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FUZZY INFERENCE BASED LEAK ESTIMATION IN WATER PIPELINES SYSTEM

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Abstract

Pipeline networks are the most widely used mode for transporting fluids and gases around the world. Leakage in this pipeline causes harmful effects when the flowing fluid/gas is hazardous. Hence the detection of leak becomes essential to avoid/minimize such undesirable effects. This paper presents the leak detection by spectral analysis methods in a laboratory pipeline system. Transient in the pressure signal in the pipeline is created by opening and closing the exit valve. These pressure variations are captured and power spectrum is obtained by using Fast Fourier Transform (FFT) method and Filter Diagonalization Method (FDM). The leaks at various positions are simulated and located using these methods and the results are compared. In order to determine the quantity of leak a 2 × 1 fuzzy inference system is created using the upstream and downstream pressure as input and the leak size as the output. Thus a complete leak detection, localization and quantification are done by using only the pressure variations in the pipeline.

Keywords:

Pipeline Detection, Spectral Analysis, FFT, FDM, Fuzzy Inference System (FIS)

1. INTRODUCTION

Leaks in piping systems pose a major operational problem around the world. Leaks may occur due to poor quality and defective pipe materials, pipe breaks resulting from poor workmanship, operational errors such as excessive pressure, closing or opening valves rapidly, corrosion, leaking fittings and accidental or deliberate damage to fixtures [2]. This results in economic loss, safety and environmental issues. Detecting, locating and repairing these leaks become a painstaking task. Different methods for leak detection have been developed.

Leak detection and localisation in the water distribution system based on pressure change and/or discharge has been as a vital research topic both for academics and industry. The current methods can generally be divided into two large groups- internal and external. Of which, flow analysis, mass balancing, analysis of pressure points, fibre optic sensors, and leak detection based on neural networks techniques are some of the promising methods used for leak detection.

In addition to these two groups, the transient-based analysis methods are in recent trends. The papers developed by different authors [3]-[6], have used transient analysis; this analysis requires a huge quantity of real-time data and hence, it has a high computational cost or, in some circumstances, it is difficult to adopt. Other authors [7]-[8] have developed and experimented methods based on spectral response analysis of water networks.

W. Mpesha [9] has developed a method that uses the frequency response which is obtained by analyzing steady-oscillatory flow in a pipe system. An oscillating valve located at the end of the pipeline is used to produce steady oscillatory flow in the system. The steady-oscillatory flow is analyzed in the frequency domain by the transfer matrix method and a frequency response diagram is developed from which leaks are detected based on the pressure and discharge amplitude peaks. W. Mpesha et al. [10] analyzed the transient flow, produced by opening or closing a valve, by time domain characteristics and transformed the results into the frequency domain by the fast Fourier transform. This method is used to develop a frequency response diagram at the valve end. The frequency response diagram of a system with leaks has additional resonant pressure amplitude peaks (the secondary pressure amplitude peaks) that are lower than the resonant pressure amplitude peaks for the system if there were no leaks (primary amplitude peaks). The location of a leak is determined from frequencies of the primary and secondary pressure amplitude peaks and the leak discharge is determined from the maximum and minimum discharge amplitudes.

Lay-Ekuakille et al. [2] proposed filter diagonalization method (FDM), for tackling FFT limitations, and its use in detection of leak in complex pipeline with the presence of bends, external noise and environmental vibrations. This paper implements the same algorithm of the FDM technique for leak detection in the laboratory pipeline system and for determining the leak size, a 2 × 1 fuzzy inference system with the difference between upstream pressure during leak and during normal condition as one input and the same at the downstream as another input and actual leak size as output is considered.

This paper is organized as follows: in section 2 the laboratory pipeline setup is explained, in section 3 spectral analysis technique used for leak detection and localization technique is discussed, the section 4 details about the fuzzy inference system used for leak size determination and about the optimization of the membership function of the FIS. The results obtained are discussed in the section 5 and the paper is concluded in section 6.

2. EXPERIMENTAL SETUP AND DATA ACQUISITION

As indicated in Fig.1, the architecture of the laboratory setup includes the following units: tank, cast iron pipe, ball valves, Rosemount 2051 DPT, and Honeywell DPT. Leak is created by opening the tapings near the flow nozzle, venturi and elbow as encircled in the Fig.A1 and Fig.A2. These leakage positions are denoted as position 1, position 2, and position 3 respectively. The actual distance of the leak position from the downstream orifice to position 3 (elbow) is 544 cm, to position 2 (venturi) is 607 cm and that to position 1 (flow nozzle) is 760 cm. The total length of the pipeline is 1506 cm. In order to obtain the location of the fault the ball valve in downstream end is opened and closed manually in a sinusoidal and square wave fashion. The resultant variation in pressure are measured by the DPT and further processed by FDM and FFT. The leakages are simulated by opening and closing one of the water taps available at the positions 1, 2 and 3. The data are acquired by LabVIEW software.

3. METHODOLOGY FOR LEAK DETECTION, LOCALIZATION AND QUANTIFICATION

3.1 SPECTRAL ANALYSIS FOR LEAK DETECTION

With any sudden change in the flow or pressure, for example closing or opening a valve or stopping a pump, a transient pressure wave is produced, which propagates along the pipeline. Any change in the physical structure of the pipeline system, such as a change in section, junction, resistance or leak alters the wave [1]. The wave is partly reflected, partially transmitted and some of it may be absorbed and thus altering systems flow and pressure response. The speed that the wave travels depends on characteristics of the pipe and fluid. As a result, each water distribution system will have different transient behaviour that depends upon the various devices within the system.

When leak occurs the difference of pressure between the outside and the inside of the pipe causes sudden fluid loss and the pressure of the leak point drops suddenly hence a rarefaction (negative pressure) wave is produced in the pipeline. Pressure transducers can be used to measure the pressure with respect to time. Transients propagate back and forth throughout the network and therefore, can be shown to carry information of leaks or features within the pipeline system. Besides its potential low cost and non-intrusive nature, this technique has the potential to locate leaks at greater distances from a measurement point than is currently possible. Practically, performance of each leak detection method varies considerably depending on the vendors, pipeline operating conditions and quality of the hardware/instrumentation system available. It is shown that there is no method, which is good for all the required attributes. However, when there is strong noise present in the pressure measurement records or when a leak is too small or too slow, it can obfuscate the leak reflection signals. The main aim of all transient leak detection methods is the same – to extract as much as possible the information from the measured transient trace in order detect and locate the presence of a leak. As mentioned, a leak affects the transient by increasing its damping rate and creating reflected signals in the resultant trace. Therefore, identification and quantification of these effects is paramount of all transient leak detection and location technique.

