Detection and Location of a Partial Blockage in Pipeline Systems Using Damping of Fluid Transients

Xiao-Jian Wang[1], Martin F Lambert[2], Angus R Simpson[3]

Abstract: A new blockage detection method using blockage-induced transient damping is developed based on a linear analytical solution for the transients in a pipeline with a blockage. The linear analysis indicates that pipe friction damping on a pipe transient is exactly exponential, while the blockage damping is exponential for each of the individual harmonic components. For each individual component, the blockage-induced damping depends on the blockage magnitude and position and is independent of measurement location and the transient event. The proposed blockage detection method is successful in detecting, locating and quantifying a pipe blockage based on the laboratory experiments.

Introduction

Blockage development is a common problem in pipeline and pipe network systems for energy, chemical and water industries. A blockage can be formed by chemical or physical depositions, or formed by a valve that has only been partially re-opened. Existence of a pipeline blockage not only reduces the operation efficiency of a pipeline system, but sometimes it can cause severe safety problems if the blockage is not identified quickly. Some methods have been proposed to detect and locate pipeline blockages. Rogers (1995) developed a ROV (remotely operated vehicle) inspection method by measuring the blockage-induced strain change of the pipe wall. Since this method can not be applied continuously, the response for a blockage occurrence is slow. Wu (1994) proposed an acoustic method based on the properties of eigenfrequency shifts of acoustic signals measured from a pipeline with a blockage. Due to the quick decay of the acoustic signals, the measurement interval needs to be less than one hundred meters. In petroleum engineering, blockage development is related to the properties of the fluid in the pipes. Therefore, analyzing the fluid properties can indicate the potential development of the blockage (Hunt 1996). Unfortunately, this method cannot provide the location of the blockage. By analysing the blockage (or leakage)-induced water head losses, Jiang et al. (1996) developed a blockage and leakage detection algorithm for the water network of a district heating system. Depending on the measurement locations, only significant

[1] Project Engineer, Tonkin Consulting, 5 Cooke Terrace, Wayville, SA 5034, Australia. Email: xiao-jian.wang@tonkin.com.au.
[2] Senior Lecturer, School of Civil & Environmental Engineering, the University of Adelaide, Adelaide, SA 5005, Australia. Email: mlambert@civeng.adelaide.edu.au.
[3] Associate Professor, Centre for Applied Modelling in Water Engineering (CAMWE), School of Civil & Environmental Engineering, the University of Adelaide, Adelaide, SA 5005, Australia. Email: asimpson@civeng.adelaide.edu.au.

leakage and blockage can be detected and located based on the numerical experiments they undertook. In the methods developed by Scott and Satterwhite (1998) and Scott and Yi (1999), the blockage was detected and characterized by a mass and momentum (friction loss) balance analysis. A detectable blockage map was developed in Scott and Yi (1999). These methods could not detect the location of a blockage although it was noticed that the transients were affected by the location of the blockage during tests. Recently, several leak detection methods using fluid transients in a pipe system have been presented (Liggett and Chen 1994; Brunone 1999; Vítkovský et al. 2000; Wang et al. 2002), and have shown enormous advantages with regard to the quickness of response and accuracy compared to other leak detection methods. Compared to acoustic signals, the fluid transients are less influenced by the surrounding environments and can propagate longer distance with less decay, which is more ideal for remote surveillance. In this paper, an analytical solution for the transients in a pipeline with a partial blockage is derived. Based on this solution, a new method for blockage detection and location is developed. The proposed method is verified using experimental experiments.

