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DETERMINATION OF IMPORTANT FLOW CHARACTERISTICS FOR LEAK DETECTION IN WATER PIPELINES-NETWORKS

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ABSTRACT

The accuracy of a leak detection method depends greatly on the flow and leak parameters in a given pipeline. This paper gives some insight into the flow characteristics around simulated small leaks. The present computational fluid dynamics studies have indicated clear distinctive features in fluid pressure and fluid acceleration that can be used for the early detection of small leaks with the magnitude of 2.75L/min in water distribution pipelines. The CFD study is based on the steady state turbulent flow simulation which was carried out for different pressure lines in 4-inch (100m) ID pipe.

Based on the CFD simulation, it was found out that the pressure gradient in the vicinity of the leaks are quite large, hence a leak detection method based on pressure gradient measurement is proposed. In addition these simulation has shown axial flow acceleration in the flow centerline of the pipe have remarkable gradient which offers another leak detection method based on the use of accelerometer.

INTRODUCTION

Water is essential in the everyday activities of living things (both plants and animal), therefore there is need for constant supply of pure and portable water to the populace. For countries that depend on water distribution networks, water scarcity is their prevailing challenge; also challenging is the assurance of supply of uncontaminated water. To ensure these objectives, a distribution source must be close to 100% efficient in their water distribution which means that actual water supplied from source must be available at the delivery points. For such a system, a leak-free distribution is required which ensures that there is no unintentional supply from the network and there is no unintentional introduction of substance into the network. A proper monitoring of health of pipe and damage detection and control must be in place.

NOMENCLATURE

ρ	[kg/m^3]	Density
R	[m^2/s^4]	Reynolds stresses
μ	[Pa/s]	Dynamic viscosity
ε	[m^2/s^3]	Turbulent dissipation rate
k	[m^2/s^2]	Turbulence kinetic energy
u, v, w	[m/s]	Components of velocity
a	[m/s^2]	Acceleration
P	[Pascal]	Pressure
g	[m/s^2]	acceleration due to gravity
Q	[L/min]	Flow rate
δ	[-]	Delta function
Subscripts		
x,y,z	[m]	Position coordinates
i, j	[-]	Vector notation for coordinates
t	[-]	Turbulence

Monitoring the health of a pipeline network includes tasks such as determining the current roughness parameters of pipes, identifying leakages and blockages, etc. [1]. Leaks can account for, on average, 10,000 gallons of water wasted in the home every year, which is enough to fill a backyard swimming pool [2]. As a result, pipe damage control and water distribution management have become high priorities for water utilities and authorities because there were greater understandings of the economic, social, and environmental costs associated with water losses. In many water distribution systems, a significant amount of water is lost due to leakage from distribution pipes, to reduce this water loss, system operators conduct systematic programs to locate and repair leaks [3]. With the global awareness on cobbling the devastating effects of leaks in water distribution networks, studies are being carried out on daily basis on optimizing the method of these leaks detection for early detection and control. Several methods have been developed for -experimental studies, field works and simulation/ computational works –the detection, several devices have been developed for pipe damage detection in water distribution networks among which is Acoustic leak detection equipment-listening rods, aqua phones, hydrophones, etc.-, leak noise correlators.

Several mechanisms are being used in detection of pipe damages and leakages. The mechanism utilizes the advantage that flow in pipes exhibit special properties at the point of leaks among which are, flow rates, pressure and sound. These properties make it possible to detect leaks by applying a relevant measuring device. Among these devices are flow tracer, pressure transducers, accelerometer and others. In the earliest period when leak detection became inevitable, visual inspection of pipes was in vogue as used by most inspection officers but in later years when need for more accurate means of location of leaks in buried pipes were required, more sophisticated devices were developed. Among the first of these devices were the invention of [4] and that of [5]. These devices used the sonic signal from flow within the pipe to locate leakages. Many leak detection methods are being developed with all methods having different places of relevance and limitation, a full evaluation of all leak detection methods with merit and demerit can be found in the review of [6].

As it has been shown that an efficient leak detection methods depend greatly on the parameters upon which the developments are based, therefore a proper parametric studies gives leak detection model information for its design. With the recent global trend on computational fluid dynamics as an efficient means of prediction real parameters, many parameters can be looked into for efficient leak detection method once a complete solution of the flow equations is available. The present study undertook a computational work in attempt to identify the best possible leak detection parameter by studying the behavior of change in different parameters within the vicinity of leaks. Other conditions studied include the effect of line pressure and multi-leak coexistence in a single pipe.