3.1.1 Fast Fourier Transform (FFT):

A Fourier transform converts time (or space) to frequency and vice versa, and an FFT is a computer algorithm used to rapidly compute such transformations. A Fast Fourier transform is an algorithm to compute the Discrete Fourier transform (DFT) and it's inverse. There are many different FFT algorithms involving a wide range of mathematics, from simple complex-number arithmetic to group theory and number theory (Fourier transform).

3.1.2 Filter Diagonalization Method (FDM):

FDM is one of the most promising methods used in processing nuclear magnetic resonance (NMR) signals. FDM is a nonlinear, parametric method for fitting time-domain signals with summation of sinusoids. It was originally designed by Wall and Neuhauser [11] to process time autocorrelation functions in quantum dynamics calculations and then reformulated and applied to spectral analysis of general experimentally measured time signals by Mandelstham [12]. In the frame of FDM, the resolution is not limited by the Fourier transform uncertainty principle. Good signal quality (e.g., high signal-to-noise ratio, perfect line shape, etc.) can be effectively converted into high resolution. In this paper the FDM Algorithm proposed by Lay-Ekuakille et al is used for determining the power spectrum.

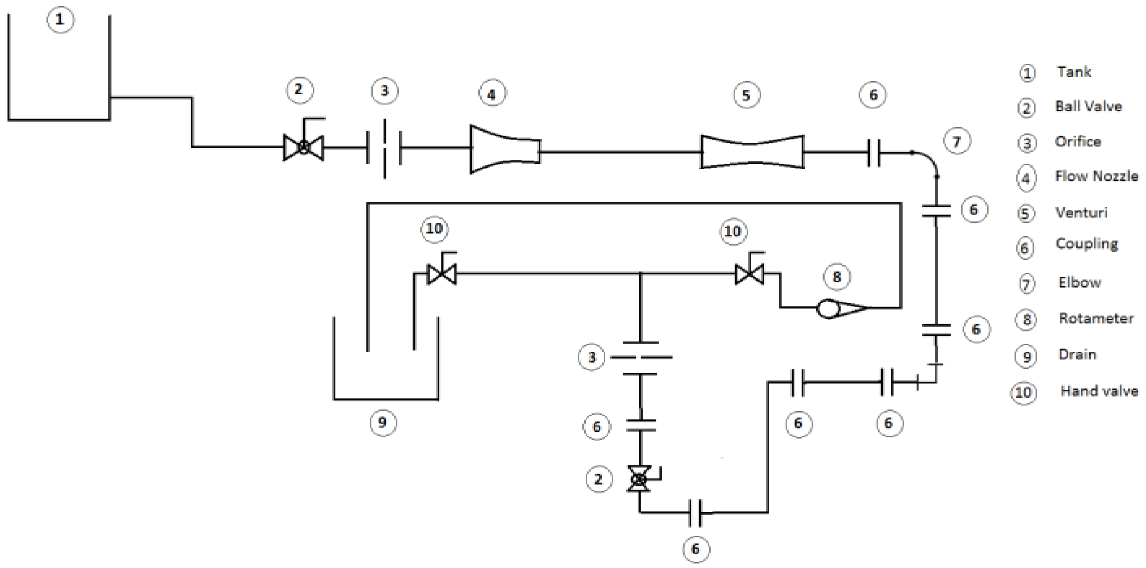

Fig.1. P and I Diagram of the experimental setup

3.2 FUZZY INFERENCE SYSTEM FOR LEAK QUANTIFICATION

Fuzzy inference systems (FIS) are widely used for process simulation or control. They can be designed either from expert knowledge or from data. They can be helpful to achieve classification tasks, offline process simulation and fault diagnosis, online decision support tools and process control. The strength of FIS relies on their twofold identity. On one hand, they are able to handle linguistic concepts and on other hand, they are able to perform nonlinear mappings between inputs and outputs.

3.2.1 Membership Function Optimization:

By optimizing the FIS Membership Functions (MFs) with respect to a performance criterion, the resulting FIS can lead to an optimal solution with respect to that criterion. Dan Simon [13] has proposed the use of Extended Kalman filter in optimizing the width of the membership function. In his paper he has viewed the optimization of fuzzy membership functions as a weighted least-squares minimization problem, where the error vector is the difference between the fuzzy system outputs and the target values for those outputs by using triangular MF with symmetrical triangles initially.

In our application we have considered a fuzzy system having the difference in pressure during normal and leak condition both in the upstream and downstream ends as inputs and the actual leak size as output, the output is denoted as L. The target vector for the fuzzy system outputs is denoted as d and expressed as in Eq.(1). $h(k)$ represents the actual outputs at the k^{th} iteration of the optimization algorithm and expressed as in Eq.(2).

$$d = [d_1 \,..........\, d^L]^T \tag{1}$$

$$h(k) = [h_1(k) \,..........\, h_L(k)]^T \tag{2}$$

In order to cast the membership function optimization problem in a form suitable for Kalman filtering, we let the membership function parameters constitute the state of a nonlinear system, and we let the output of the fuzzy system constitute the output of the nonlinear system to which the Kalman filter is applied.

Let we consider that our fuzzy system has μ fuzzy sets for the first input, v fuzzy sets for the second input, and k fuzzy sets for the output. We denote the centroid and half-width of the i^{th} fuzzy membership function of the j^{th} input by c_{ij} and b_{ij}, respectively, and we denote the centroid and half-width of the i^{th} fuzzy membership function of the output by γ_i and β_i, respectively. The state of the nonlinear system can then be represented as in Eq.(3).

$$X = \left[b_{11}c_{11} \ldots b_{\mu 1}c_{\mu 1}\; b_{12}c_{12} .. b_{v2}c_{v2}\; \beta_1\gamma_1 \ldots \beta_k\gamma_k\right]T \tag{3}$$

The vector x thus consists of all of the fuzzy membership function parameters arranged in a linear array. The nonlinear system model to which the Kalman filter can be applied is given in Eq.(4) and Eq.(5).

$$x_{n+1} = x_n \tag{4}$$

$$d_n = h(x_n) \tag{5}$$

where, $h(x_n)$ is the fuzzy system's nonlinear mapping between the membership function parameters and the single output of the fuzzy system.