An Analytical Solution

A partial blockage in a pipeline system can be considered as an orifice as depicted in Fig. 1. Governing equations for the unsteady flow in a pipe section including a blockage are expressed as (Wang 2002)

$$\frac{\partial H}{\partial x} + \frac{1}{gA}\frac{\partial Q}{\partial t} + \frac{Q}{gA^2}\frac{\partial Q}{\partial x} + \frac{fQ^2}{2DgA^2} - \Delta H_B \delta(x - x_B) = 0 \qquad (1)$$

$$\frac{\partial H}{\partial t} + \frac{Q}{A}\frac{\partial H}{\partial x} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \qquad (2)$$

where x = distance along the pipe, t = time, H = piezometric head, and Q = the flow rate in the pipeline, D = pipe diameter, g = gravitational acceleration, A = pipe cross-sectional area, a = wave speed in the fluid, x_B = location of the blockage, $\delta(x - x_B)$ = Dirac delta function, and ΔH_B = head loss across the blockage and is expressed as

$$\Delta H_B = \frac{K_B Q^2}{2gA^2} \qquad (3)$$

where K_B is the head loss coefficient of the blockage and is used as the indicator of the blockage size. If the flow rate is known, the blocked-pipe cross-sectional area or diameter of the blockage can be estimated from K_B (Miller, 1983).

By approaching a partial blockage using a Dirac delta function, the length of the blockage is considered as negligible. Although a pipeline blockage normally has a finite length (less than several meters), such an approximation is reasonable for a long pipeline of several kilometers. If the length of a blockage is not negligible compared to the length of the pipeline, then the delta-function approach is not valid, and such a blockage can be considered as a pipe section with a suitable friction factor and cross-sectional area.

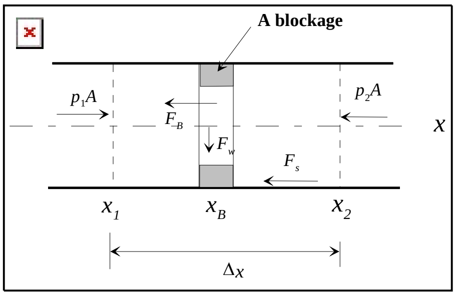


Fig. 1 Free-body diagram for a pipe section with a blockage

The following dimensionless quantities are used to non-dimensionalize (1), (2) and (3):

$$H^* = \frac{H}{H_S},\ t^* = \frac{t}{L/a},\ x^* = \frac{x}{L},\ Q^* = \frac{Q}{Q_0},\ \text{and}\ \delta(x^* - x_B^*) = \delta(x - x_B)L \tag{4}$$

in which $H_s = \dfrac{aV_0}{g}$ is the Joukowsky pressure head rise (that results from an instantaneous reduction of velocity V_0 to zero), L = the pipe length, and Q_0 = a reference flow rate. Substituting (3) into (1), and using (4) in (1) and (2) gives

$$\frac{\partial H^*}{\partial t^*} + \frac{V_0}{a}\frac{Q^*\partial H^*}{\partial x^*} + \frac{\partial Q^*}{\partial x^*} = 0 \tag{5}$$

$$\frac{\partial H^*}{\partial x^*} + \frac{\partial Q^*}{\partial t^*} + \frac{V_0}{a}Q^*\frac{\partial Q^*}{\partial x^*} + \frac{fLQ_0}{2DAa}\left(Q^*\right)^2 - \frac{V_0}{a}\frac{K_B(Q^*)^2}{2}\delta\left(x^* - x_B^*\right) = 0 \tag{6}$$

Because V_0/a is normally small, the second term in (5) and the third term in (6) can be neglected. The dimensionless equations become

$$\frac{\partial H^*}{\partial t^*} + \frac{\partial Q^*}{\partial x^*} = 0 \tag{7}$$

$$\frac{\partial H^*}{\partial x^*} + \frac{\partial Q^*}{\partial t^*} + [R + G\delta(x^* - x_B^*)]Q^{*2} = 0 \tag{8}$$

in which $R = \dfrac{fLQ_0}{2DaA}$ = friction resistance parameter, and $G = \dfrac{K_BQ_0}{2aA}$ = blockage resistance parameter. The dimensionless quantities R, and G are used to characterize the transient problem in a pipeline with a blockage. Noticing that

$$R = \frac{fLQ_0}{2DaA} = \frac{\dfrac{fL}{D}\dfrac{Q_0^2}{2gA^2}}{\dfrac{aQ_0}{gA}} = \frac{H_f}{H_S},\ \text{and}\ G = \frac{K_BQ_0}{2aA} = \frac{K_B\dfrac{Q_0^2}{2gA^2}}{\dfrac{aQ_0}{gA}} = \frac{\Delta H_B}{H_s} \tag{9}$$

in which parameter R is the ratio of friction head loss H_f to Joukowsky pressure head rise H_s, and parameter G is the ratio of blockage-induced head loss ΔH_B to Joukowsky pressure head rise H_s.

