Pipe network blockage detection by frequency response and genetic algorithm technique

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ABSTRACT

This paper deals with detection of pipeline blockage location. For this, four branched pipe network models, viz. Model 1, Model 2, Model 3 and Model 4, are considered. The first two models are considered for analytical analysis and the second two models are considered for experimental analysis. For Model 1 and Model 2, the transfer matrix method is used to develop pressure frequency diagrams. Number of peaks exceeding the threshold value is considered as a variable to find the blockage location. In Model 3 and Model 4, blockage is created by partial valve closure and periodic oscillation is created by the end valve, manually. Time domain transient pressure data are analysed by the discrete Fourier transformation technique. Afterwards, an attempt is made to establish a relationship towards detection of blockage location using a genetic algorithm. This method is applied for 10%, 20%, 30% and 40% blockage of mean pipe diameter. It is found that location of blockage is independent of number of oscillations. Pressure and velocity of fluid inside the pipeline has negligible influence towards the calculation of blockage detection. New relationships and sensitivity analysis show that blockage location is directly proportional to length of maximum straight pipeline, and square root of pressure peaks.

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Key words | blockage detection, discrete Fourier transformation, frequency response method, genetic algorithm, sensitivity analysis, transfer matrix method

INTRODUCTION

Blockage is an important fault in pipelines. It occurs in the pipe due to the deposition of debris and minerals. Blockage interrupts the expected fluid flow and sometimes may cause damage to the pipeline. So a blockage should be detected as early as possible. Different methodologies, viz. acoustic reflectometry, vibration analysis, frequency response method (FRM), stochastic successive linear estimator, radio-isotope technology, etc., are used to find faults in long-length pipelines (length >1 km), which may be simply straight or branched (Liggett & Chen 1994; Jiang *et al.* 1996; Scott & Yi 1999; Massari *et al.* 2014; Datta & Sarkar 2016). Some of these methods are very costly, whereas some of the techniques are too lengthy. Among the above methods, FRM is versatile as it can be used to locate leakage along with

blockages in a pipeline. It gives accurate fault locations by investigating the peak patterns of different parameters (Lee *et al.* 2005). Out of several FRMs, scattered waves are used for the rough blockage detection in the pipeline with some experimental validation (Duan *et al.* 2014a). In water pipelines, wave perturbation analysis provides a relationship between the positions of multiple discrete blockages in the pipeline (Duan *et al.* 2014b). In a high-pressure water pipeline, non-uniform blockages can be detected by analysing the behaviour of transient waves (Duan *et al.* 2017). Another method for detecting pipeline blockages is the impedance method. This is a type of FRM that contains a long algebraic equation and works within the time domain (Wang *et al.* 2005; Kim 2014, 2016). In addition, the resonance method,

which uses the Bragg resonance condition, is used to locate the blockage position in a pipeline (Louati & Ghidaoui 2017; Louati *et al.* 2017). Out of these methods, FRM using the transfer matrix method (TMM) is found to be effortless and well organized (Mpesha *et al.* 2001, 2002). Initially, this method is used to detect leaks in a straight pipeline. Later, for both single and branched long pipelines, the frequency response technique using TMM was used for blockage detection (Mohapatra *et al.* 2006; Chaudhry 2014). Therefore, in accordance with the literature, the following objectives are considered for this research:

- To apply an analytical method (TMM method) on a case study proposed by Mohapatra *et al.* (2006) for a long pipeline (length >1 km), and further extend it for a complex long branched pipe network to show the applicability of the model.
- To modify the above-mentioned blockage detection process for the short length branched pipeline (length <1 km) using experimentation.
- To explore the applicability of the above-mentioned process for different percentages of the blockage, viz. 10%, 20%, 30% and 40% of mean pipeline diameter.

METHODOLOGY

The methodology adopted in this study to fulfil the objective of the present work is described in a flowchart (Figure 1). In this research, such a blockage detection model is considered where the blockage position is near the reservoir or source of water. The whole process is divided mainly into two parts. Initially, TMM is used to show the relationship between locations of blockages with different parameters, which is generally considered as an analytical method to locate blockages for long branched pipelines. The applicability of this method is checked for short branched pipelines in this study. Later, an experiment is carried out on two models consisting of a short branched pipeline to determine responses of different parameters like velocity and pressure with respect to time. Finally, the frequency response technique is applied on these data to find out blockage location and simultaneously the relationship between different parameters is established.

Analytical analysis

In this research, analytical analysis uses TMM where three different matrices such as field matrix, point matrix and overall transfer matrix (Mohapatra *et al.* 2006; Sattar *et al.* 2008) are introduced and shown by Equations (1)–(5). The field matrix for a pipe having number of sections i and length L_i' is shown by Equation (1).

$$F_i = \begin{bmatrix} \cosh \zeta_i L_i' & -\dfrac{1}{Z_c}\sinh \zeta_i L_i' & 0 \\ -Z_c \sinh \zeta_i L_i' & \cosh \zeta_i L_i' & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{1}$$

where ζ is a propagation constant $\left(\zeta = \sqrt{-\omega^2/a^2 + jgA\omega R/a^2}\right)$, ω is frequency, $j = \sqrt{-1}$, R is a linearized resistance term for turbulent flow and can be represented by $R = fq/gDA^2$, q is mean discharge, D is the inner diameter of the pipe, and Z_c is characteristic impedance $(Z_c = \zeta_i a_i^2 / jwgA_i)$. If mean pressure head and mean pressure head loss are denoted by H and H_1, mean discharge through the pipe is q, and mean relative valve opening and amplitude of valve motion are denoted by t and k, then different point matrices can be represented by the following equations:

$$P_{ov}' = \begin{bmatrix} 1 & 0 & 0 \\ -\dfrac{2H}{q} & 1 & \dfrac{2Hk}{t} \\ 0 & 0 & 1 \end{bmatrix} \tag{2}$$

$$P_{b}' = \begin{bmatrix} 1 & 0 & 0 \\ -\dfrac{2H_1}{q} & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{3}$$

$$P_{bde}' = \begin{bmatrix} 1 & \dfrac{v_{12}}{v_{11}} & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{4}$$