MATHEMATICAL MODELING

For the present study, a pipe of 100mm diameter was taken as it represents the mostly used pipe in distribution networks with a length of 4m and 2 leaks were located at position 1m and 3m along the pipe. To represent the most experienced form of leaks in pipe, the leaks were approximated with a circular dimension. As observed from the review of literature, the major challenge of most models of leak detection that have been developed is ability to detect a very small leak in a long pipe as it was a limitation of the ITA method studied by [7], therefore the present study settled for small leakages of 2mm diameter. The 2D representations of the problem are provided in the figure 1 below.

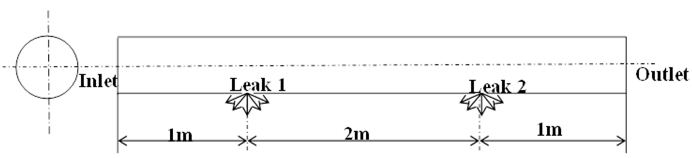

Fig.1 2-D representation of the problem

Governing Equations

The flow in pipe has a general axial symmetry configuration along the azimuthal direction, and this can be described by a cylindrical coordinate with all non-zero coordinates.

$$\frac{\partial u_j}{\partial x_j} = 0 \quad (1)$$

$$\frac{\partial(\rho u_i u_j)}{\partial x_j} = \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u'_i u'_j}\right) \quad (2)$$

Being a turbulent study, the above equations are known as Reynolds Averaging Navier Stoke equation. The simulation was carried out at constant density with the assumption that water is an incompressible fluid and flowing with Mach number of less than 0.3, also assuming a steady state condition. The choice of evaluation of the last term of equation 2 brought about model equation.

<u>The Standard k-ε Model:</u> this model made focus on the mechanism that affect turbulence kinetic energy [8]. The mechanism that affects the T.K.E being the turbulent viscosity is computed after which the Reynolds stresses are evaluated from Boussinesq relation

$$-\rho R_{ij} = \mu_t\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \frac{2}{3}\rho k \delta_{ij} \quad (3)$$

Alongside with continuity equations and two other momentum equations (3D), the standard k-ε model makes use of 2 transport equations for the turbulence kinetic energy and dissipation rate. These equations are given as:

$$\frac{\partial}{\partial x_i}(\rho u_i k) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + 2\mu_t E_{ij}.E_{ij} - \rho \quad (4)$$

$$\frac{\partial}{\partial x_i}(\rho u_i \varepsilon) = \frac{\partial}{\partial x_i}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_i}\right] + 2\mu_t E_{ij}.E_{ij} - C_2\rho\frac{\varepsilon^2}{k} \quad (5)$$

Where the constant employed are

C_μ=0.09; C_1=1.44; C_2=1.92; σ_k=1; σ_ε=1.3

$$\mu_t = \rho C_\mu \frac{k^2}{\varepsilon}, \qquad E_{ij} = \frac{1}{2}\left(\frac{\partial u_j}{\partial u_i} + \frac{\partial u_i}{\partial u_j}\right) \quad (6)$$

The combination of these equations makes 6 equations that were solved to establish all the parameters required in the study. These governing equations were discretized by a numerical scheme employing a control volume method and finite volume set of algebraic equations were obtained. These equations were solved by a commercial CFD package, employing the SIMPLE algorithm for handling pressure linkages with details in [9].

Boundary Conditions

To assume a real flow situation the following boundary conditions were taken with their corresponding justifications.

Inlet Boundary Condition: the velocity inlet boundary condition was imposed so has to comply with the direction of flow of supply through a pipe from a source. To avoid the effect of erosion in the pipe the velocity was taken to be 1m/s [6], which represent a flow rate of 7.85L/s which is line with the international standard of 2.5m/s maximum velocity in water pipe distribution

Outlet Boundary Condition: the pressure outlet condition is imposed so as to liken the simulation to the real condition that flow in pipes having specific pressure. This condition makes the result of the simulation viable to be used for design a model for real situation. Values of gauge pressure ranging from 1bar to 5bars were used in this study.