4. RESULTS AND DISCUSSION

4.1 DETERMINATION OF LEAK LOCATION

The downstream pressure is recorded by varying the downstream valve in a square wave fashion for a time period of 20s for various leak positions. The leak position 1 is near flownozzle, leak position 2 is near venturi and leak position 3 is near elbow. The Fig.2-Fig.5 shows the downstream pressure variation with respect to time while varying the valve at a time period of 20s in a square wave manner without leak and with leak at positions 1, 2 and 3 respectively.

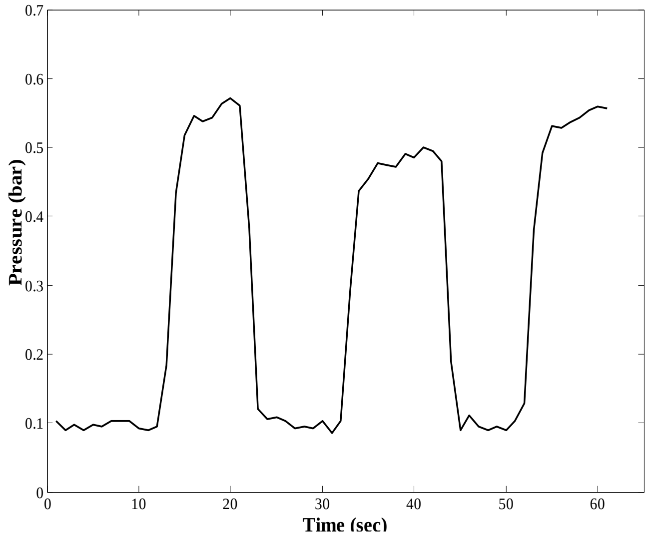

Fig.2. Downstream pressure variation without leak

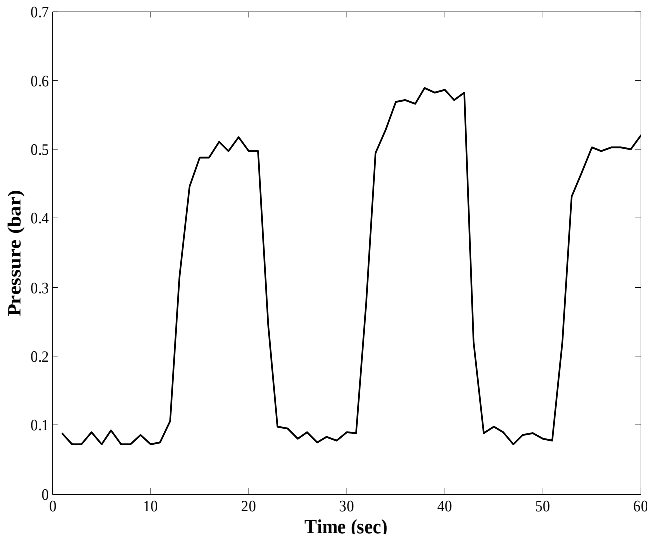

Fig.3. Downstream pressure variation with leak at position 1

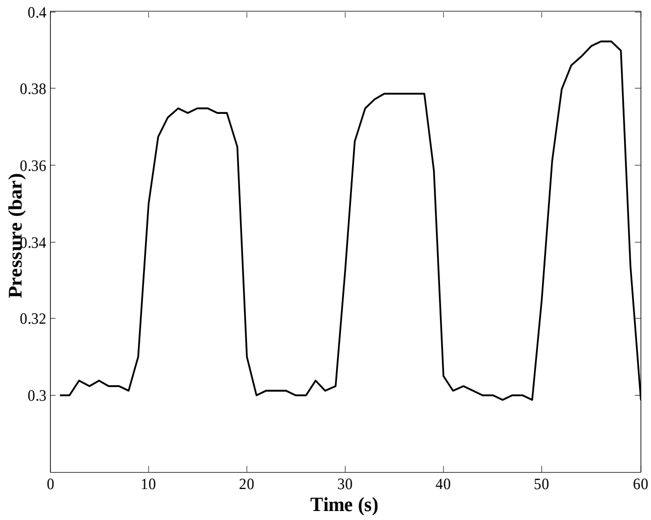

Fig.4. Downstream pressure variation with leak at position 2

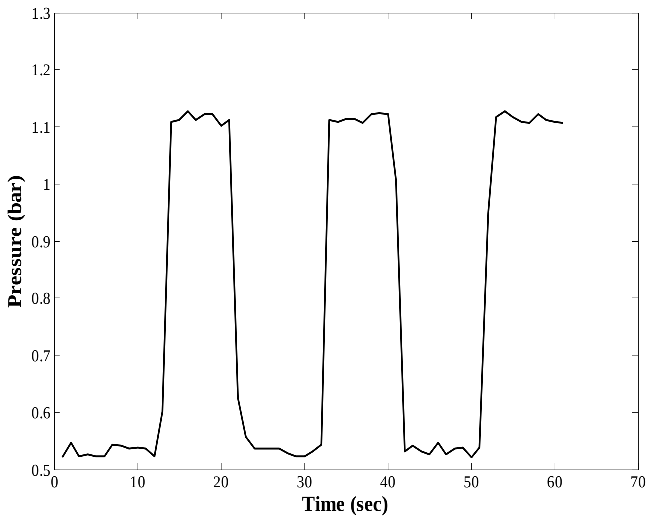

Fig.5. Downstream pressure variation with leak at position 3

The Fig.6-Fig.9 shows the downstream pressure variation with respect to time while varying the valve at a time period of 10s in a sine wave manner without leak and with leak at positions 1, 2 and 3 respectively.

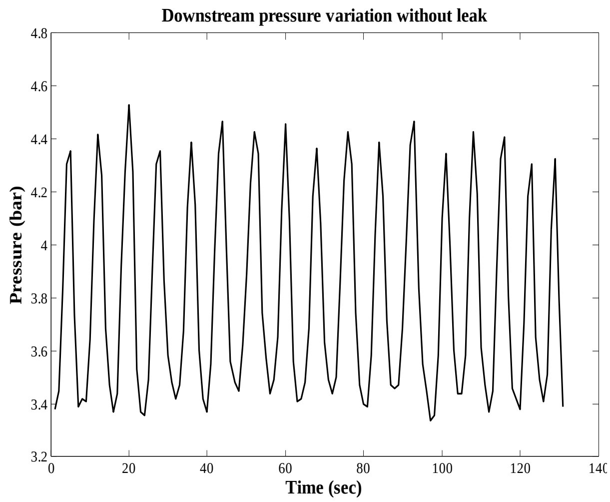

Fig.6. Downstream pressure variation without leak (sine wave)