Equations (2)–(4) represent point matrices for an oscillating valve, partial blockage and for a branch pipe having a dead end. Here, v_{12} and v_{11} are overall transfer matrix elements for the branch pipe network. Therefore, the overall transfer matrix for a whole pipeline can be represented by
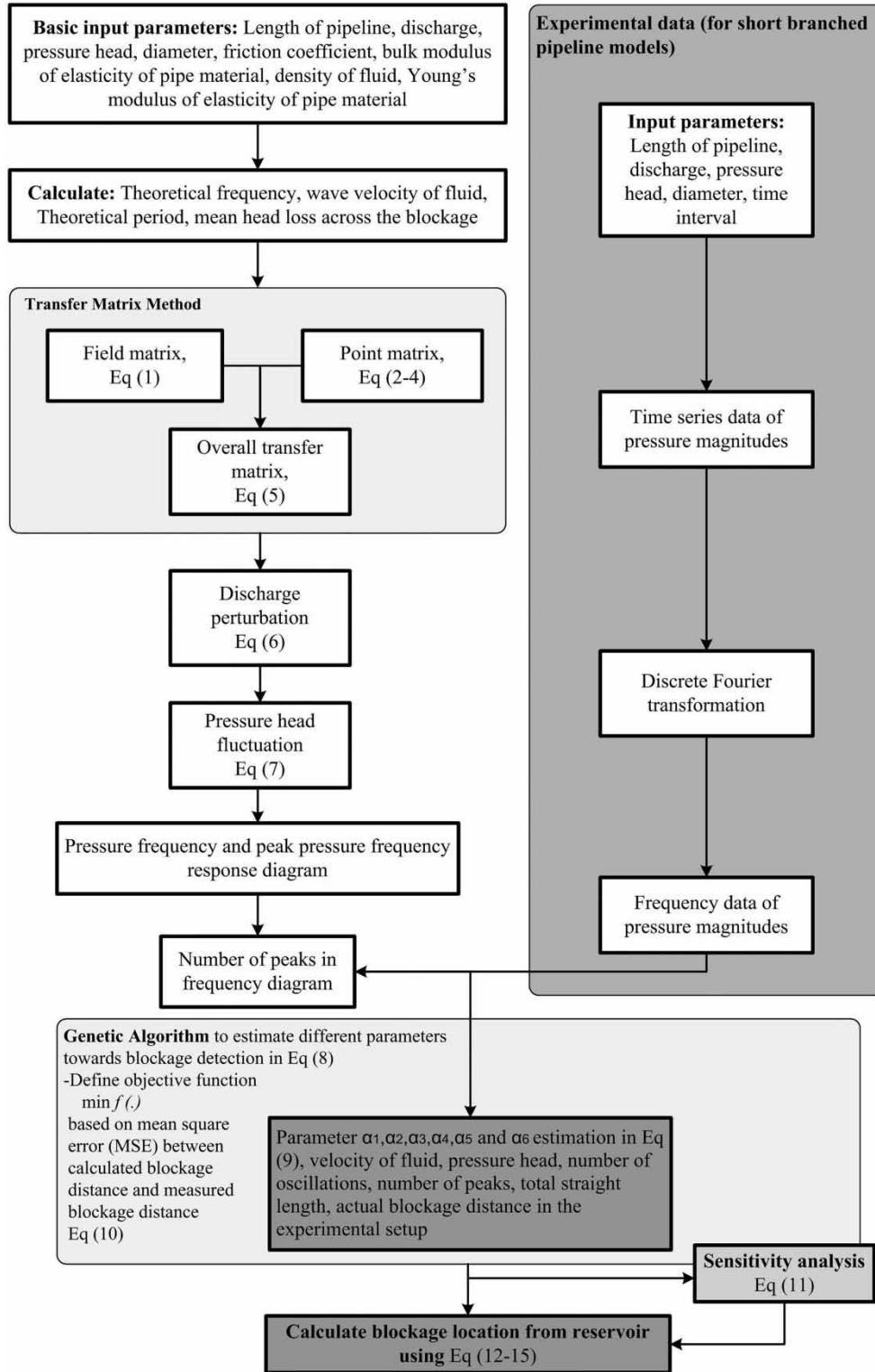
Basic input parameters: Length of pipeline, discharge, pressure head, diameter, friction coefficient, bulk modulus of elasticity of pipe material, density of fluid, Young's modulus of elasticity of pipe material

Calculate: Theoretical frequency, wave velocity of fluid, Theoretical period, mean head loss across the blockage

Transfer Matrix Method

Field matrix, Eq (1)

Point matrix, Eq (2-4)

Overall transfer matrix, Eq (5)

Discharge perturbation Eq (6)

Pressure head fluctuation Eq (7)

Pressure frequency and peak pressure frequency response diagram

Number of peaks in frequency diagram

Experimental data (for short branched pipeline models)

Input parameters: Length of pipeline, discharge, pressure head, diameter, time interval

Time series data of pressure magnitudes

Discrete Fourier transformation

Frequency data of pressure magnitudes

Genetic Algorithm to estimate different parameters towards blockage detection in Eq (8)
-Define objective function
   $\min f(.)$
based on mean square error (MSE) between calculated blockage distance and measured blockage distance Eq (10)

Parameter $\alpha_1, \alpha_2, \alpha_3, \alpha_4, \alpha_5$ and α_6 estimation in Eq (9), velocity of fluid, pressure head, number of oscillations, number of peaks, total straight length, actual blockage distance in the experimental setup

Sensitivity analysis Eq (11)

Calculate blockage location from reservoir using Eq (12-15)

Figure 1 │ Flowchart of methodology.

the following equation:

$$U = F_n P'_n \dots\dots\dots F_2 P'_2 F_1 \quad (5)$$

where F and P' denote field and point matrices, and numbers of components are denoted by 'n'. P'_{ov}, P'_b and P'_{bde} may replace P'_n based on the structure of the piping network system. Using elements such as u_{23}, u_{21}, etc. of the overall transfer matrix from the above equation, another equation can be written as follows:

$$q_1^{R'} = \frac{u_{23} - \dfrac{2H}{q}u_{13} + \dfrac{2Hk}{t}u_{33}}{u_{21} - \dfrac{2H}{q}u_{11} + \dfrac{2Hk}{t}u_{31}} \quad (6)$$

Amplitude of pressure head fluctuation ($h_1^{L'}$) can be written as follows:

$$h_1^{L'} = u_{21}q_1^{R'} + u_{23} \quad (7)$$

The state vectors just to the left and to the right of a section are shown by superscripts R' and L'. Finally, a pressure frequency response diagram (PFRD) has been developed using non-dimensional pressure amplitude ($h_r = 2|h_1^{L'}|/H$) and non-dimensional frequency ($\omega_r = \omega/\omega_2$), where ω_2 is theoretical frequency and is given by $\omega_2 = 2\pi/T$. T is the sum of the period of each of the pipes (Mohapatra *et al.* 2006). From the pressure frequency diagram, by joining the peaks of non-dimensional pressure amplitudes, the peak pressure frequency response diagram (PPFRD) is obtained.