Expressing H^* and Q^* as a steady-state values plus a small transient quantity gives

$$H^* = H_0^* + h^* \text{ and } Q^* = Q_0^* + q^* \qquad (10)$$

where h^* = a non-dimensional head deviation from a non-dimensional steady head H_0^*, and q^* = a non-dimensional flow deviation from a non-dimensional steady flow Q_0^*. Substituting (10) into (7) and (8) yields

$$\frac{\partial h^*}{\partial t^*} + \frac{\partial q^*}{\partial x^*} = 0 \qquad (11)$$

$$\frac{\partial h^*}{\partial x^*} + \frac{\partial q^*}{\partial t^*} + [R + G\delta(x^* - x_B^*)](2q^* + q^{*2}) = 0 \qquad (12)$$

Although a governing equation of h^* is preferred (to measure transient pressure is more accurate than to measure transient flow rate), due to the presence of the delta function in (17) and the difficulty in finding the *x*-derivative of the delta function, the variable q^* cannot be eliminated. Applying the operation $\dfrac{\partial[\text{Eq.}\,(11)]}{\partial x^*} - \dfrac{\partial[\text{Eq.}\,(12)]}{\partial t^*}$ gives the governing equation in terms of q^* as

$$\frac{\partial^2 q^*}{\partial x^{*2}} = \frac{\partial^2 q^*}{\partial t^{*2}} + [2R + 2G\delta(x^* - x_B^*)](1 + q^*)\frac{\partial q^*}{\partial t^*} \qquad (13)$$

The last term of (13) is non-linear. For a small transient where $q^* << 1.0$, (13) is simplified to

$$\frac{\partial^2 q^*}{\partial x^{*2}} = \frac{\partial^2 q^*}{\partial t^{*2}} + [2R + 2G\delta(x^* - x_B^*)]\frac{\partial q^*}{\partial t^*} \qquad (14)$$

For a pipeline connecting two reservoirs with constant water elevations

$$h^*(0\,,\,t^*) = 0 \text{ and } h^*(1\,,\,t^*) = 0 \qquad (15)$$

Substituting (15) into the continuity equation (11) gives flow boundary conditions

$$\frac{\partial q^*(0,t^*)}{\partial x^*} = 0 \quad \text{and} \quad \frac{\partial q^*(1,t^*)}{\partial x^*} = 0 \qquad (16)$$

If a known transient has been initiated in the pipeline, the initial flow conditions are given as

$$q^*(x^*,0) = f_q(x^*) \text{ and } \frac{\partial q^*(x^*,0)}{\partial t^*} = g_q(x^*) \qquad (17)$$

By applying a Fourier expansion (Wang 2002, Appendix C), the solution of (14) subject to the boundary condition in (17) is

$$q^*(x^*,t^*) = \sum_{n=1}^{\infty}\left\{e^{-(R+R_{nB})t^*}\left[(A'_n\cos(n\pi t^*) + B'_n\sin(n\pi t^*)\right]\cos(n\pi x^*)\right\} \qquad (18)$$

in which

$$R_{nB} = 2G\cos^2(n\pi x_B^*) \qquad (19)$$

= blockage damping parameter for Fourier component n , and x_B^* = dimensionless blockage location along the pipeline. The values of the Fourier coefficients in (18) are calculated using the initial conditions as

$$A'_n = 2\int_0^1 f_q(x^*)\cos(n\pi x^*)dx^* \quad (n = 1, 2, 3,......) \tag{20}$$

$$B'_n = \frac{1}{n\pi}[\int_0^1 2g_q(x^*)\cos(n\pi x^*)dx^* + A_n(R + R_{nB})] \quad (n = 1, 2, 3,......) \tag{21}$$