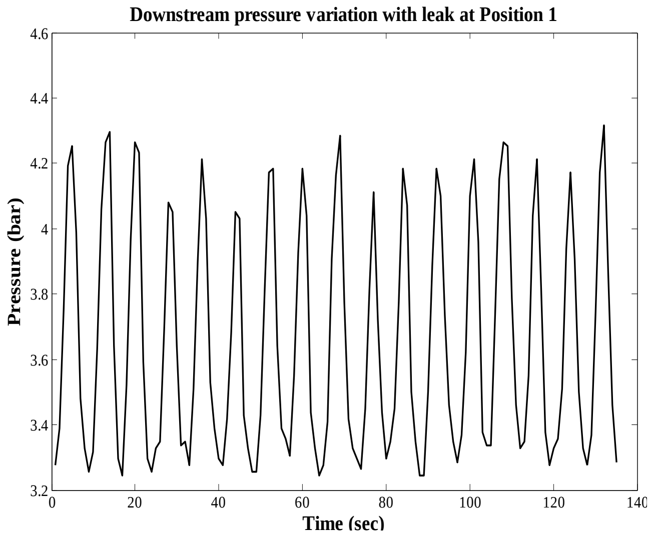

Fig.7. Downstream pressure variation with leak at position 1 (sine wave)

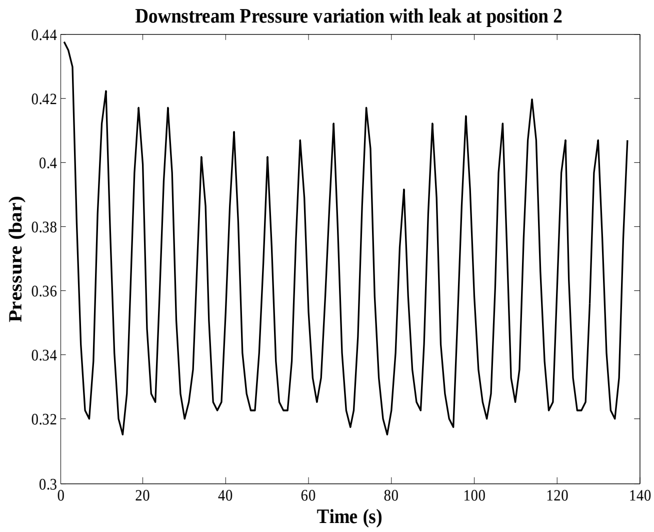

Fig.8. Downstream pressure variation with leak at position 2 (sine wave)

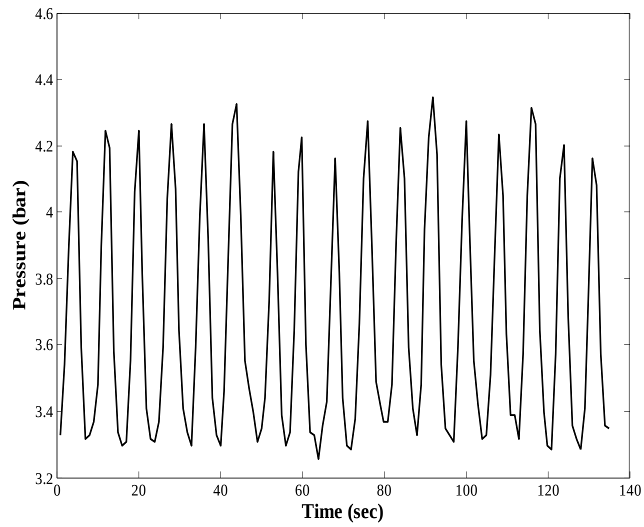

Fig.9. Downstream pressure variation with leak at position 3 (sine wave)

After detecting leaks by means of FFT algorithm, the same procedure is repeated using the FDM technique. Tests are carried out on the same acquired signals, allowing a comparison to be made between the commonly used FFT and the application based on FDM. An attempt to overcome FFT limitations for spectral response analysis, namely due to the presence of bends, external noise and environmental vibrations, quality of pipeline in terms of friction coefficient, etc. has to be done. Adapting FDM is one of the possible solutions in order to preserve resolution and precision in recovering leak detection [2]. The power spectrum obtained by the above mentioned FDM algorithm for different leak positions is shown in the following Fig.10. By using the amplitude of the spectrum from the graph the leak location is calculated by fitting a straight line using linear regression method. The results were tabulated as shown in the Table.1 and Table.2.

The obtained data were averaged, and a calibration straight line was traced out for interpolation with the following Eq.(6).

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

where, y is the leak location and x is the amplitude of the power spectrum obtained from the FDM algorithm.

The above equation is obtained using linear regression and calculated as m = -6.16 and c = 869.83

Table.1. Leak position obtained using downstream pressure while varying in square wave fashion

Leak Position	**Actual Leak Position (cm)**	**Leak Position using FDM (cm)**	**Leak Position using FFT (cm)**
Leak at position 1	760	760.55	759.12
Leak at position 2	607	576.96	573.63
Leak at position 3	544	534.54	530.3

Table.2. Leak position obtained using downstream pressure while varying in sine wave fashion

Leak Position	**Actual Leak Position (cm)**	**Leak Position using FDM (cm)**	**Leak Position using FFT (cm)**
Leak at position 1	760	761.1	756.45
Leak at position 2	607	596.2	593.9
Leak at position 3	544	541.5	560.24

