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Investigation of Leak Behavior in a Horizontal Pipe with Pressure Based Detection Scheme

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Abstract

Leaks are one of the most significant reasons behind unaccounted resource losses in almost every fluid distribution network. Leaks- need to be managed very carefully, otherwise, may have catastrophic economic and environmental impact. In this thesis, pressure and velocity characteristics of a leak in a long horizontal pipe has been studied to design a detection scheme for the leak. For accomplishing this goal both computational and empirical results are compared to properly verify the accuracy of the scheme. Ansys Fluent has been used for performing CFD analysis where pressure and velocity variation before and after the leak has been observed. Experimentation have been conducted in the fluid machinery laboratory. Finally, the characteristic trend has been compared in order to propose a simple yet meticulous detection scheme by linear regression of static pressure data points along the pipe length resulting reduced false alarm when used in a hybrid leak detection system.

Keywords: Pipe Leak, Detection, ANSYS Fluent, Pressure, Experimental data

1. Introduction

Leak is a serious issue and in most cases cannot be taken for granted. The deleterious effects associated with the occurrence of leaks may present serious problems and thus has to be quickly detected, located and repaired. And Public water pipeline systems comprise hundreds, and in many cases thousands, of kilometer s of mains, consisting of short individual pipes linked by joints every few meters [1]. Leaks have several bad impacts. It has both environmental and economic impacts. Although some previous studies are found in the literature, the whole area of leak detection is yet to be matured [2]. The goal in this research is to try to develop the best possible way to detect and understand leak phenomenon which is not heavily equipment sensitive and can be implemented in all sizes of systems to provide an economic operation of the system. Here, mainly dealing is done with pressure changes for the study as it is quite easier to measure than other sensitive parameters of pipelines. Pressure gauges are relatively cheaper and using them is not very difficult. So, pressure is selected as the main parameter to find out the effects of leaks on the parameter. The pressure deviation model seems to be the most predictive leak detection method [3]. When a leak occurs in a pipe line system pressure before and after the leak changes with significant characteristics. These characteristics can be studied to find out relation between those measures and the leak that triggered those values. The target is to accomplish this feat by the CFD (Computational Fluid Dynamics) analysis and physical experimentation of a horizontal pipe line carrying a flowing fluid. From the findings of both experimental and simulation studies it is wanted- to develop a valid relationship between the severity of leak and the pressure changes before and after the leak region for proper evaluation and detection. Existing techniques have multiplied over the years and basically can be classified into two categories. *Externally Based Methods* are Acoustic emission systems, Fiber optic sensing technologies, Flow Monitoring Technique, Vapor or liquid sensing tubes, Soil monitoring etc. *Internally Based Methods* are Negative Wave Propagation, SCADA-based systems**,** Chemical based systems**,** Software based dynamic modeling**,** General optical methods, Real time transient modeling**,** Statistical method**,** Digital signal processing etc. Research in the past 15 years has shown that leakage from gas or liquid filled systems, such as pipelines can be well identified and localized using Acoustic Emission (AE) [4]. Considering all evidences including latest technological innovations, no single technique has yet become the standard choice of the industry due to the various limitations involved in the different techniques [5]. Therefore, comes the concept of hybrid leak detection systems and this paper.

2. Mathematical Formulation

The objective of this study is to predict pressure distributions for the case of steady flow. As well as calculations of response of pressure frequency domain to input perturbations were conducted. Thus, the flow in a pipe and response to a leak was studied. The influence size of the leak on the water pressure distribution was also investigated. FLUENT 19.2 CFD student package was used for the present calculations. The 3D time-averaged Navier–Stokes governing equations and the k–ε model are described in the following.

Mass and Momentum conservation. The equation for conservation of mass can be written as

$$\frac{\partial \rho}{\partial t} + \nabla \, . \, (\rho \vec{u}) = 0 \tag{1}$$

The equation for the conservation of momentum can be expressed as in [6],

$$\frac{\partial (\rho \vec{u})}{\partial t} + \nabla \, . \, (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \, . \, \bar{\bar{\tau}} \tag{2}$$

Conservation Equation for Turbulence model. The model assumes that the turbulent viscosity μ_t is related to the turbulent kinetic energy and dissipation through the following ratio

$$\mu_t = \frac{\rho C_\mu \kappa^2}{\varepsilon} \tag{3}$$

Where, C_μ is a typical model constant with default value of 0.09 for flow with high Reynolds number. The turbulent kinetic energy κ, defined by the variation of the velocity fluctuations and can be described as in [7],

$$\frac{\partial (\rho \kappa)}{\partial t} + \nabla \, . \, (\rho \bar{u} \kappa) = \nabla \, . \left[\left(\frac{\mu_{eff}}{\sigma_\kappa} \right) \nabla \kappa \right] + P_\kappa - \rho \varepsilon \tag{4}$$

