solution to a few specialized companies. Hence, the initial investigation of detecting leaks via using temperature gradient measurements is proposed in this work as an attempt to develop a technique that is less costly but still effective in indicating the existence of leaks. This initial investigation is carried out using a straight-horizontal water plastic pipe generally found in ordinary houses, so that the heat transfer mechanism of such situation can be modeled via finite volume method (FVM) considering steady-state condition and the developed code (situations) validated using the software OpenFoam. The simulations were carried out considering a range over which the Reynolds number relies within according to the average leak flow rates commonly found in ordinary residential buildings in Brazil. Moreover, the Nusselt and temperature gradient were then evaluated regarding their variability in the fully developed flow region, as a function of the variation of the external environment condition.

Keywords: OpenFOAM, leak indication, water pipe

1 Introduction

Potable water losses during its distribution is a problem that have been increased along the years, due to time degradation and others several conditions. On the way to get a more competitive scenario and ensure potable water in the large cities, the water companies have been under increasing pressure and concerned to prevent water losses.

In Brazil the average water loss is about 38% reaching do 70% in some states, such as Maranhão (O Globo, 2018 [1]), In São Paulo State, the water company SABESP responsible for suppling water to about 375 cities englobing 28.2 million people, invested 1 billion BRL (Brazilian real) to prevent water losses and to reduce non-revenue water by less than 20% in 2021 [2].

Several solutions have been developed to detect non-revenue water and leak location in water distribution systems, like the acoustic technique that uses filtering procedures together with the cross-correlation function (Fuchs and Riehle, 1990 [3] and Hunaidi et al, 2004 [4]), pressure monitoring models, that compare the water flow and pressure histories taken during the night shift (Fantozzi et al, 2009 [5] and Abdulshaheed et al, 2017 [6]) and transient pressure based leak detection methods (Colombo et al, 2019 [7]) that studied the pressure transient via opening and closing valves. All these techniques have positive and negative points, for example, the acoustic technique requires expensive equipment and a more sophisticated signal processing procedure, pressure monitoring models need a precise modeling and statistical analysis, and the transient pressure-based leak detection methods, which is cheaper and simpler among those, can lead to a great number of false positive.

The method investigated in this paper uses the temperature difference between the external medium (air) and the fluid in the pipe (water), which can be used to aid in leak detection via a cheap and simple way that can be used in combination with others methods for non-revenue water detection.

2 Description and Simulation of the Case Study

As mentioned previously, the present work studies the application of temperature variation as a possible indicator of the existence of leaks in pipeline network found in ordinary houses. The model herein described is used to conduct the simulation and further analysis of the problem. This model is composed of a pipe filled with water and an external medium, which is air that flows across the pipe. This model is set via the Finite Volume Method (FVM) and performed using software OpenFOAM. The proposed technique requires that the water system (pipeline network) has a certain ”rest” interval, so that, any water flow, which can be due to water usage or the presence of a constant leak rate can lead to a temperature variation during the transient response of the system, so that, a pattern is stablished. It is believed that this method is more suitable for residential buildings (ordinary houses), which normally have a minimum consumption rate at night. Moreover, the evaluation of the temperature transients together with the time required to establish a minimum temperature variation over which leak detection can be estimated as a function of the external air velocity variation is investigated. The temperature transient is evaluated in a small section of pipe that represents the connection between the consumer system to the distribution network (water mains), considering a minimum flow in the steady-state condition. This can be disturbed by a step input (abrupt change in the water flow rate) representing an ideal consumption, such as opening and closing a water tap. For the simulations herein conducted, it is used an ordinary pipe commonly found in residential areas in Brazil.Table 1 depicts the pipe geometry and material properties.

Table 1. Geometry and material properties of the pipe used to conduct the simulations.

Pipe geometry properties		Pipe general properties [8]	
Outer Diameter D_{ext} [mm]	25.4	Density ρ $[kg/m^3]$	1470
Wall Thickness s [mm]	1.7	thermal conductivity k $[W/m\,K]$	0.1
Length L [mm]	1000	specific heat c_p $[J/kg]$	840

Different scenarios can be set up to investigate the feasibility of the technique proposed in this work. For this, it is considered three main scenarios where the simulations will be conducted. Furthermore, these scenarios are proposed based on limits given by water companies, in this case, the water company SABESP. The first scenario considers the acceptable level of leakage which a system can present. The second scenario is related to the non-acceptable situation (presence of leaks) when the system has no demand/usage. The last one is concerning the normal water usage, such as by opening a water tap. Table 2 summarizes the bounds of these scenarios.