The transient pressure can be measured more accurately and less expensively than the transient flow rate in a pipeline due to the low accuracy and slow response of the flow meters. The solution for transient pressure is obtained by integrating the continuity equation (11) with respect to t^* as

$$h^*(x^*,t^*) = \int -\frac{\partial q^*(x^*,t^*)}{\partial x^*}dt^* \tag{22}$$

Substituting (18) into (22) gives

$$h^*(x^*,t^*) = \sum_{n=1}^{\infty}\left\{e^{-(R+R_{nB})t^*}\left[A_n\cos(n\pi t^*) + B_n\sin(n\pi t^*)\right]\sin(n\pi x^*)\right\} \tag{23}$$

where the Fourier coefficients are

$$A_n = -\frac{A'_n(R + R_{nB}) + B'_n n\pi}{(R + R_{nB})^2 + (n\pi)^2}, \text{ and } B_n = \frac{A'_n n\pi - B'_n(R + R_{nB})}{(R + R_{nB})^2 + (n\pi)^2} \tag{24}$$

However, more generally the Fourier coefficients A_n and B_n can be determined from initial conditions on pipeline pressure, which can be expressed as

$$h^*(x^*,0) = f_h(x^*) \text{ and } \frac{\partial h^*(x^*,0)}{\partial t^*} = g_h(x^*) \tag{25}$$

and

$$A_n = 2\int_0^1 f_h(x^*)\sin(n\pi x^*)dx^* \quad (n = 1, 2, 3,...) \tag{26}$$

$$B_n = \frac{2}{n\pi}\int_0^1 g_h(x^*)\sin(n\pi x^*)dx^* + \frac{(R + R_{nB})A_n}{n\pi} \quad (n = 1, 2, 3,...) \tag{27}$$

Detection of a blockage

Eq. (23) shows that any measured transient in a pipeline that includes a blockage is the summation of a series of harmonic components that are each exponentially damped with the damping rate of $R + R_{nB}$ ($n = 1, 2, 3,\ldots$). In a pipeline without any blockages, the damping of each Fourier component is independent of the component number, n, and depends only on the friction damping factor, R. Therefore, given steady flow conditions followed by a transient event, presence of a pipeline blockage is indicated by:

1. The damping rates $R+R_{nB}$ of the decomposed harmonic components are significantly different from each other, and

2. The damping rates for some components are larger than the friction-damping factor R.

Location of a blockage

For each of the Fourier components, the blockage-induced damping is a function of blockage magnitude and location. However, the ratio of any two blockage-induced damping coefficients defined in (19) is a function of blockage location only, which is expressed as

$$\frac{R_{n_2 B}}{R_{n_1 B}} = \frac{\cos^2(n_2 \pi x_B^*)}{\cos^2(n_1 \pi x_B^*)} \tag{28}$$

Therefore, the location of the blockage can be determined from the ratio of any two blockage-induced damping coefficients. Since the friction damping factor R can be calculated from the steady flow condition based on an estimated pipe friction factor f (influence of errors in the friction factor f on the blockage detection has been investigated in a sensitivity analysis in Wang 2002), the blockage-induced damping for any component R_{nB} is easily obtained by subtraction. Fig. 2 is a plot of the theoretical relationship between the damping ratios of harmonic components $n_2 = 2$, $n_1 = 1$ and harmonic components $n_2 = 3$, $n_1 = 1$ with the corresponding blockage locations in a pipeline.