The dissipation rate of the turbulent kinetic energy ε, is modeled as

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \, . \, (\rho \bar{u} \varepsilon) = \nabla \, . \left[\left(\frac{\mu_{eff}}{\sigma_\varepsilon} \right) \nabla \varepsilon \right] + C_{\varepsilon 1} \frac{\varepsilon}{\kappa} (P_\kappa + C_{\varepsilon 3} P_b) - C_{\varepsilon 2} \rho \frac{\varepsilon^2}{\kappa} \tag{5}$$

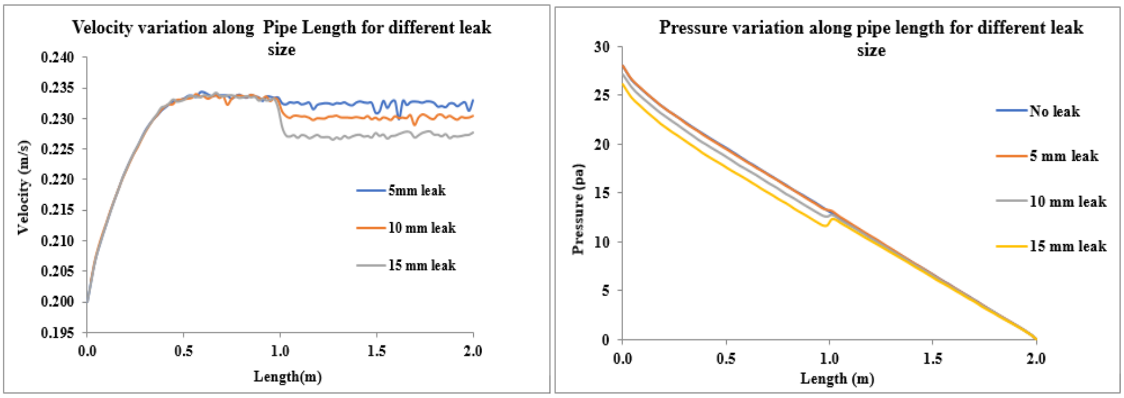
P_κ *and* P_b Represents the generation of turbulence of kinetic energy due to the mean velocity gradient and due to buoyancy respectively. It is important to remind buoyancy effects on ε are often neglected in the transport equation for ε. The model constants $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, σ_κ *and* σ_ε have the following default respective values 1.44, 1.92, 1.0 and 1.3. $\bar{u}$ is the velocity vector average in time.

The present calculations were conducted within the flow domain of a pipe of diameter D=0.0508 m and length of L=2m. A three-dimensional inflation mesh with around 483,765 cells were used. As there is no sufficient discrepancy on the gradient pressure along the pipe for specifically defined three different analysis (medium, fine, super fine) considering the simulation time and computational cost, it can be concluded that medium mesh is the most adequate for this study. For turbulent condition a flow velocity of 0.2 m/s were used. On the other hand, for high Reynolds numbers (Re>4000, for pipe flow) the flow has turbulent characteristics, a random and chaotic state of motion where velocity and pressure change continuously with time [8]. In addition a second order upwind scheme in space was selected. Enhanced wall treat method was chosen in the solution procedure that helped to understand leak phenomena better. All data collected from the simulations, velocity and pressure, were collected from the mid-section of the pipe (not from direct under the leak). The present calculations were performed using Fluent 19.2 and utilizing the standard k–ε model. The pressure outlet at the leak hole and the main outlet both were taken equal to the atmospheric condition, thus, $P_{leak}=P_{atm}=P_{outlet}= 0$ (gage)

3. Results and Discussion

2.1 Simulation Results

The CFD analysis gave us some important results in the form of plots, pressure versus length plot being the main plot for our experimental studies. All these graphs are organized below.



(a) (b)

FIGURE 1. Shows the variation of (a) pressure along pipe length (b) velocity along pipe length for no leak, 5 mm diameter leak, 10 mm diameter leak and 15 mm diameter leak conditions.