Table 2. Studied flow conditions. Adapted from SABESP [9]

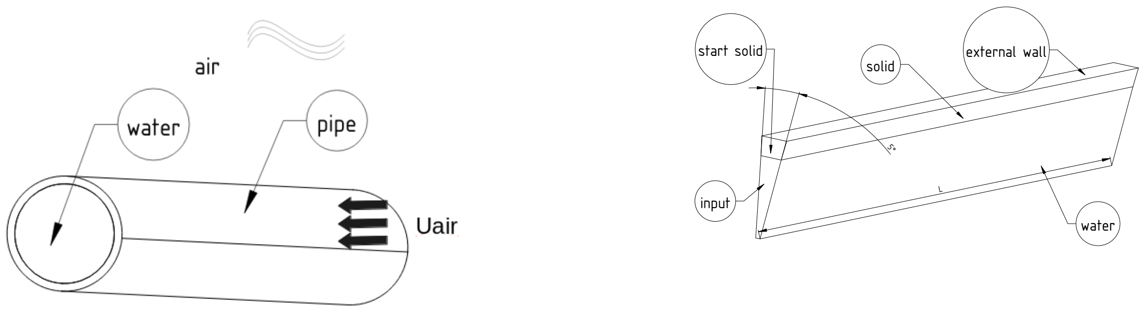
Example	Estimated Flow	Re_D
Acceptable leaking tap	10 [l/day]	6
not acceptable leaking tap	50 [l/day]	30
Thin trickle of water	250 [l/day]	150
Water tap partially opened	2.5 [l/min]	2000
water tap with fized-flow regulator	6 [l/min]	5000
Full open tap	15 [l/min]	13000

However, it should be noted that leakages can be present in any point along the pipe system and the total water wastage can be simulated by adding up their flows. Besides, the measurements are conducted next to the pipe inlet system, so that the influence of the total water flow is kept and can be detected. Although simulations were also performed considering Reynolds above 5000, the results did not show much difference from the ones obtained in the laminar flow regime. Hence, only laminar flow simulations are presenting for convenience and less computational cost.

2.1 Modeling the pipe system and the surrounding medium

The pipe system was modeled via FVM using OpenFOAM, since it deals with heat transfer phenomena as conduction and convection mechanisms. Besides, the mass, energy and momentum conservation equations were solved using the chtMultiRegionFoam application, which uses PIMPLE (Pressure Implicit with Splitting of

Operator) algorithm. The simulations were carried out using the system depicted by the scheme in Figure 1(a), which is simplified and represented by circular sector figure 1(b), neglecting the effects of natural convection. The simplified system will be covered latter in the following sections.



(a) Full domain

(b) Circular sector used in transient analysis

Figure 1. Schematic of (a) the system under analysis (full model) and (b) simplified model

2.2 Modeling the pipe

The heat flux through the solid is obtained by applying the energy equation. Considering that the thermo-physical properties of the solid are constant, so that the heat diffusion equation can be given as:

$$\frac{1}{\alpha}\frac{\partial T}{\partial t} = \frac{\partial T^2}{\partial x^2} + \frac{\partial T^2}{\partial y^2} + \frac{\partial T^2}{\partial z^2}, \tag{1}$$

where x, y, z are the coordinates, t time and $\alpha = k/\rho c_p$ is thermal diffusivity. It is important to observe that the temperature boundary conditions in the steady state case is given by $T(x, y, z, 0) = T_{water}$, so that, the steady state results are the temperature boundary conditions in the transient analysis.