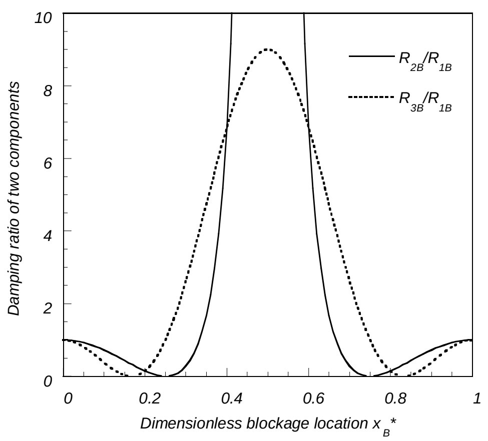


Fig. 2 Ratio of blockage damping coefficients of two Fourier components

Due to the symmetric character of the cosine squared function, the relationship between the damping ratio of two harmonic components and the blockage location is not unique. Two or up to four blockage locations correspond to one value of the damping ratio R_{2B}/R_{1B} except for $x_B^* = 0.5$, which is a unique point because the blockage damping $R_{1B} = 0$ at $x_B^* = 0.5$. For the damping ratio of higher harmonic components, one damping ratio corresponds to more possible blockage locations; therefore, only harmonic components of $n < 4$ are used for blockage detection analysis in this study.

Magnitude of a blockage

Once the position of the blockage has been determined, the blockage magnitude can be easily calculated based on the definition of R_{nB} in (19). It is

$$G = \frac{R_{nB}}{2\cos^2(n\pi x_B^*)} \quad (n = 1, 2, 3, \ldots) \qquad (29)$$

where n is any one of the components. Theoretically, the blockage magnitude calculated using different components should be the same. Different measurement positions and different forms of transients can be used for added confirmation and to increase accuracy if necessary.

Laboratory experimental verification

Experimental tests were conducted in a single pipeline in the Robin Hydraulics Laboratory at the University of Adelaide to verify the practical feasibility of the proposed blockage detection method. The experimental setup is shown in Fig. 3. A blockage is simulated by a partially closed valve (Valve 1) located near the Tank 1.

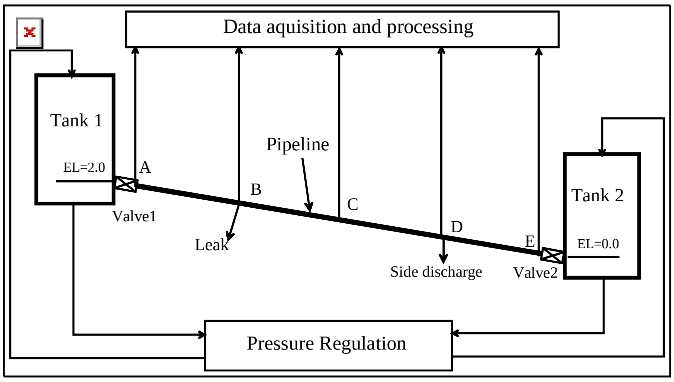
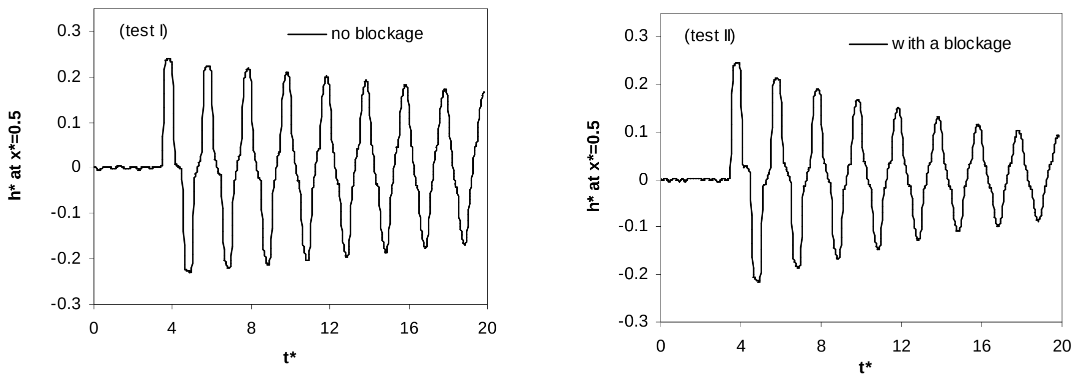