Leak Outlet condition: the pressure outlet conditions were impose on these boundaries as the leaks were expected to be exposed to atmospheric condition in which zero gauge pressures were set. This represents the condition experienced with a sprinkler/emitter intentionally created in a pipe network.

Pipe walls: the pipe wall was treated with the standard wall condition of no slip as it is conventional for flows through a stationary pipe with a predefined roughness.

Mesh Independency Test

For the mesh independence of the solution, 3 meshes were used and simulations were done under the above given boundary conditions with the pressure outlet condition set at 2bars gauge pressure. The properties of the mesh alongside the leak flow rates are given in the Table 1.

Table 1: Mesh Independence study
(Line pressure = 2bars, average velocity =1m/s)

Mesh	Number of Cells	Leak1 flow rate (kg/s)	Leak2 flow rate (kg/s)
M1	174,320	0.0434	0.0436
M2	907,759	0.0458	0.0457
M3	2,039,666	0.0464	0.0465

Considering the results in the Table 1 and assuming mesh independency with less that 2% in the predicted leak flow rate, therefore the solution obtained using mesh two are mesh independent and hence this mesh is used for the rest of the computation

RESULTS AND DISCUSSIONS

Model Validation

The present study was carried out with different working pressures so as to validate the result with the experimentally available data and theoretical calculation of flow through an orifice. In recent researches it was found that the rate of flow from a water distribution depends on the working pressure contrary to the past view given in the orifice equation represented as in the equation below

$$Q = C_d A\sqrt{2gh} \qquad (7)$$

In a broader view of the equation, the flow rate, Q can be represented in term of the working as pressure with equation (8) as given in most of the literature cited in this study:

$$Q = CP^{\alpha} \qquad (8)$$

Where the C is the leakage coefficient of discharge and P is the working pressure in the pipe while α is the leak exponent. Theoretical orifice value for round holes was found to be 0.5. In the experiment carried out by [10], the leakage exponential for steel and uPVC pipes with round hole was found to be 0.52. Similarly, in the work of [11], he described modeling of leak in EPANET with the above equation, and that the pressure exponent is assigned to be 0.5. The flow rates through the leaks were collected for the model and presented in Table 2 below. These results are shown in figure 2 and figure 3 with addition of best fitting curve represented by equation (9).

$$Q = 0.0061P^{0.5007} \qquad (9)$$

This result went in agreement with the experimental results given in the literatures with the pressure exponent 0.5007. In addition, the leak coefficient is of the order represented by Torricelli’s equation of orifice.

Table 2: Leak flow rate for different line pressure at velocity 1m/s through a straight pipe

Pressure (bars)	Leak1 flow rate(L/min)	Leak2 flow rate(L/min)
1	1.946992	1.93987
2	2.754918	2.745224
3	3.374982	3.363153
4	3.897731	3.884152
5	4.358291	4.343148

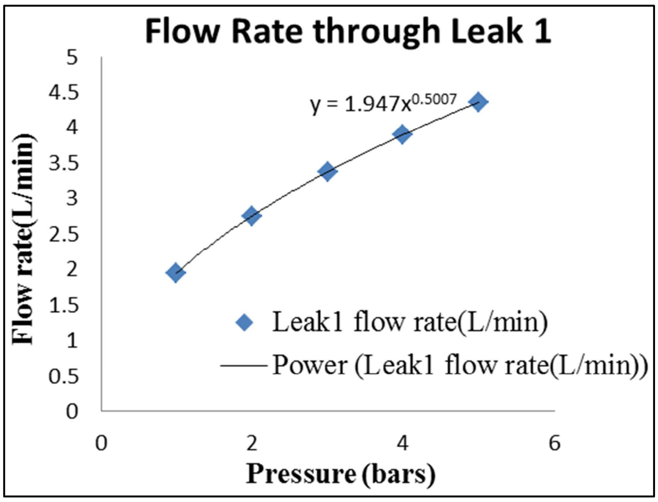

Fig.2 Plot of flow rate of leak 1 against line pressure.