2.3 Modeling the fluid

Considering incompressible water and constant viscosity, the mass conservation equation can be written as:

$$\nabla \cdot \mathbf{u} = 0, \tag{2}$$

where $\mathbf{u}$ is the velocity vector. Neglecting the terms related to the potential and kinetic energy and considering constant thermal conductivity and specific heat, the energy equation for the fluid is given by:

$$\frac{\partial T}{\partial t} + \mathrm{u}\frac{\partial T}{\partial x} + \mathrm{v}\frac{\partial T}{\partial y} + \mathrm{w}\frac{\partial T}{\partial z} = \alpha \nabla^2 T, \tag{3}$$

where u, v, w are components of the vector $\mathbf{u}$. The momentum equation for laminar flow, incompressible Newtonian fluid is given by:

$$\rho\left(\frac{\partial \mathbf{u}}{\partial t} + \mathbf{u}\cdot\nabla\mathbf{u}\right) = \rho\mathbf{g} - \nabla p + \mu\nabla^2\mathbf{u}, \tag{4}$$

where g is the gravitational acceleration, p is the pressure field.

A common practice in problems involving convection heat exchange is the convective coefficient (h) estimation in a nondimensional form, called Nusselt. These estimations are conducted via empirical equations estimated under some controlled conditions and extrapolated to real applications. Hence, these equations were used to simplify the model as the one given in Fig. 1(b) and also, to verify the mesh quality of the FVM model. The simplification for the fluid medium (air and water) was carried out through the externalWallHeatFluxTemperature function, and the convection heat exchange coefficient, which is required during the calculation, was obtained through the Nusselt equation. The equation for the air proposed by Churchil and Bernstein, 1977 [10] is given by:

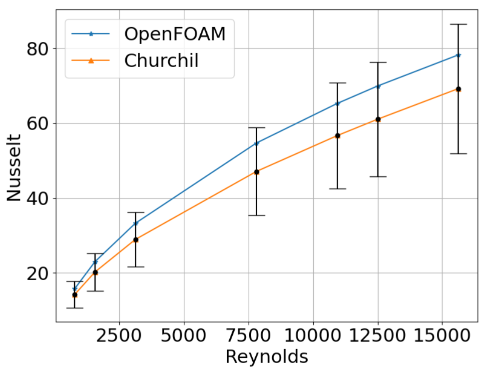
$$Nu_{cyl} = \frac{hD}{k} = \frac{0.62Re^{1/2}Pr^{1/3}}{[1+(0.4/Pr)^{2/3}]^{1/4}}\left[1+\left(\frac{Re}{282000}\right)^{5/8}\right]^{4/5}, \tag{5}$$

where Re is the Reynolds number, Pr is the Prandtl number, k is air the thermal diffusivity, and D is the pipe outer diameter of the tube, and h is the air convection heat transfer coefficient. The average Nusselt of the air was calculated using the full domain to check if the mesh used can lead to a similar Nusselt estimation as the one presented at eq. 5. The average Nusselt calculated via OpenFOAM was performed as presented by Magnusson [11]. Figure 2(a) shows the Nusselt evaluated via Eq.5 (red line) and via the OpenFOAM (blue line) together with the acceptable error of 25% given when using the theoretical equation. It is observed that the trend and values for both cases are very similar, with a maximum error of about 17% for both cases, depicting that the error is withing the acceptable range. This reinforces that the mesh is well deployed in the model.

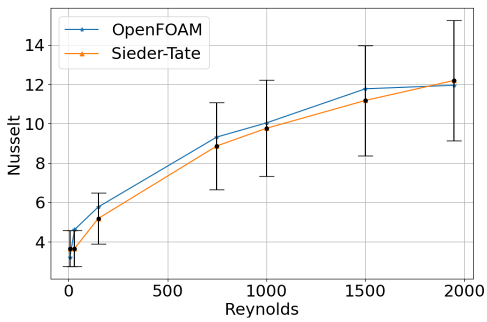
The average Nusselt of the water was calculated using the simplified domain, that is, a mesh composed of water, pipe and application of the boundary condition externalWallHeatFluxTemperature for the air in the steady-state condition and compared with the correlation proposed by Sieder and Tate [12]:

$$Nu = 1.86\,(Re\,Pr\,D/L)^{1/3}\,(\mu/\mu_w)^{0.14}, \tag{6}$$

where L is the length of the pipe and μ the viscosity of the fluid in the pipe and μ_w is the viscosity of the fluid evaluated at T_{wall}. Figure 1(b) depicts the result for this simulation. Likewise for the air, the error is within the acceptable range reinforcing that the mesh was set properly and the simplification will not affect the results provided.