Empirical relationship for blockage detection

Numbers of peaks (N') are obtained from the PPFRD, considering peaks above a threshold value (in general 85% of maximum peak). By using peaks, the location of the blockage can be estimated with the help of the following equation (Chaudhry 2014):

$$X = C\frac{LN'}{\omega} \quad (8)$$

Here, N' is number of peaks, L is longest straight pipeline, ω is frequency, and the value of coefficient C varies

for straight and branched pipelines. The value of C for a single straight long pipeline is 2.00 (Chaudhry 2014), whereas the value of C for a long branched pipeline is 2.08 (Mohapatra *et al.* 2006). These values are adopted from several numerical experimentations. Therefore, another objective of this study is to explore modified values of C for short branched pipelines.

Models for analysis

Four branched pipeline models are considered for the analysis where two models are considered for analytical analysis and another two models are considered for experimental analysis. These pipeline models are named Model 1, Model 2, Model 3 and Model 4. Model 1 and Model 2 are considered as long length branched pipelines for analytical analysis shown in Figure 2(a) and 2(b) whereas Model 3 and Model 4 are considered as short branched pipelines for experimental analysis shown in Figure 2(c) and 2(d). For Model 1, L_{11} is the distance of the blockage shown by 'B' from the water tank and is taken as 400 m. Similarly, lengths of other sections are $L_{21} = 400$ m, $L_{31} = 800$ m, and $L_{41} = 800$ m. An oscillating valve is attached at the end of the pipeline shown by 'OV'. J_1 is the junction of the pipeline and a closed valve is shown by 'V'. Compared to Model 1, one extra branch pipe having a dead end is taken into consideration for Model 2 to create the complex pipe network, shown in Figure 2(b). L_{12} is the distance of the blockage from the water tank and is taken as 600 m. Similarly, lengths of other sections are $L_{22} = 200$ m, $L_{32} = 400$ m, $L_{42} = 400$ m, $L_{52} = 400$ m, and $L_{62} = 400$ m. J_1 and J_2 are junctions of the pipeline and V_1 and V_2 are closed valves. For Model 1 and Model 2, mean discharge is 0.1 m³/s, mean pressure head is 50 m, length of the main pipeline is 1,600 m, and diameter of the pipeline is 0.304 m. The friction coefficient for the pipe is considered as $f = 0.01$ and pressure wave velocity $a = 1,200$ m/s.

Experimental set-up

The experiment was performed in the Fluid Mechanics and Fluid Machine Laboratory of the Department of Mechanical Engineering, IIT(ISM) Dhanbad. The description of the experimental set-up is given as follows.
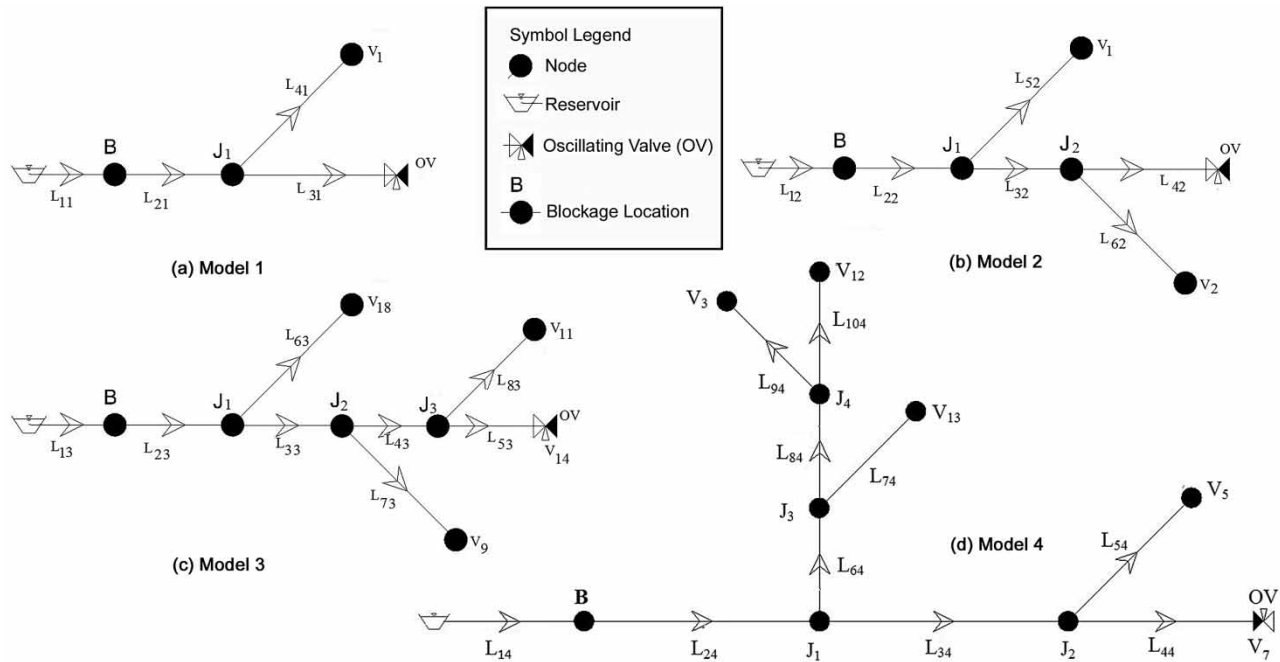
Figure 2 | Schematic representations of different models.