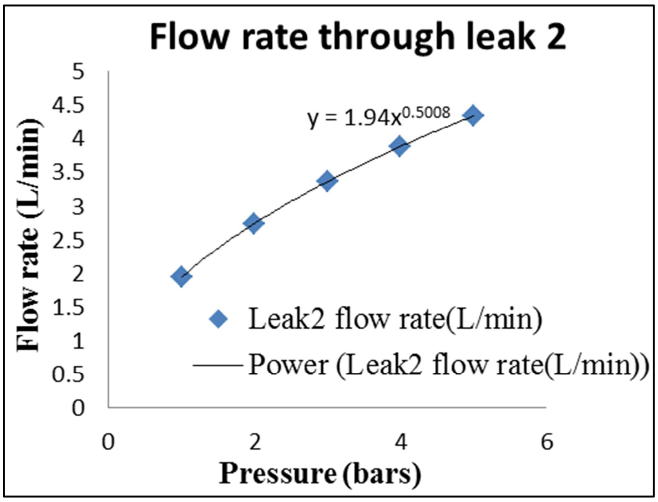

Fig.3 Plot of flow rate of leak 2 against line pressure.

Pressure Behavior within the vicinity of leaks

To study the behavior of pressure within the vicinity of the leaks, a straight pipe with 1bar pressure line was considered. A faraway observation of the contour plot depicts that the pressure remain constant in the pipe as shown in the contour plot in fig.4, a close up look in the vicinity of the leaks reveals a localized gradient toward the leak as shown in fig.5.

For better understanding of the pressure variation along the pipe, plots of pressures along some lines through the length of the pipe were made. A plot of the pressure along the line 2mm below the leaks in figure 6 shows the pressure is fairly constant with variation predominantly between 2.0and 2.01bars but there are clear distinctions a few millimeters before the leaks with a sudden great reduction and recovery to fairly constant state, this indicates that steady state pressure close to the leak deviates greatly with magnitudes detectable by a pressure sensor. At a distance of 10mm below the leak, the effect of the pressure change in the vicinity of the leaks became slightly dispersed as shown in figure 7. From these it can be shown that the effect of the presence of leak on pressure variation becomes harder to be noticed as the transducer moves away from the leaks. Following the unpredictable pattern of leaks and damages occurrence, the best position for a transducer to be placed to have an even evaluation of the surfaces of the pipe is the center. A plot of the pressure along the centerline of the pipe shows a fairly noticeable kink in the leaks vicinity as shown in the figure 8. The changes are better explained with Bernoulli equation as due to the velocity increment as a result of addition flow rate in the direction the leaks. To better appreciate the causes of the sharp pressure change at the vicinity of the leaks, the vectors of the magnitude of the velocities around the leakages were observed with high gradient toward the leak plane. These show that the velocity magnitude increases relatively as one move towards the leaks and dies away as one move away from the leak along the pipe. The factor that determines the effectiveness of any pressure transducer in leak monitoring is the ability to detection irrespective of position of the leaks, thus it is required to get a parameter that gives a high magnitude of distinction in the vicinities of the leaks along the centerline.

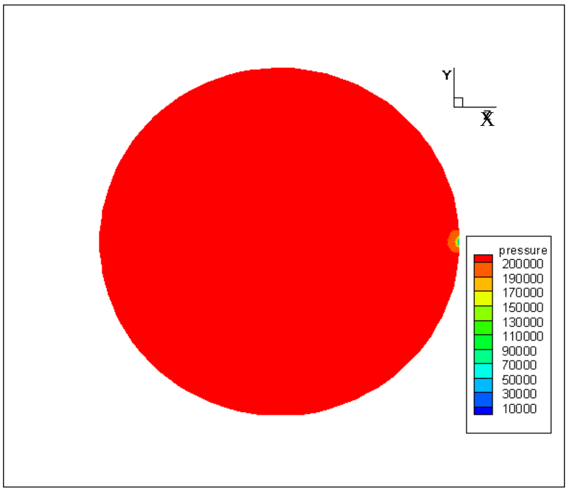

Fig.4 Faraway view of contour of pressure on plane across leak1 (V=1m/s P=2bars)