(a) Average Nusselt external flow: Full domain mesh 1909200 volumes



(b) Average Nusselt internal flow: Reduced domain mesh 54000 volumes

Figure 2. Average Nusselt as a function of Reynolds of air figure 2(a) and water figure 2(b)

2.4 Results: Transient analysis via computational approach

The transient study was conducted in order to identify the critical time for the system to achieve the steady state regime (thermal equilibrium) under specific conditions. Hence, making a parallel with lumped systems and the variation of the internal energy of a solid, the time constant defined by b is given by:

$$b = \frac{hA_s}{mc_p}, \tag{7}$$

where As corresponds to the convection heat exchange area, m solid mass and c_p solid specific heat. The higher the value of the time constant b, the faster the system reaches the state of thermal equilibrium. Hence, the parameters that influence convection heat exchange together with the final equilibrium temperature will also affect the equilibrium time length, such as water flow and air velocity. The temperature range over which the system can rely on is between the air and water temperatures, the ones that drive the system temperature, especially when towards the equilibrium. The following normalized form of the temperature is used to calculated the variation of the temperature of the system as a function of time for convenience:

$$T^* = \frac{T - T_{air}}{T_{ss} - T_{air}}, \tag{8}$$

where T_{ss} is the temperature in steady-state condition, this normalized form express the distance of the steady-state condition, this can be greater than or equal to 1, if it is closer to 1, then the temperature at the point is close to steady state condition.

The indication of the existence of leaks is based on the analysis of the temperature response curve of a system initially in thermal steady-state condition and disturbed by a step input, representing an ideal consumption. Figure 3 shows 4 cases with different Reynolds' number simulating 4 different water usage (flow rate). The simulations are carried out by considering a flow with step-like behavior, as mentioned previously. The step input start at $t_0 = 10$ seconds in order to verify that the system is really in steady state condition before the step input, with a duration of Δt : 90 seconds.

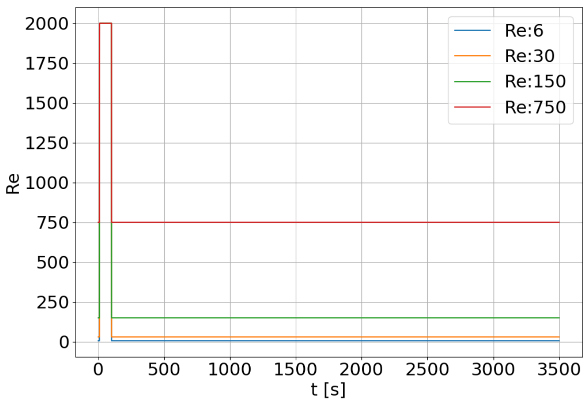


Figure 3. System disturbance, step input, flow representing ideal consumption for four different cases.

The temperature transient on the outer wall of the pipe was evaluated at distances 250, 500 and $750mm$ from the inlet of the pipe under the investigation, but only the ones measured at $l = 500mm$ will be used in this analysis as there is no difference of the conclusions obtained for these cases. It is emphasized here that the option to evaluate the temperature transient on the external wall of the pipe is to verify the feasibility of indicating the presence of leaks in the pipeline network without installing internal sensors in the pipe (non-invasive measurements). The system in steady-state condition and with low flow rate presents a high temperature variation when subjected to any disturbance, and this variation is attenuated as the residual flow increases, as shown in the figure 4. This residual flow is caused by leaks, or any device left opened in the system. Besides, the variation of the amplitude in different conditions is a function of the variation of the thermal capacity rate defined by the equation:

$$C_{water} = \dot{m}(t)\, c_p, \tag{9}$$

where c_p is the water specific heat and $\dot{m}$ is the mass flow that flows inside the pipe, which changes over time due to the consumption. The indication of the existence of a leak is given by comparing the temperature transient over time, such that:

$$f(x) < g(x), \quad (10)$$

where $f(x)$ measurement of the temperature at the outer wall over time and $g(x)$ transient temperature with base flow equivalent to Re : 6 Figure 4 shows this phenomena. It is observed that higher the Reynolds, more rapidly the temperature decays reaching the equilibrium (stead-state condition). This can be used to the detection of leaks in the system.