Description of experimental set-up

The experimental set-up for investigation of steady and unsteady analysis of flows is composed of (1) water tank, (2) pump, (3) mild steel (MS) pipe, (4) pressure reducing valve (PRV), (5) pressure sensor, (6) flow sensor, (7) globe valve, (8) ball valve, (9) non-return valve (NRV), (10) by-pass valve, (11) strainer, and (12) control panel. A schematic isometric view of the set-up with detailed description and position of nodes, sensors and pipe segments is shown in Figure 3. Using the above set-up, experiments are performed on Model 3 and Model 4. Length of the main pipeline for Model 3 is 8 m and for Model 4 it is 9.29 m.

In Model 3, V9, V11, V14, V17 and V18 (of Figure 3) are closed fully in order to disconnect the network from the other part of the set-up and to resemble a branch pipe network as shown in Figure 2(c) where L_{13} is the distance of the blockage from the water tank, and is taken as 0.93 m. J_1, J_2 and J_3 are the junctions. The oscillating valve is shown by OV. Lengths of other sections are $L_{23} = 1.17$ m, $L_{33} = 1.90$ m, $L_{43} = 2.00$ m, $L_{53} = 2.00$ m, $L_{63} = 0.86$ m, $L_{73} = 0.40$ m, and $L_{83} = 1.67$ m. Mean discharge is measured as 0.0018 m³/s.

In Model 4, V3, V5, V12 and V13 (of Figure 3) are closed in order to disconnect the network from the other part of the set-up and to resemble a branch pipe network as shown in Figure 2(d) where L_{14} is the distance of the blockage from the water tank. The magnitude of L_{14} is considered as 1.16 m. J_1, J_2, J_3 and J_4 are the junctions. The oscillating valve is shown by OV. Lengths of other sections are $L_{24} = 6.14$ m, $L_{34} = 1.63$ m, $L_{44} = 0.36$ m, $L_{54} = 0.304$ m, $L_{64} = 0.86$ m, $L_{74} = 0.304$ m, $L_{84} = 0.279$ m, $L_{94} = 1.143$ m, and $L_{104} = 0.56$ m. Mean discharge through the pipeline is measured as 0.0016 m³/s.

V14 and V7 are the end valves used in Model 3 and Model 4 for creating oscillatory flow in the pipeline. The diameter of the pipeline is 0.08 m, and the length of the main pipeline for Model 3 is 8 m and for Model 4 it is 9.29 m. During the experiment, artificial blockages of approximately 10%, 20%, 30% and 40% of mean diameter are created. Manual oscillation having a frequency of 1 Hz (valve closing time is 1 second) is performed by end valves. The time domain data are collected and are converted to frequency domain by discrete Fourier transformation (DFT). Number of peaks from the frequency diagram by DFT are further used for the calculation of the blockage location in the pipeline (Jenkins & Desai 1986).
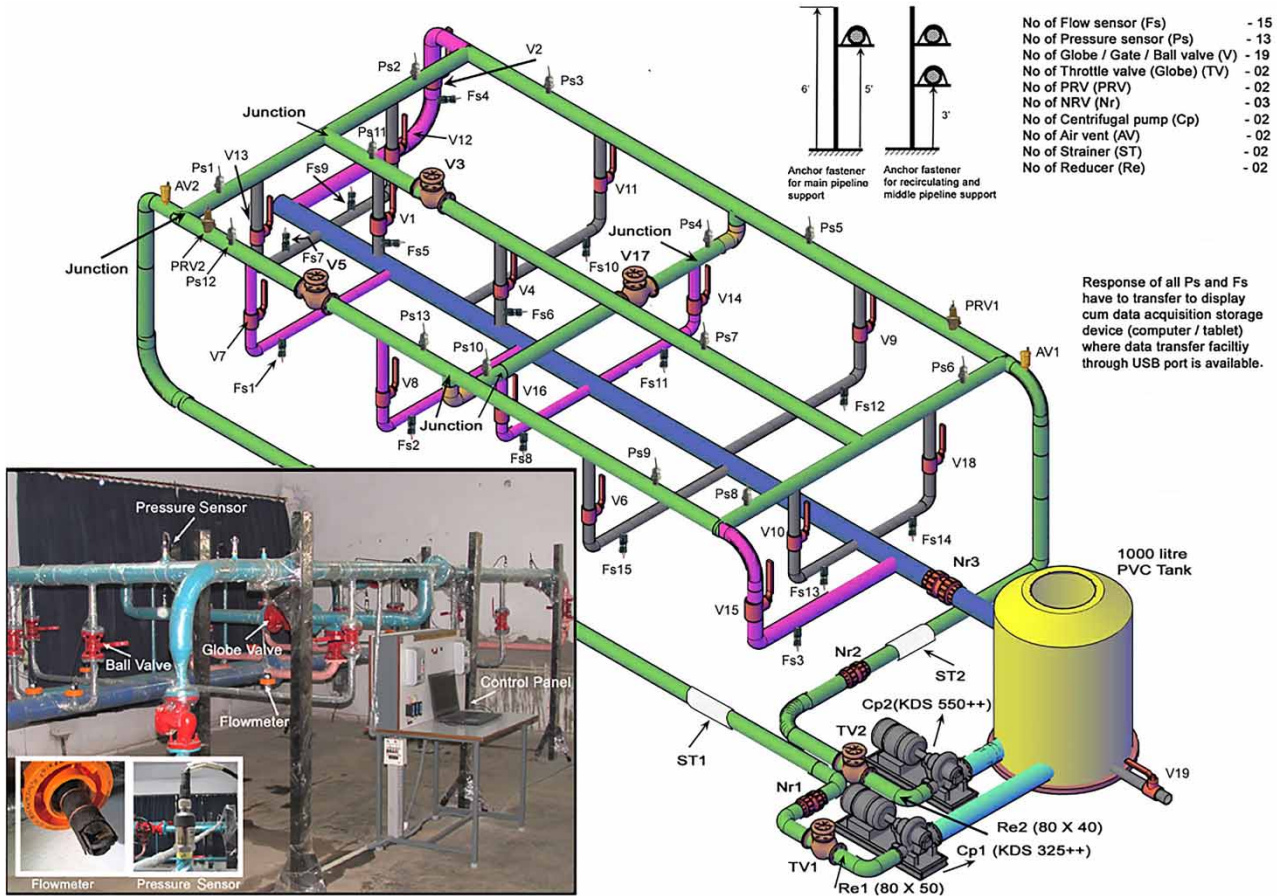
Figure 3 | Isometric view of experimental set-up along with a close view of flowmeter, pressure sensor and pictorial representation of the actual set-up.