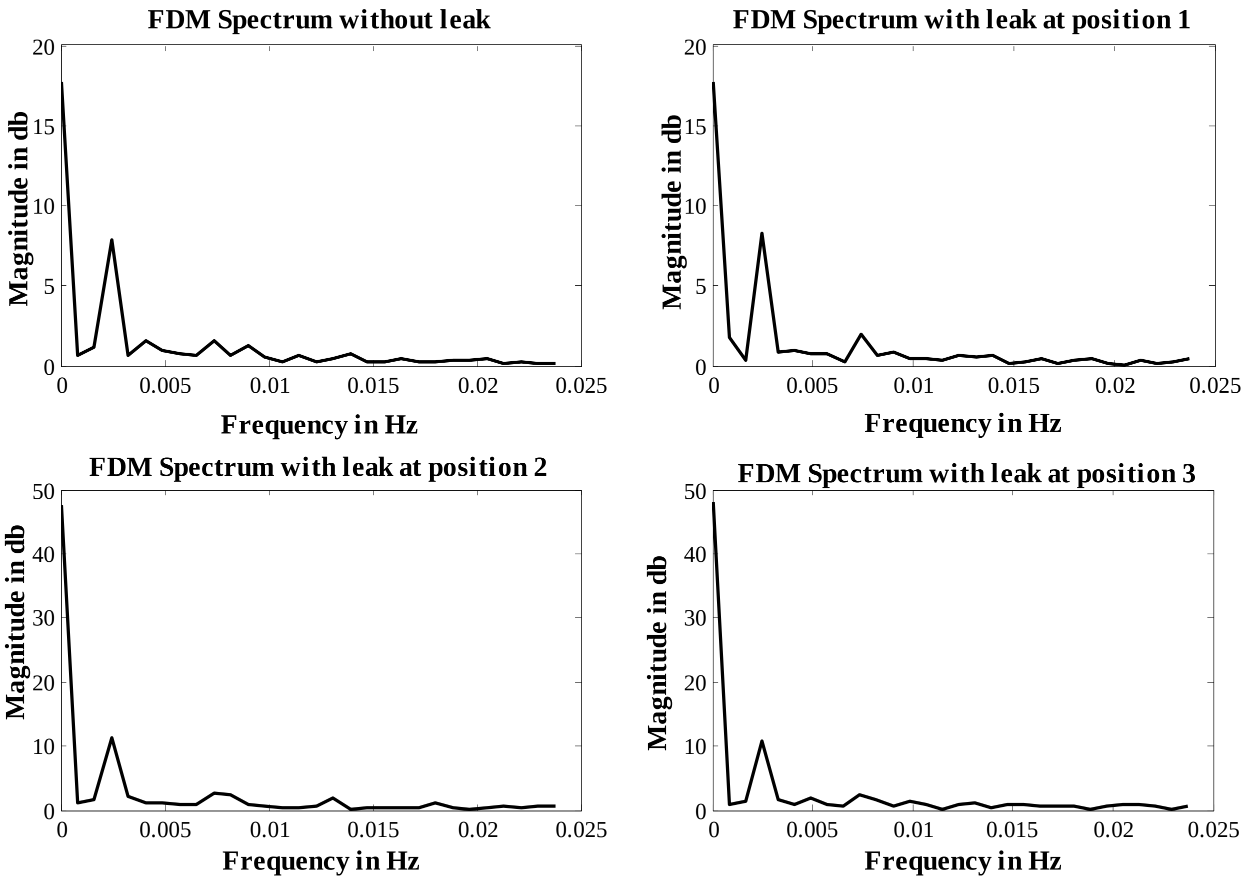

Fig.10. FDM Spectrum obtained for various position of leak

4.2 DETERMINATION OF LEAK SIZE

Upstream and downstream pressure variations for different leak sizes at positions 1, 2 and 3 were recorded using the LabVIEW software. Fig.11 to Fig.13 shows the pressure variations during different leak size and leak positions. From these figures it is evident that there is a variation in pressure at the upstream and downstream side depending upon the severity of leak. Hence the difference in pressure during normal and leaky condition at upstream and downstream ends are taken as the two antecedent attributes for developing the fuzzy inference system and the consequent attribute being the corresponding leak size. Therefore a two input and a single output fuzzy inference system is designed with the above mentioned attributes.

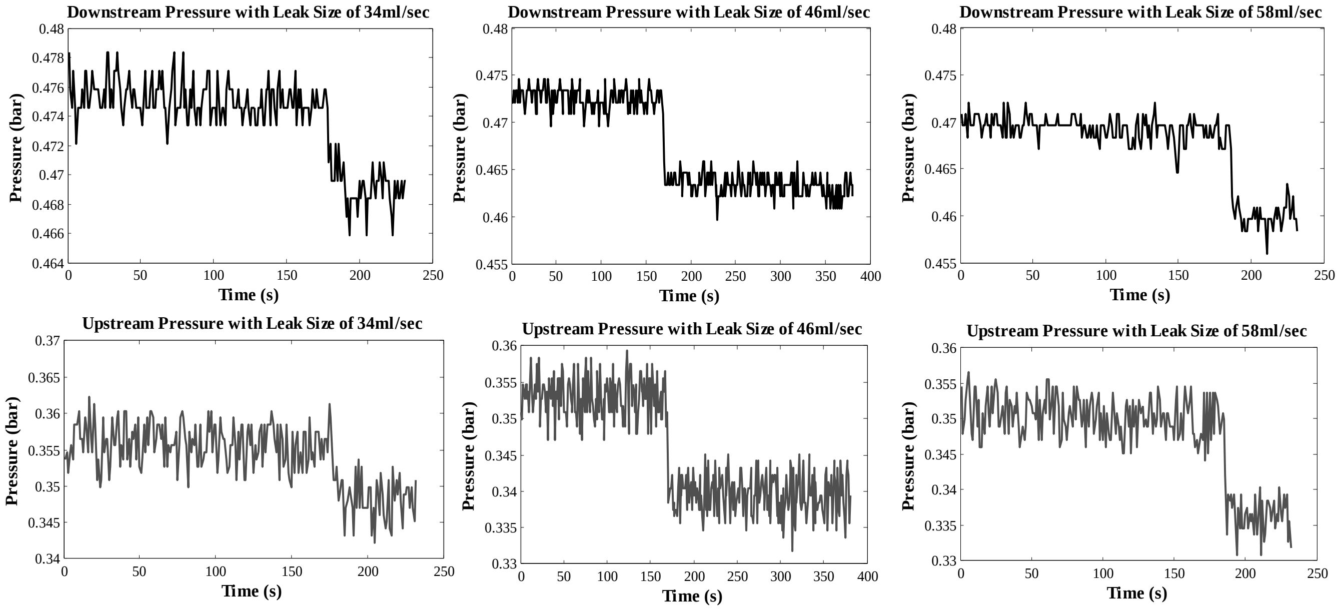

Fig.11. Upstream and downstream pressure variations for various leak size at position 1