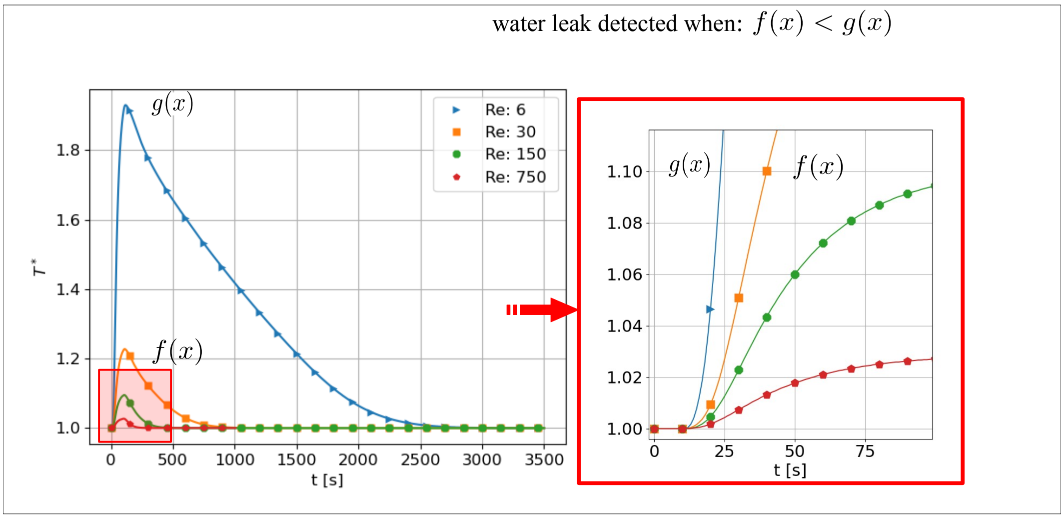


Figure 4. The normalized temperature transient on the outer wall of the tube $l = 500mm$.

In order to verify the influence of the air velocity of the external environment, a simulation of the temperature transient was carried out in the admissible leakage condition, (10l/day), subject to a disturbance by varying the convection heat transfer coefficient, as shown in the figure 5 . It is observed that the time taken to the system reach the equilibrium has not changed, so it suggests that the water flow if the main factor responsible for it.

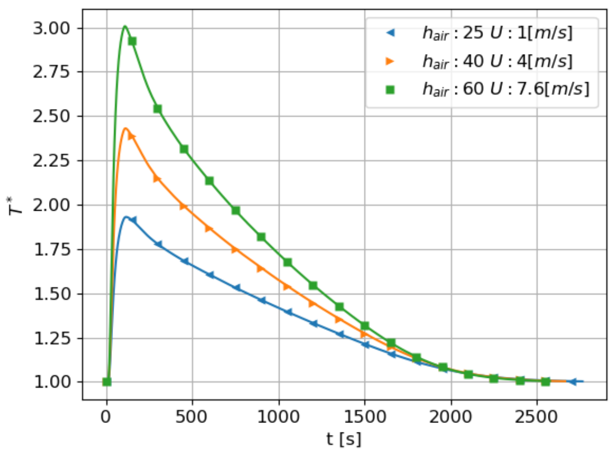


Figure 5. Normalized temperature transient on the external wall in the permissible leakage condition (Re=6), varying air convection heat transfer coefficient.

3 Conclusions

The proposed study evaluated the feasibility of detecting leaks from the analysis of the temperature transient on the external wall of horizontal pipes. For this initial study, several simplifications were conducted regarding the model. Hence, these simulations were simplified by restricting the water flow to a laminar regime, neglecting radiation, considering constant water density, and so on. Leak detection estimation could be conducted due to the temperature variation and time taken for the system to reach the equilibrium position in situation considering non-leakage and leakage in the pipeline system. The minimum consumption time for the system to reach the steady state regime was relatively high (2500 seconds) for the most critical condition, which is the situation considering no leak. Besides, this technique is more effective when used during night shift, due to the low water consumption and smaller variation of environment temperature. The variation of the air velocity only affects the temperature amplitude, having no influence on the equilibrium time. This is mainly controlled by the water flow.

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