Application of genetic algorithm

A genetic algorithm (GA) is a type of optimization algorithm that can find the optimal solution for a computational problem and minimizes or maximizes a particular function. This algorithm works similarly to the biological process of reproduction and natural selection to solve for the 'fittest' solutions (Azamathulla *et al.* 2008; Park *et al.* 2012; Fallah *et al.* 2013). In this paper, a GA is applied to estimate the value of 'C' (Equation (8)) based on experimental data, which was primarily processed by the frequency response technique in order to find N'.

Objective function

To execute the GA, an objective function needs to be defined for optimizing the parameters. In this part, initially,

it is assumed that unlike the term 'C' mentioned in Equation (8), the blockage location is dependent on the number of oscillations, or O, made by the valve in the pipeline, velocity of the fluid through pipeline v, and pressure head of fluid through pipeline P. Moreover, it is also assumed that the variables L and N' are not linearly related to the blockage location. Hence the blockage location for a short branched pipeline can be written as follows:

$$X_{comp} = \{\alpha_1 \times O^{\alpha_2} \times v^{\alpha_3} \times P^{\alpha_4}\} \times \frac{L^{\alpha_5} N'^{\alpha_6}}{\omega} \qquad (9)$$

where α_1, α_2, α_3, α_4, α_5 and α_6 are the parameters to be determined through the GA. α_1 is used instead of 'C' in the above equation. Here, MSE error is calculated between actual blockage location X_{act} and computed blockage location X_{comp} and it is to be minimized using the GA.

Therefore, the objective function for the GA can be written as follows (it is to be noted that the actual blockage location is known from the experimental set-up):

$$\min f(.) = \frac{\sum\limits_{i=1}^{m} (X_{act} - X_{comp})^2}{m-1} \tag{10}$$

where $f(.)$ is the function of the parameters α_1, α_2, α_3, α_4, α_5 and α_6 and m is the total set of experimental data available. Each set contains the values of v, P, O, N', L and X_{act}. In this research, MATLAB is used for the optimization where different GA parameters are set; viz., population size is 20, cross over fraction is 0.8, mutation is 0.01, and maximum number of generations is 100.

Sensitivity analysis

Sensitivity analysis (SA) identifies the most influential variable in a model; that is, the change of which input variable will affect the output most for a model. Generally, two types of SA are performed: (i) deterministic approach and (ii) probabilistic approach. In deterministic SA (Loucks & Van Beek 2017), one input parameter is varied at a time while the others remain unchanged. This analysis uses different charts (tornado chart and spider chart) to show the sensitivity of the input variables. During this analysis, a range of input values and base values needs to be defined, upon which the analysis is to be carried out.

In the probabilistic approach, among various methods, the variance based approach or global SA is well accepted for showing the dependency of output variance on the input factors. If variance of output (Y) is denoted by $V(Y)$ and model inputs are $X_{i......}X_n$ for $i = 1, 2, … n$, then the variance of output is decomposed by the following equation (Saltelli *et al.* 2008; Hall *et al.* 2009):

$$V(Y) = \sum_i V_i + \sum_{\substack{i,j \\ i<j}} V_{ij} + \sum_{\substack{ijl \\ i,j \\ j<l}} V_{ijn} \ldots \ldots V_{123.....n} \tag{11}$$

In the above equation, V_i is part of the variance of Y. To show the influence of different inputs for determining the output variance, the first-order sensitivity index, S_i {$S_i = V_i/V(Y) = V[E_{X\sim i}(Y|X_i)]/V(Y)$} is calculated. $V[E_{X\sim i} (Y|X_i)]$

is the variance of conditional expectation of Y given X_i, and $X_{\sim i}$ indicates the set of all variables except X_i. In this analysis, both deterministic and probabilistic sensitivity approaches are tried to identify the most influential variable.

RESULTS AND DISCUSSION

Outcomes of analytical analysis

During the analysis of the pipeline, pressure frequency response and peak pressure frequency response diagrams are obtained. The number of peaks are shown in the PPFRD. The maximum frequency for both models is set as 50. For Model 1, the number of peaks obtained from the frequency response diagram (FRD) is 6 (Figure 4(a)). The blockage location for the corresponding peak is 400 m.

For Model 2, the number of peaks obtained from the FRD is 9 (Figure 4(b)). Blockage location for the corresponding peak is 600 m. For Model 2, the frequency range is the same as for Model 1.

Experimental results

Experiments were conducted on the two models. Manual oscillations having a frequency of 1 Hz were developed periodically by using end valves. Figure 4(c) shows a sample of the PFRD for Model 3 and Figure 4(d) shows a sample of the PFRD for Model 4 in 10% blockage condition. Here the number of peaks that cross the threshold line shown in Figure 4(c) and 4(d) are considered for the calculation. The number of peaks above the threshold value obtained from experiment under different operating conditions for Model 3 and Model 4 is shown in Table 1. It is observed that the number of peaks changes when the experiment is conducted under different line pressures and for greater head loss in the pipeline. Henceforth, GA is applied towards exploring the relationship between different parameters.