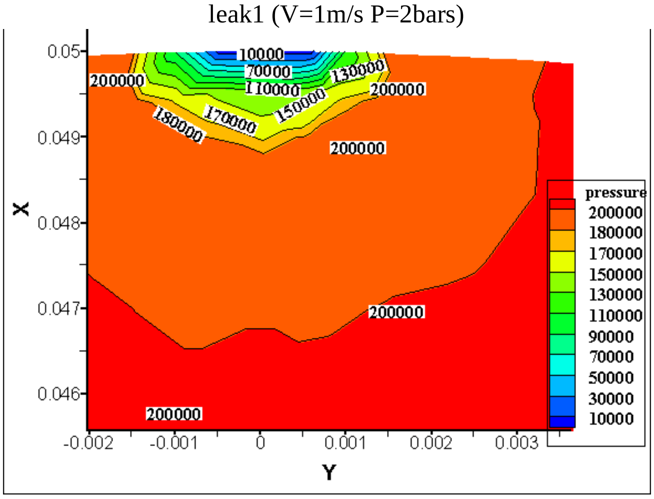

Fig.5 close up view of contour of pressure in vicinity of leak1 (V=1m/s P=2bars)

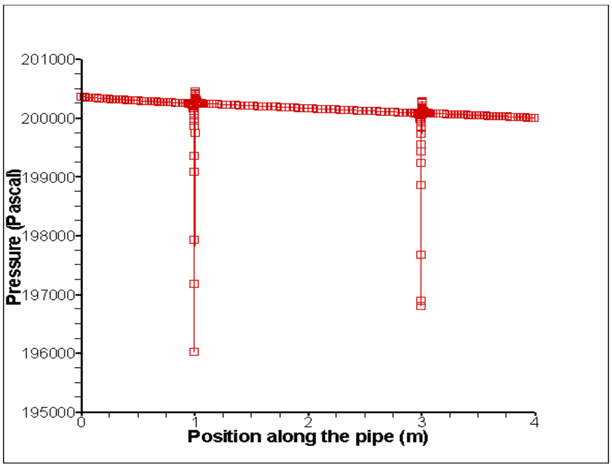

Fig.6 Pressure along line 2mm below the leaks (v=1m/s P=2bars)

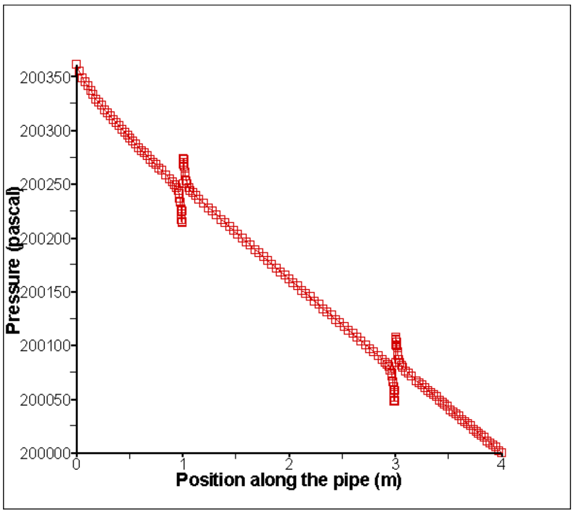

Fig.7 Pressure along line 10mm below the leaks (v=1m/s P=2bars)

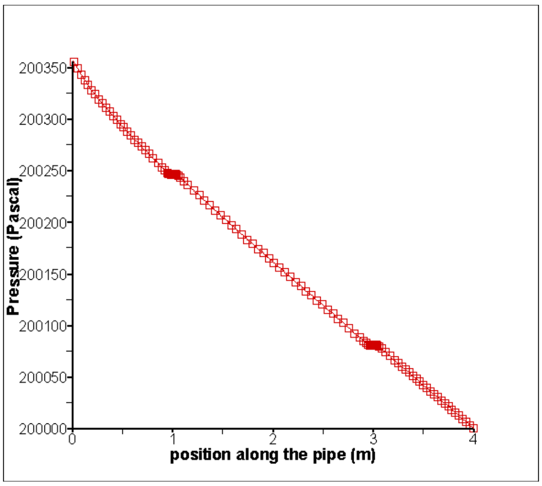

Fig.8 Pressure along line the centerline (v=1m/s P=2bars)