Fig. 3 Laboratory setup for blockage detection

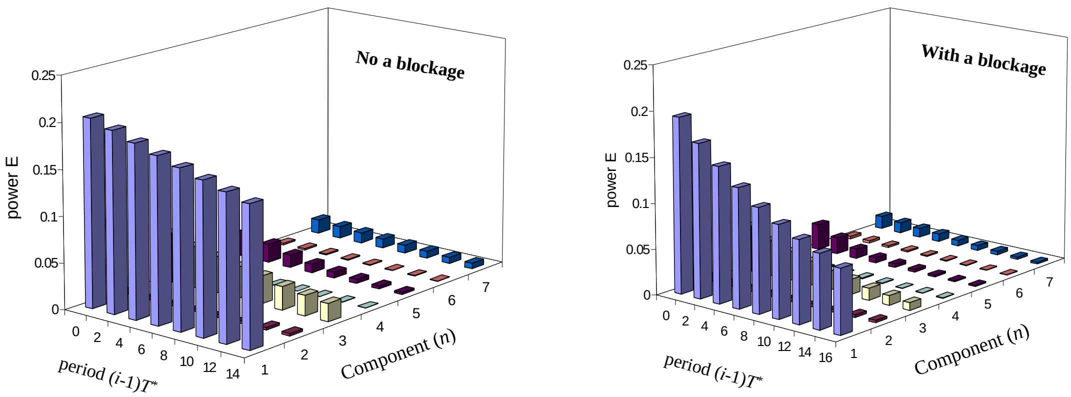
Two tests were conducted. Test I is a no–blockage case (Valve 1 is fully open) and in Test II, the Valve 1 is partially closed. The flow conditions are as follows:

Length of the pipeline	L = 37.2 m,
Pipe diameter	D = 0.022 m,
Thickness of the pipe wall	e = 1.6 mm,
Wave speed	a = 1,320 m/s,

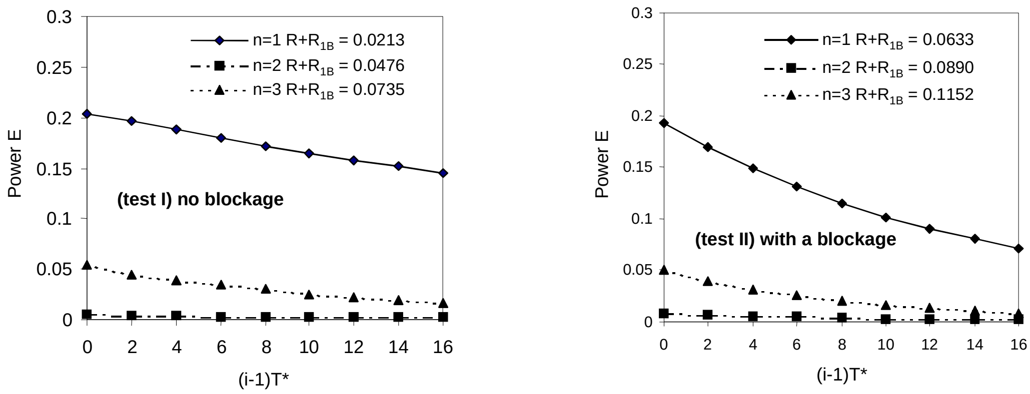
In both Test I and Test II, the heads at two tanks are set as H_1 = 27.53 m, and H_2 = 26.60 m. In Test I, the Valve 1 is fully open, and the steady flow velocity in the pipeline was V_0 = 0.80 m/s. Given the Reynolds number of Re = 15400, the Darcy-Weisbach friction factor is calculated as f = 0.017 (smooth pipe) and the steady friction damping factor is calculated as R = 0.0087. In Test II, the Valve 1 is partially closed, the steady flow in the pipeline is reduced to V_0 = 0.36 m/s, and the steady friction damping factor is calculated as R = 0.0036. Based on the total head loss and the steady flow in the pipeline, the head loss coefficient of the partially closed Valve 1 is calculated as K_B = 114.9.