Modification of blockage detection equation through GA

The GA optimizes different parameters such as α_1, α_2, α_3, α_4, α_5 and α_6 mentioned in Equation (9). Table 2 shows
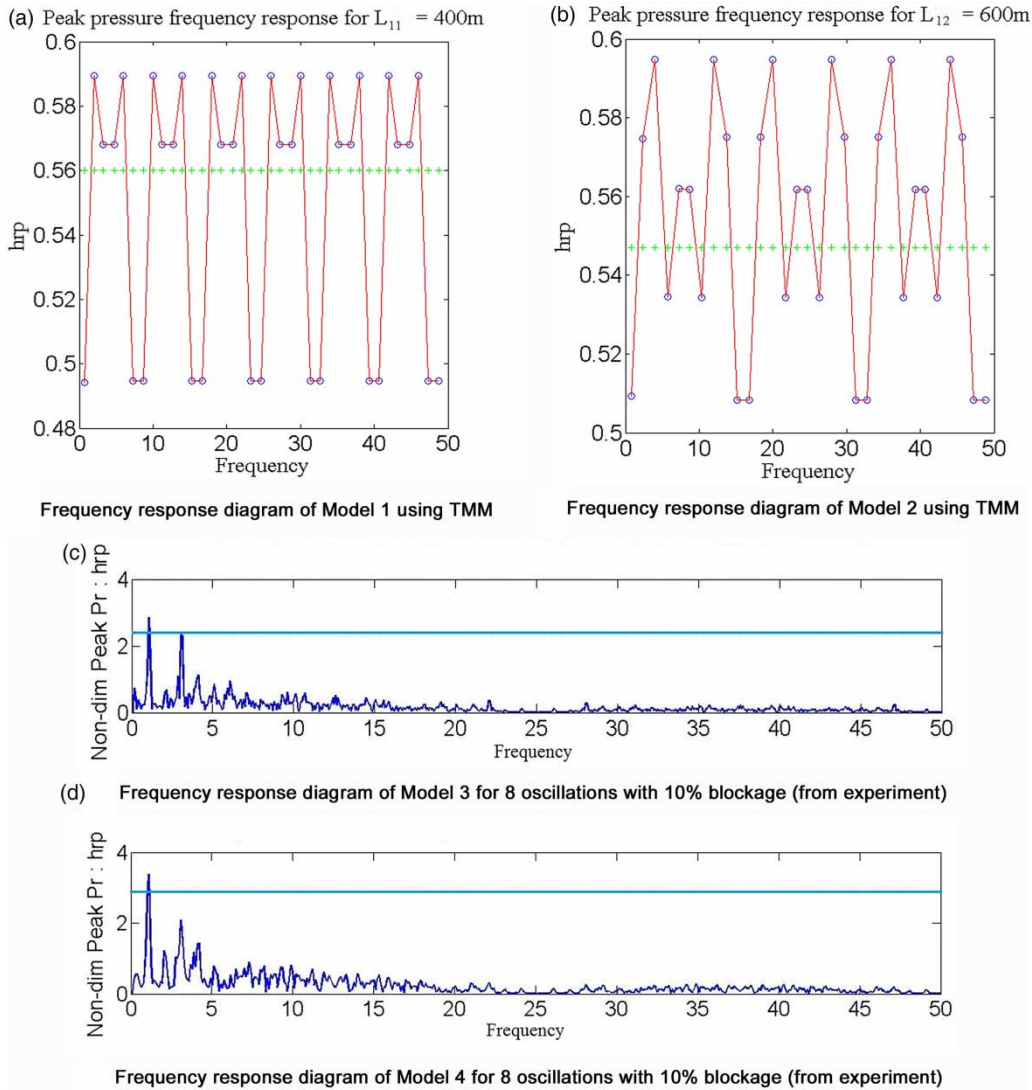
(a) Peak pressure frequency response for $L_{11} = 400m$

Frequency response diagram of Model 1 using TMM

(b) Peak pressure frequency response for $L_{12} = 600m$

Frequency response diagram of Model 2 using TMM

(c)

(d) Frequency response diagram of Model 3 for 8 oscillations with 10% blockage (from experiment)

Frequency response diagram of Model 4 for 8 oscillations with 10% blockage (from experiment)

Figure 4 | Frequency response diagrams of Model 1, Model 2, Model 3 and Model 4.

optimum values of blockage parameters for different blockage percentages in the pipeline. The optimum values of parameters are found after several trial runs in the GA. $f(.)$ is the objective function (Equation (10)) of the parameters α_1, α_2, α_3, α_4, α_5 and α_6. The objective function is basically the MSE error calculated between the actual blockage location X_{act} and computed blockage location X_{comp}.

The minimum value of the objective function (Table 2) in the 10% blockage condition is 0.15908. Accordingly, an equation (Equation (12)) has been

formed for detection of blockage in short branched pipelines.

$$X_{comp} = \{2.178 \times v^{0.01} P^{0.11}\} \times \frac{L\sqrt{N'}}{\omega} \qquad (12)$$

Similarly, the minimum value of objective functions in 20%, 30% and 40% blockage conditions are 0.14053, 0.14032 and 0.17165. Accordingly, the following equations (Equations (13)–(15)) have been formed for detection of

Table 1 | Sample of frequency response results for Model 3 and Model 4 under different operating conditions with different percentages of blockage

Sl. no.	Operating pressure (bar)	Blockage percentage	No. of oscillations created through valve	Velocity of flow (m/s)	Frequency response obtained from time series data Number of peaks
Model 3					
1	1.7	10%	3 times	0.35	3
			4 times	0.35	1
			5 times	0.35	2
			6 times	0.35	2
			7 times	0.35	2
			8 times	0.35	1
2	1.8	20%	3 times	0.39	2
			4 times	0.39	1
			5 times	0.39	2
			6 times	0.39	1
			7 times	0.39	2
			8 times	0.39	2
3	2.0	30%	3 times	0.45	3
			4 times	0.45	2
			5 times	0.45	1
			6 times	0.45	2
			7 times	0.45	2
			8 times	0.45	2
4	2.1	40%	3 times	0.47	1
			4 times	0.47	3
			5 times	0.47	2
			6 times	0.47	1
			7 times	0.47	2
			8 times	0.47	2
Model 4					
5	1.5	10%	3 times	0.33	2
			4 times	0.33	1
			5 times	0.33	2
			6 times	0.33	2
			7 times	0.33	2
			8 times	0.33	1
6	1.7	20%	3 times	0.35	2
			4 times	0.35	1
			5 times	0.35	1
			6 times	0.35	2
			7 times	0.35	2
			8 times	0.35	2
7	1.8	30%	3 times	0.36	1
			4 times	0.36	1
			5 times	0.36	2
			6 times	0.36	2
			7 times	0.36	2
			8 times	0.36	1
8	1.9	40%	3 times	0.38	1
			4 times	0.38	1
			5 times	0.38	1
			6 times	0.38	2
			7 times	0.38	1
			8 times	0.38	1