Effect of Pressure gradient

Measurement of pressure gradient in a pipe is amounting to either having two pressure transducers taking measurement along the pipe simultaneously or a single transducer taking two differently reading sequentially along the pipe while studying the difference in the measurements. Considering the pressure gradient across the pipe cross-section, there appears to be a wider localization of the pressure values coupled with higher ranges of values compared to that of the pressure. The plot shown in figure 9 represents the effect of the leaks on the pressure gradient along the pipe centerline with the both the maximum and minimum values close to the leaks on the either sides. As observed with the pressure, the closer the transducer to the leak the more the effect is felt. The pressure gradient 2mm below the leaks gave a clear distinction in the vicinity of the leaks with about 25KPa/m around the leaks, this is a very good value for monitoring despite the leaks being small with a flow rate of 2.72L/min. Along the centerline the pressure gradient gave a wider distinction of the leaks vicinities with the gradient forming local maxima at the leak points with the values being limited to the range of -10 to 100Pa/m within the vicinity of the leaks. This sounds more appropriate than the pressure measurement as well-defined changes is noticed in the leaks vicinity also this eliminates the inaccuracy that may set in as a result of sensor resolution and threshold value and the correlation of the result can be handled with the data acquisition setup.

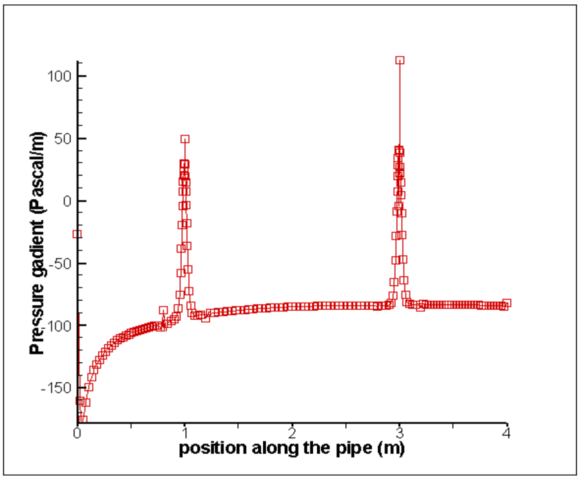

Fig.9 Pressure gradient along the centerline (v=1m/s P=2bars)

Study of Acceleration around the leak

Another parameter for leaks detection is the acceleration. A study on the acceleration of the flow in the pipe was carried out to evaluate the behavior of leaks vicinity acceleration in attempt to know the ability of accelerometer as a transducer in water pipe leak detection. The following equations were modeled into the solver to define the acceleration parameter in the three axes and the overall magnitude of acceleration.

$$a_x = u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z} \quad (10)$$

$$a_y = u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z} \quad (11)$$

$$a_z = u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z} \quad (12)$$

$$a = \sqrt{(a_x^2 + a_y^2 + a_z^2)} \quad (13)$$

The three acceleration parameters are required if a three axial accelerometer is to be used for the measurement and thus these three parameters were observed.

The acceleration value from the inlet of the pipe remained fairly constant with magnitude of 0 due to non-disturbance relative to x-axis along the pipe at 2mm below the leaks until approaching the leaks where there is a rapid increment up to 9000m/s^2 in vicinity of leak 1 and a quick recovery from it to fairly constant value was noticed till vicinity of leak two where a similar hike was noticed of slightly reduced magnitude. These clear distinctions were noticed for the plots of the x-acceleration at other distances below the leaks. It is noted that similar to what was observed with the pressure, the magnitude of the distinction reduces as the lines of examination move away from the leaks and a plot to evaluate the effect of the x-acceleration along the center of the pipe shows a clears definition of 0.08m/s^2 and before the leaks and -0.08m/s^2 after the leaks to recovery as shown in figure 10 below. This represents a clear definition for an accelerometer to pick up despite being along the centerline.

A similar distinction is observed with the acceleration in y–direction with a wider evident of presence of the leaks as the definitions occur in wider vicinity but with a relatively lower magnitude. This is due to the nature of the velocity profile in y-direction as the leak flow rate does not directly affect the y-acceleration as it does on the x-acceleration