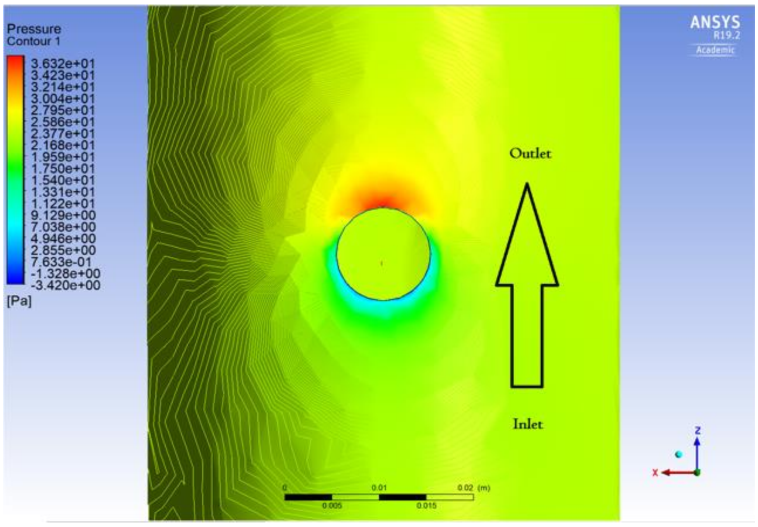


FIGURE 2. Zoom-in view of pressure, Pa, contours at the leak vicinity (low pressure highly localized).

We designed our scheme on the basis of this pressure versus length plot in Figure 1(b). We can see that with increasing leak size the pressure drop follows a trend which can be approximated as parallel. We also see that from our experiment which validates this approximation. The pressure contour in Figure 2 shows a very interesting behavior just downstream of the leak that pressure increases slightly which can be defined using Bernoulli's equation. Because of the slight drop of the velocity in the velocity results in increase of pressure. Another important observation from Figure 1 is- always upstream of the leak indicates leak's presence.

4.2 Experimental Results

For performing this experiment several pre-setups were done. Five polymer-glass tubes were used for measuring pressure heads. Three of those were installed before the valve that simulated leak condition and the other two were mounted after the valve. The number of pressure taps were limited for reducing experimental complexity as well as ensuring feasibility of the scheme. Each tap needed precise positioning along with sealing for eliminating any sorts of water leakage through the sides of the taps. The readings were taken in fully open and fully closed valve conditions. The full open valve represented a leak condition and full closed valve represented no leak condition for the system. The volumetric flow rate was also measured from taking several readings of flow from the outlet for a particular time.

From our experiment we get the following pressure versus length data in Table 1, Table 2 and plot the graph in Figure 3.

TABLE 1. Pressure along the pipe length (No leak)

X(m)	H(cm)	H(cm)	H avg.	P(pa)
0.263	31.8	32.2	32	3139.2
0.512	25.5	26.3	25.9	2540.79
0.757	19.8	21	20.4	2001.24
1.13	12.1	12.7	12.4	1216.44
1.255	10.2	9.2	9.7	951.57

TABLE 2. Pressure along the pipe length (With Leak)

X(m)	H(cm)	H(cm)	H avg.	P(pa)
0.263	30	29.5	29.75	2918.48
0.512	23.5	24	23.75	2329.88
0.757	17.8	17.2	17.5	1716.75
1.13	12	12.6	12.3	1206.63
1.255	9.2	9.6	9.4	922.14

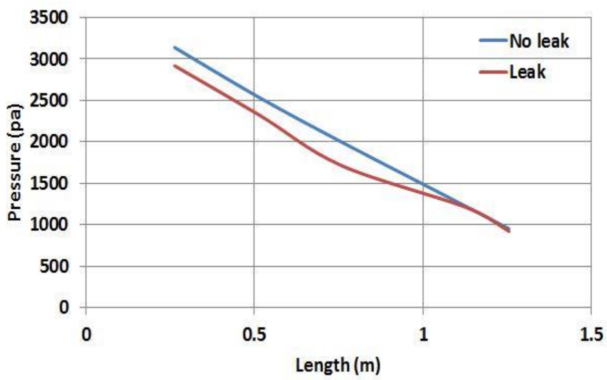


FIGURE 3. Shows pressure variation along pipe length for leak condition and no leak condition (Experimentally found data)

This experimental plot in Figure 3 closely resembles the trend that was observed in Figure 1(b). This validates the approximation of considering the plots before and after the leak- almost parallel to each other and the distance between these plots being an indicating parameter for the leak.