Table 2 | Optimum values of blockage parameters with minimum error and sensitivity indices of input variables for different percentages of blockage

Parameters		10% blockage	20% blockage	30% blockage	40% blockage
α_1		2.178	2.185	2.181	2.162
α_2		0	0	0	0
α_3		0.01	0.01	0.01	0.01
α_4		0.11	0.12	0.11	0.114
α_5		1	1	1	1
α_6		0.5	0.5	0.5	0.5
$f(.)$		0.15908	0.14053	0.14032	0.17165
Minimum % error		*1.9*	*8.1*	*10.3*	*4.4*
		Sensitivity indices (S_i)			
Variables for sensitivity analysis	L	0.0088	0.0357	0.0285	0.0190
	N'	0.9715	0.9470	0.9447	0.9560
	P	0.0013	0.0034	0.0029	0.0026
	v	0.0001	0.0032	0.0129	0.0117
	Total	0.9817	0.9893	0.9890	0.9893

blockage in short branched pipelines.

$$X_{comp} = \{2.185 \times v^{0.01} P^{0.12}\} \times \frac{L\sqrt{N'}}{\omega} \tag{13}$$

$$X_{comp} = \{2.181 \times v^{0.01} P^{0.11}\} \times \frac{L\sqrt{N'}}{\omega} \tag{14}$$

$$X_{comp} = \{2.162 \times v^{0.01} P^{0.114}\} \times \frac{L\sqrt{N'}}{\omega} \tag{15}$$

It is found that the minimum percentage error for a blockage location obtained for a pipeline having 10% blockage using Equation (12) is 1.9% whereas for a pipeline having 20%, 30% and 40% blockage it is 8.1%, 10.3%, and 4.4%. The value of α_1 varies a little, viz. 2.178, 2.185, 2.181, 2.162, corresponding to 10%, 20%, 30% and 40% blockage respectively. Other parameter values (α_2, α_3, α_4, α_5 and α_6) obtained through the GA for different percentages of blockage vary very little. It is observed that the number of oscillations created manually has no effect on the calculation of blockage detection where it is used to carry out more accurate analysis of signals to obtain precise results. Also, velocity and pressure in

the pipeline have negligible effect on blockage detection. Most importantly, the square root of the number of peaks above the threshold value is to be considered while the frequency value is obtained by DFT for short branched pipelines for minimum MSE value.

Results of sensitivity analysis

In this research, deterministic and variance based approaches are used to show the sensitivity of input variables on the output of blockage detection results shown in Equations (12)–(15) for Model 3 and Model 4 under different percentages of blockage conditions. Here, it is observed that input variables, viz. velocity of water through pipeline (v), pressure (P), length of main pipeline (L) and number of peaks (N'), influence the detection of the location of the blockage in the pipeline. However, this exercise is carried out for different percentages of blockage. Here, ranges of data (i.e. minimum and maximum) and base value (average) are considered for analysis. Percentage of changes for different input values for 10% blockage condition and corresponding output values are shown by a tornado chart (Figure 5(a)) and spider chart (Figure 5(b)). The tornado chart indicates the comparison between the relative importance of input variables and the spider chart shows the dependency of the model's output on input variables by implementing the same percentage changes for each input variable. In this research, it is observed that the spider curve representing the number of peaks (N'), is steeper than that for other variables. This means N' is an important variable for the detection of blockage in the pipeline.

In the variance based approach for the different samples of data, standard deviations and mean values are calculated. Finally, sensitivity indices (S_i) of input variables for different percentages of blockage conditions are shown in Table 2 and sensitivity indices of input variables for 10% blockage condition is shown in Figure 5(c). It is found (Table 2) that total sensitivity indices (S_i) capture approximately 98% of total variance for all blockage conditions. This means only 2% of the variation is due to nonlinear effects. It is also observed that the number of peaks (N') is most influential.
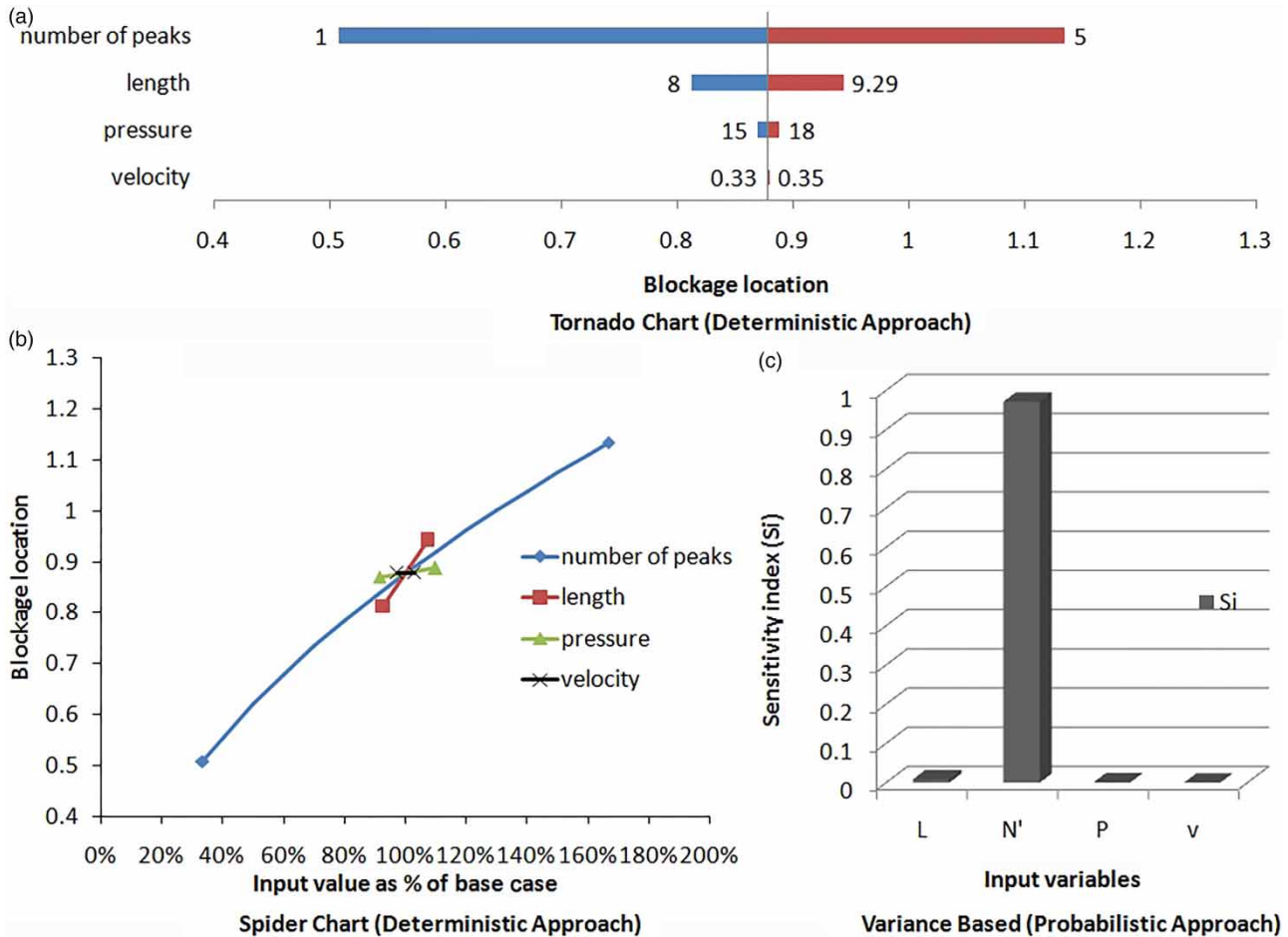
Figure 5 │ Sensitivity analysis results: (a) tornado chart (deterministic approach); (b) spider chart (deterministic approach); (c) variance based (probabilistic approach).