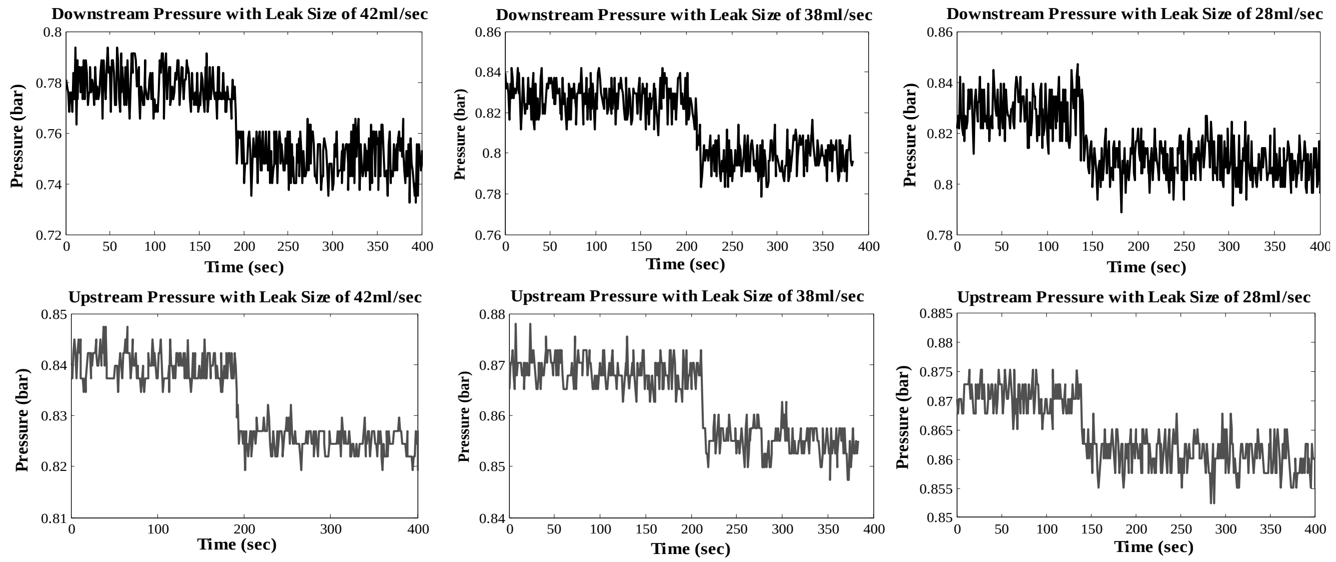

Fig.12. Upstream and downstream pressure variations for various leak size at position 2

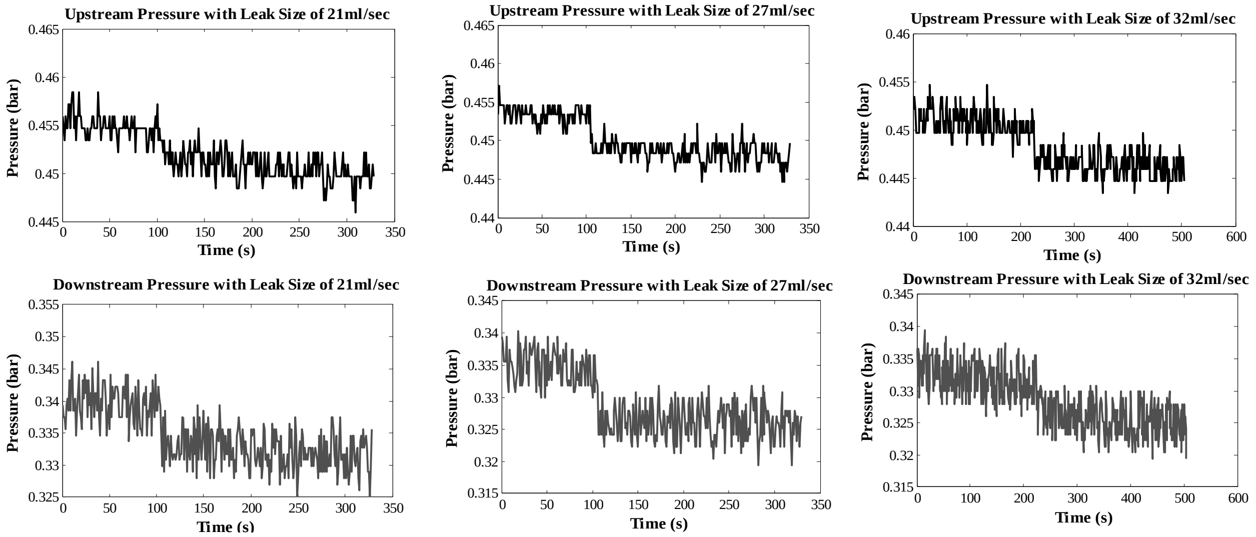

Fig.13. Upstream and downstream pressure variations for various leak size at position 3

4.2.1 Referential Points of the Antecedents and Consequent:

The number of referential points used for each antecedent decides the size of the rule base. If the number is too large, there will be too many rules in the rule base, and the subsequent training and inference process will be more demanding. If it is too small, the points may not be able to cover the range of an antecedent attribute. In this paper we use 5 referential points for upstream pressure (USP) and they are very small (VS), small (S), medium (M), large (L), very large (VL).

$$\text{i.e., } A_1^k \in \{VS, S, M, L, VL\}$$

Similarly we use 5 referential points for downstream pressure (DSP) and they are VS, S, M, L, and VL.

$$\text{i.e., } A_2^k \in \{VS, S, M, L, VL\}$$

For the consequent attribute, 5 referential points are used for leak size: zero (Z), small (S), medium (M), high (H) and very high (VH). i.e. D = (D_1, D_2, D_3, D_4, D_5) = (Z, S, M, H, VH)

The referential points defined above for the antecedent and consequent attributes are in linguistic terms and need to be quantified. By examining the acquired pressure variations and the recorded leak size value, the following equivalent relationships between the linguistic terms and numerical values are assumed so that the values roughly cover the corresponding attribute value range.

For Upstream Pressure difference it is assumed as,

VS = 0.0065, S = 0.0088, M = 0.0111, L = 0.0133, VL = 0.0156

For Downstream Pressure difference it is assumed as,

VS = 0.0026, S = 0.0045, M = 0.0063, L = 0.0082, VL= 0.01

(all pressure values in bar)

For Leak size it is assumed as,

VS = 21, S = 30.25, M = 39.5, H = 48.75, VH = 58

(all values of leak size are in ml/sec)

For each linguistic levels of each input and output a triangular membership function is assumed initially.