(a) Measured transients



(b) Frequency analysis



(c) Damping analysis

Fig. 4 Laboratory experimental verification of blockage detection technique

In Test I, the valves at locations A and E (see Fig. 3) and the side-discharge valve at D are opened and a steady state condition is achieved. The side-discharge solenoid valve at D is then closed quickly. In Test II, the valve 1 at A is partially closed, and the valve at location E is fully open. The side-discharge valve at D is open until steady state conditions are obtained. The side-discharge valve at D is then sharply closed. During the tests, pressures are measured by five pressure transducers at points A, B, C, D, and E. Measured pressures in the middle of the pipeline (x^* = 0.50) from both Test I and Test II are plotted in Fig. 4(a). The blockage-induced damping of Test II is obvious compared to the transient in Test I that has no blockage.

Fig. 4(b) shows the computed amplitudes of different harmonic components by decomposing the transient signal into a Fourier series period by period. Each component was fitted to an exponential function, and the damping coefficient of each component was calculated.

The damping coefficients of the first three components (n = 1, 2, 3) for both Test I and Test II are presented in Fig. 4(c). For the no-blockage case (Test I), friction damping coefficients of the first three harmonic components are R_1 = 0.0213, R_2 = 0.0476, R_3 = 0.0735, all being larger than the steady friction damping factor R_s = 0.0087, calculated using steady state friction. The differences between the measured and the calculated damping values are due to unsteady friction. It accounts for 46%, 76% and 84% of the total for the first three components.

In Test I and Test II, since the transients were initiated by closing the side-discharge valve in the same amount of time, the unsteady friction damping effects are approximately the same. Therefore, in Test II the friction damping coefficients for the first three components are R_1 = 0.0161, R_2 = 0.0424 and R_3 = 0.0683. By subtracting the friction damping from the total damping, blockage-induced damping coefficients for the first three components (n = 1, 2, 3) are R_{1B} = 0.0472, R_{2B} = 0.0466, R_{3B} = 0.0469. The ratios of damping coefficients R_{2B} and R_{1B}, and R_{3B} and R_{1B} are $\frac{R_{2B}}{R_{1B}} = 0.994$, and $\frac{R_{3B}}{R_{1B}} = 0.994$. Corresponding blockage locations for these damping ratios are x_B^* = 0.0 (or x_B^* = 1.0) by applying these two ratios in Fig. 2. This is same as the real blockage location x_B^* = 0.0. Using R_{1B} = 0.0472, R_{2B} = 0.0466 and leak location x_B^* = 0.0, the head loss coefficient for the blockage is calculated from (29), as K_B = 188.8. The value of the head loss coefficient calculated from the transient experiment is about 40% larger than that based on steady-state test of K_B = 114.9. The reason for this difference is due to the assumption of theoretical blockage head loss relationship in (3). The actual relationship between head loss and flow rates through the blockage is not exact power of two.

Conclusions

The behaviour of a blockage on pipeline transients has been studied analytically and experimentally. A general conclusion of these investigations is that transients in a pipeline can be used for blockage detection. A technique for blockage detection, location and quantification has been developed. Experimental examples have shown that blockage with cross-sectional area of 20% of the pipe cross section can be detected and located. The proposed blockage detection technique is simple to use and apply; however, this method may not be applicable in complex systems such as pipe networks.

The analytical solution indicates that transients in pipelines are damped by both friction and blockages. Blockage-induced damping is exactly exponential for each of the individual harmonic components. Compared to leak-induced damping (Wang et al. 2002), which is related to pressure in the pipeline and is independent of flow rate in the pipeline, blockage damping is proportional to flow rate, and does not have a direct relationship with the pressure in the pipeline. Therefore, blockage detection should be conducted at conditions of a considerable flow rate in order to produce best performance. In addition, blockage-induced transient damping and leak-induced transient damping (Wang et al. 2002) have different modes. The relationship between blockage location and blockage damping is a cosine-square function while leak location and leak damping is a sine-square function. As a result, leak locations and blockage locations along a single pipeline have different responses to a transient event.

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