CONCLUSIONS

In this study, an objective is set to determine the position of a blockage in the pipeline network system. For this purpose, an FRD is used. The FRD is generated through both analytical and experimental analysis. Analytical analysis is carried out for a long pipeline (length >1 km) through two models, viz. Model 1 and Model 2, using the TMM, where the blockage location is estimated using a function of the straight length of the pipeline, and frequency and number of peaks above a threshold value (i.e. 85% of the peak pressure). During this analysis, the following observations were made:

(i) With the increase in distance of blockage from the reservoir, the number of peaks generated corresponding to the oscillations made at the end node of the

network also increases in the peak pressure frequency diagram.

(ii) For a blockage having a fixed location, if inlet pressure head is increased, the number of peaks above the threshold value also increases in the PPFRD.

(iii) The same method, when applied for the short pipeline (length <1 km), especially in a branched pipeline, with the same proposed relationship, is found to give inconsistent results.

Therefore the relationship is proposed to be modified in this study, where frequency data is obtained from measurement. In this process, a number of experiments have been carried out on an experimental set-up of a pipe network. Almost 150 sets of such data are considered for the analysis. A GA is used to obtain optimized values of

different parameters towards modifying the blockage detection equation for the short branched pipeline by minimizing the summation of errors between the actual blockage location (in the set-up, which is known) and calculated blockage location by varying the above parameter values. In this analysis, the percentage of blockage is not considered as a parameter in the GA analysis, as in practical cases, since the location is unknown, measuring blockage percentage in the blockage area is difficult. However, an equation is developed for different blockage percentages. The following observations are made from this analysis:

(i) Results show four distinct equations, viz. Equations (12)–(15) are obtained for blockage location corresponding to 10%, 20%, 30% and 40% blockage in pipeline with the help of the GA for the short length branched pipeline (length <1 km) within selected pressure limits (1.5–2.1 bar).

(ii) In general, in the above-mentioned equations, the common aspects are: unlike the long length pipeline, for the short length branched pipe network, location of blockage is proportional to the square root of the number of peaks obtained from the FRD. Therefore, the influence of the number of peaks on detecting the blockage location is decreased.

(iii) The possible reasons for this relationship may be that in a short branched pipeline, responses of other parameters are influencing the relationship, and lots of noise is present in the signal of the short length and short diameter pipeline, having highly turbulent flow, where the presence of bubbles is also greater compared to long pipelines.

(iv) Furthermore, as manual operation is carried out for the creation of oscillations within a very close proximity to the placement of the pressure transducer and end node, pressure signals are noisy.

(v) It is found that the location is independent of the number of oscillations created by the end valve. However, it is also observed during the experiment and FRD analysis that if pressure data is picked from the dataset having multiple numbers of oscillations (>6) and considered for analysis of FRD, it gives a very accurate result. The possible reason for this may be

that after such oscillations, responses of the system became stable.

(vi) Further, the above-mentioned results show that fluid velocity and line pressure have an effect on location of blockage; however, it is negligible. The possible reason for this may be the presence of lots of bends and valves within a very close proximity.

(vii) From the results (Table 2), it is also observed for a pipeline having 10% blockage that the value of the coefficient in the empirical Equation (12) is 2.178, which differs from the value of the coefficient in Equation (8) for long length branched pipelines, i.e. 2.08.

(viii) For 20% blockage, the value of the coefficient in Equation (13) is 2.185. Similarly, for 30% blockage and 40% blockage in Equations (14) and (15) the values are 2.181 and 2.162. Other parameter values ($\alpha_2, \alpha_3, \alpha_4, \alpha_5$ and α_6) vary very little for different blockage conditions.

(ix) Therefore it can be concluded that variation of percentage of blockage doesn't create a big impact on the detection process of blockage location in short branched pipelines and any one equation can be chosen for the detection of blockage in the pipe.

(x) However, the percentage of error for blockage location using Equation (12) considering 10% blockage in the pipe is 1.9%, which is the minimum among other blockage conditions and the error percentage corresponding to the 30% blockage percentage gives the maximum error value of 10.3%. Therefore, Equation (12) can be used satisfactorily for finding the blockage location in the pipeline.

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