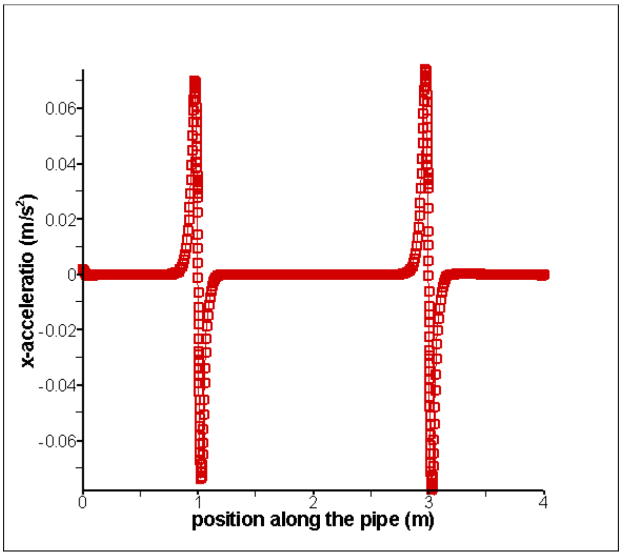

Fig.10 x-component of acceleration along the centerline (v=1m/s P=2bars)

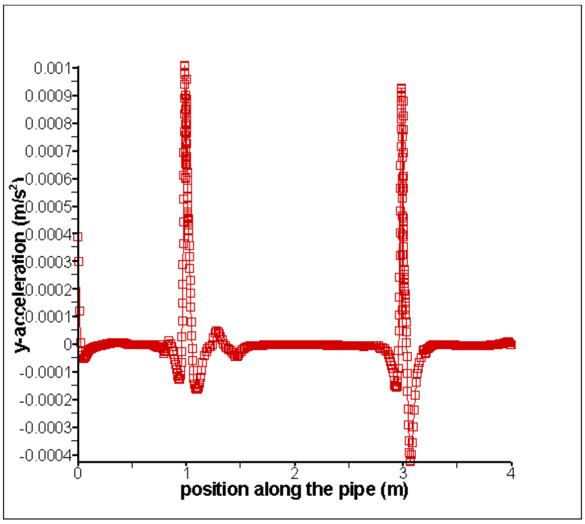

Fig.11 y-component of acceleration along the centerline (v=1m/s P=2bars)

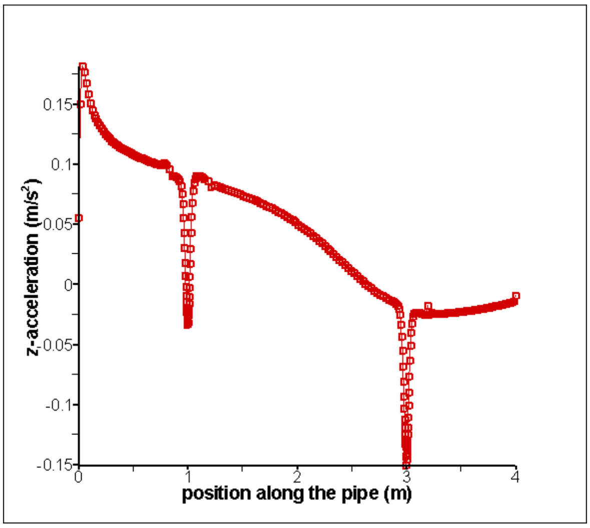

Fig.12 z-component of acceleration along the centerline (v=1m/s P=2bars)

The plot in figure 11 shows the y-acceleration along the center of the pipe. In z-direction a similar distinction is noticed and a wider displacement along the centerline owing to disturbances along the center with respect to z-directions with relatively high magnitude of hike at the points of the leaks.

The study of the acceleration within the pipe shows that a well-defined distinction is expected in one of the three direction of the vector irrespective of the position of the leaks and the orientation. Thus it can be deduced that a three axial accelerometer picks ups a the existence of leaks with the definition in one of it axes of measurement depending on the location and orientation of the leaks and therefore can be reliable in early leak detection of unpredictable nature.

CONCLUSIONS

Three-dimensional CFD turbulent flow calculations had been carried out to investigate the flow characteristics close to simulated small leaks in water distribution pipelines. The main objective of the study is to identify clearly observable trends in the flow variables which can be adopted for reliable and robust leak detection methods. The CFD Simulations were carried out using the commercial CFD package with scrutinized computational mesh in order to produce more accurate results. The simulations results were validated against experimental and theoretical orifice equation; and an excellent agreement was found. In terms of reliable leak detection methods two variable had been identified. The first variable that showed clear effect of the leak is the pressure gradient in the vicinity (within 2 leak diameters). The second clearly observable variable affected by the leaks is the flow acceleration. Lab experiments are being setup to implement these methods for leak detection.

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