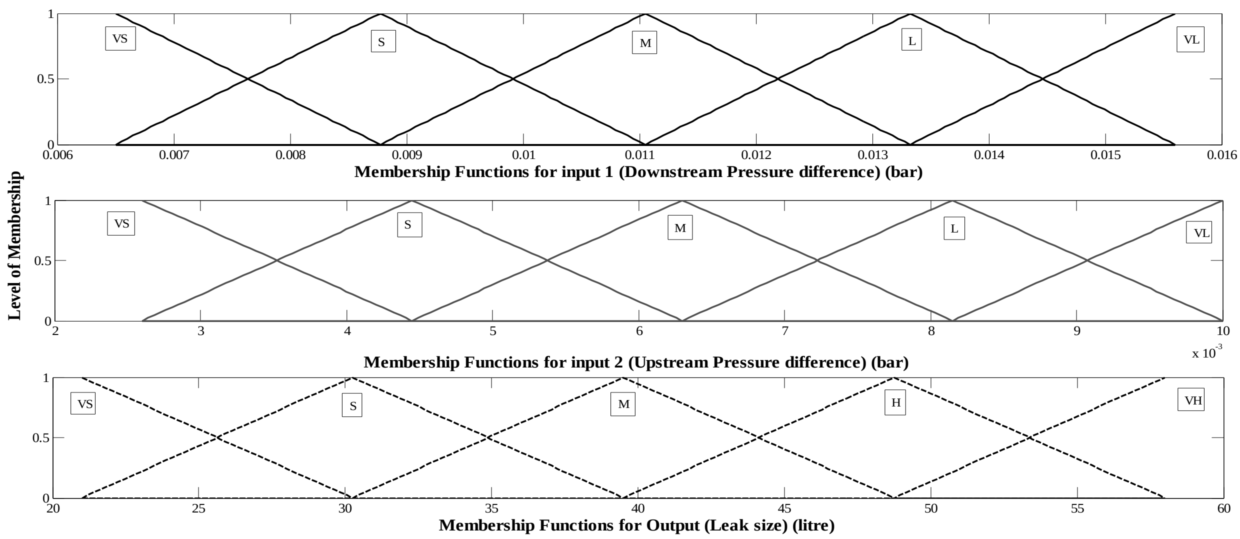

Fig.14. Membership function of input and output variables of the fuzzy inference system

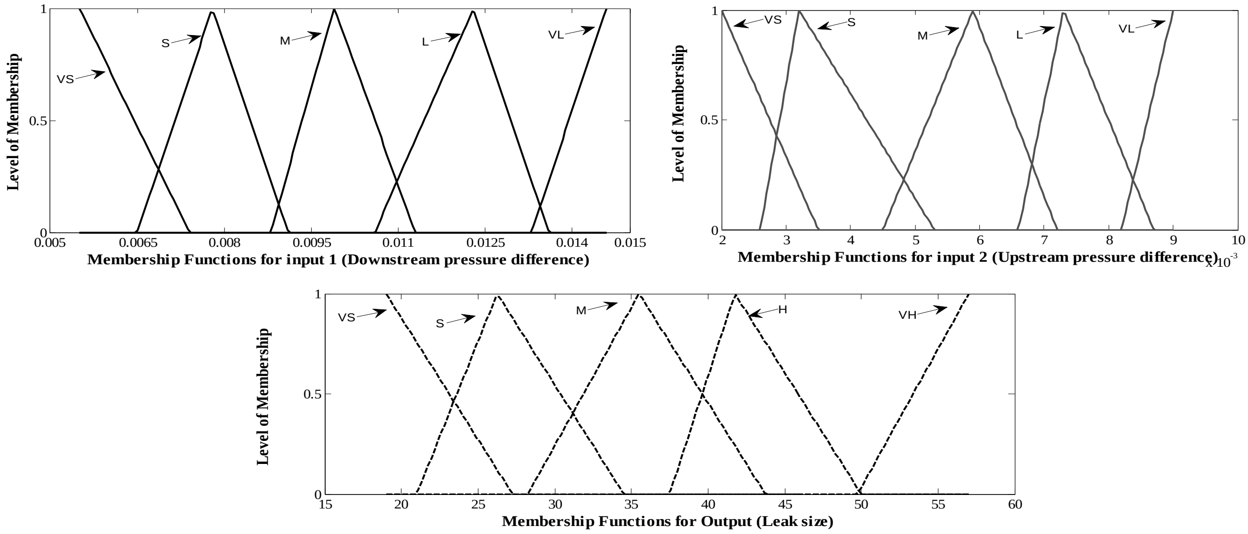

Fig.15. Optimized membership function of input and output variables of the fuzzy inference system

The membership function of the input and output variables after optimization is as shown in the Fig.15.

4.2.2 Rule Base:

Using the linguistic terms or their equivalent referential numerical values, one of the rules for leak size estimation may look like this:

IF USP is VS AND DSP is VS THEN LeakSize is VS.

Since both the inputs are divided into 5 linguistic levels each, there are 25 combinations of the 2 antecedents leading to 25 rules in total in the rule base. The rule base used in the design of FIS is given in the following Table.3.

Table.3. Rule base Matrix

USP / DSP	**VS**	**S**	**M**	**L**	**VL**
VS	VS	VS	S	S	VS
S	VS	S	H	VS	VS
M	S	S	M	M	H
L	M	M	H	H	VH
VL	S	S	M	H	VH

The Fig.16 shows the actual leak size and the estimated leak size for the same antecedent values. It demonstrates that the estimated outcomes should be optimized to get a satisfactory result. Fig.18 shows the estimated leak size after optimizing the width of the membership function. The error between the actual and the estimated leak size is further minimized by increasing the number of epochs from 100 to 500. This is shown in the Fig.19. The estimated and actual leak size for training and test data is shown in Table.4 and Table.5.