Linear regression method has been implemented to propose a scheme based on this distance which requires a threshold value that has to be determined experimentally for each system for proper detection. To generate these lines, several co-ordinates from the systems are needed and these coordinates can then be used to approximate a line by the following system, generating two straight lines from pressure versus length plot points, one from upstream points, equation 6 and second from the downstream points, equation 7 (without leak condition)- by this method, we may approximate these lines as parallel, as seen in both simulation and experimentation. For an ideal straight pipe having no bends or joints- these two lines must superpose each other. Let the equations of these 2 lines are,

$$y = mx + c_1 \tag{6}$$

$$y = mx + c_2 \tag{7}$$

Here, m can be taken as the slope of any of the lines. Then the distance between these lines can be found by the following equation derived from simple co-ordinate geometry,

$$x = \frac{|c_1 - c_2|}{\sqrt{(1+m^2)}} \tag{8}$$

This distance is our threshold for the system- which will be needed to dictate for finding out if there is a significant leak happening in the system. This has to be determined empirically for every system over and over after a certain period of time. Another equation 9 can be generated using same linear regression method and considering it parallel to equation 6 and 7 from the upstream points of the pressure plot (after the leak phenomenon). Let the equation be,

$$y = mx + c_3 \tag{9}$$

Determining the threshold for no leak condition- a significant leak can be detected if the instantaneous value of the distance between this equation 9 and equation 7 (Say D) crosses the threshold value. It can be expressed in a ratio term. A case study also has been performed which successfully shows indication of leak in the system using the method. For getting the threshold value we need to generate two equations by the described linear regression method from the no leak condition data. Equation 10 will be generated from the three data points before the valve and equation 11 will be generated from the two data points after the valve. Equation 11 will be approximated as parallel to equation 10 and have same slope component. Performing the regression, the two equations are,

$$y = -2303.83x + 3736.901 \tag{10}$$

$$y = -2303.83x + 3831.179 \tag{11}$$

Distance between equation 10 and equation 11, threshold = 0.04092. Now when after the occurrence of leak, we need another equation (equation 12) which will be generated from the data of leak condition for the 3 points before the valve or upstream. We also approximate the equation to be parallel to the equation 10 and will consider having same slope.

$$Y = -2303.83x + 3498.192 \tag{12}$$

Now distance between equation 10 and equation 12, D = 0.10361. Here the value of D is 253 percent higher than the threshold value which indicates a leak!

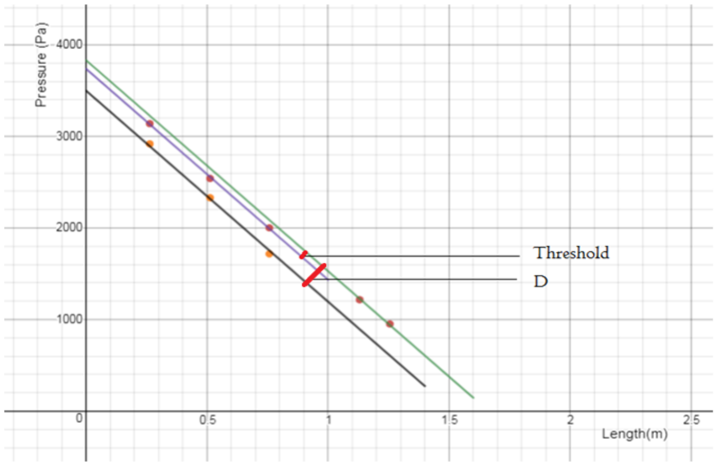


FIGURE 4. Shows how leak can be detected with proposed scheme using regression method by comparing threshold value with the value of D

4. Conclusions

The work in this thesis is mainly analysis of leak behavior in horizontal pipes and proposition of a detection scheme based on pressure. Considering all evidences including latest technological innovations, no single technique has yet become the standard choice of the industry due to the various limitations involved in the different techniques [9]. We observed from the detail analysis that the effect of leak on the pressure is far more prominent before the leak position than after it. So the goal was to introduce a simple yet very effective and economic method of leak detection scheme that will reduce false alarm. We observed that the pressure plots along the length is almost parallel to each other whatever may be the leak size, which is a very important observation for our scheme design. There is also vast scope for future research; for instance velocity, dynamic pressure, pressure co-efficient and other parameters can also be considered to observe the leak phenomena and there inter relationship. Schemes can be designed for systems having multiple leaks and different orientations. A microcontroller can be used to monitor this ratio all the time and warn at the time of this ratio crossing unity. The threshold can be chosen with a tolerance for preventing false alarm. The same approach has been taken for experimental case study. Thus this scheme provides insight about the occurrence of leak and its severity and used to reduce false alarm when combined with another high precision localization scheme.

5. References

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