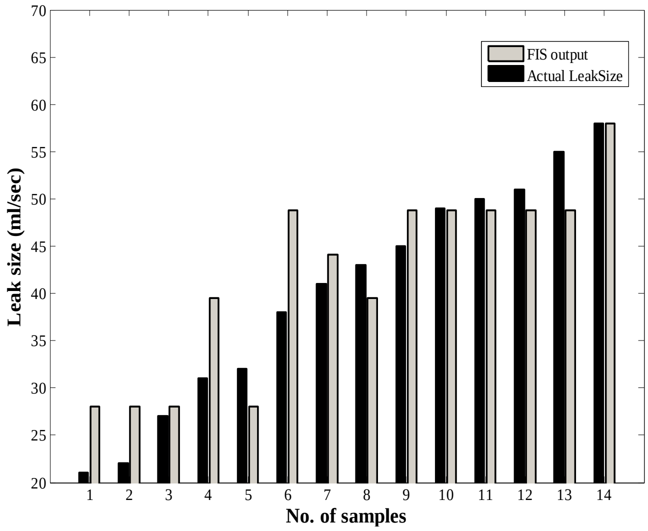

Fig.16. Estimated leak size using Fuzzy inference system without optimization

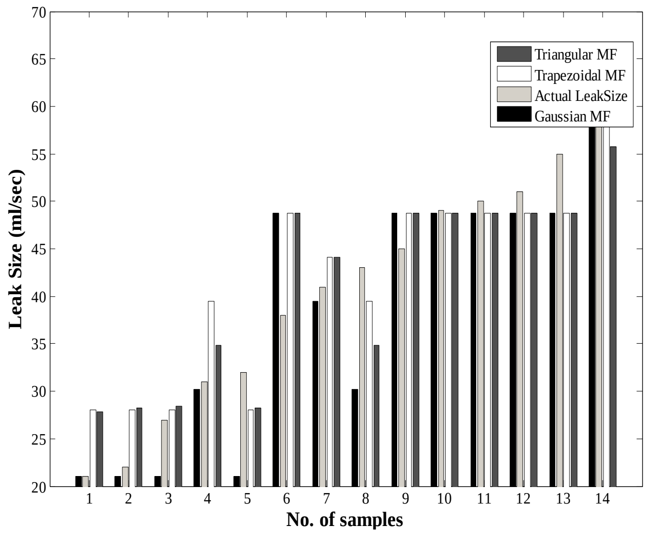

Fig.17. Estimated leak size using Fuzzy inference system with and without optimization

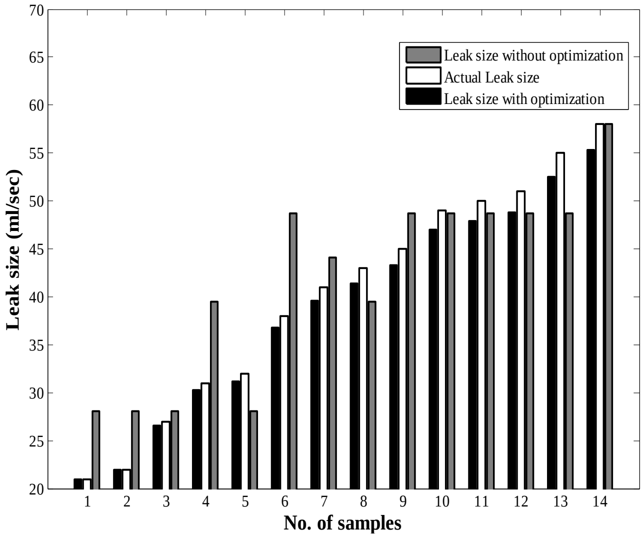

Fig.18. Estimated leak size using Fuzzy inference system with and without optimization

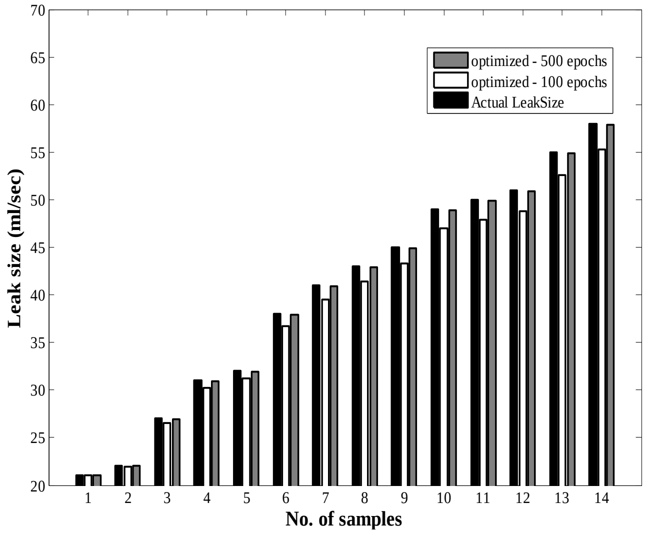

Fig.19. Estimated leak size using Fuzzy inference system with optimization with increased epochs

Table.4. Comparison of estimated leak with the actual leak using training data

Actual Leak Size (ml/sec)	Estimated Leak Size without optimization	Estimated Leak Size with optimization (100 epochs)	Estimated Leak Size with optimization
21	28.03	21.00	21.00
22	28.03	21.92	21.99
27	28.03	26.56	26.98
31	39.50	30.27	30.97
32	28.03	31.20	31.97
38	48.75	36.76	37.96
41	44.12	39.55	40.95
43	39.50	41.40	42.94
45	48.75	43.26	44.94
49	48.75	46.97	48.93
50	48.75	47.89	49.93
51	48.75	48.82	50.93
55	48.75	52.53	54.92
58	58.00	55.31	57.91

Table.5. Comparison of estimated leak size with actual leak size using test data

Actual Leak Size (ml/sec)	Estimated Leak Size without optimization (ml/sec)	Estimated Leak Size with optimization (100 epochs) (ml/sec)	Estimated Leak Size with optimization (500 epochs) (ml/sec)
27	28.03	26.56	26.98
38	39.50	36.76	37.96
42	46.38	40.47	41.95

5. CONCLUSION

Leak detection and estimation of leak is carried out in the laboratory pipeline system. Pressure variations in the pipeline for various leak position are captured and power spectrum is created for each pressure signal using FFT and FDM techniques. The leak location is calculated from the peak amplitudes of the spectrum by fitting a straight line using linear regression. From Table.1 and Table.2, it is clear that both the methods produced error in calculating the correct location of leak and it is observed that FDM techniques have produced a better result than FFT method. For estimating the leak size a two input single output fuzzy inference system is created with the upstream and downstream pressure variations as input to the FIS. The pipeline used here is complex having several obstructions and bends. Thus it is concluded the techniques for leak localization and estimation discussed in this paper provide a better solution for leakage problems in complex pipelines.

APPENDIX

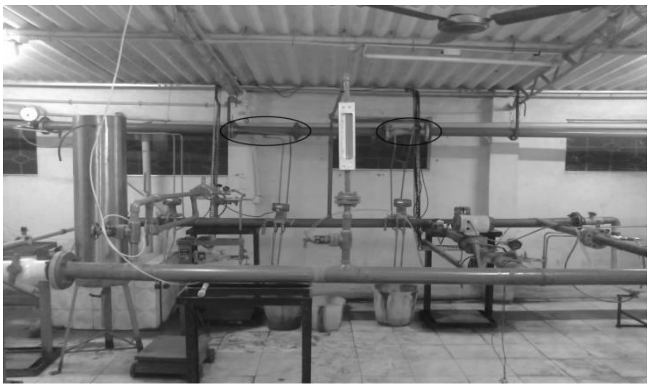

Fig.A1. Experimental setup with leak position 1 & 2 near flow nozzle and Venturi (encircled)

Fig.A2. Experimental setup with leak position 3 near elbow (encircled)

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