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Modeling of transient flows in viscoelastic pipe network with partial blockage

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ABSTRACT

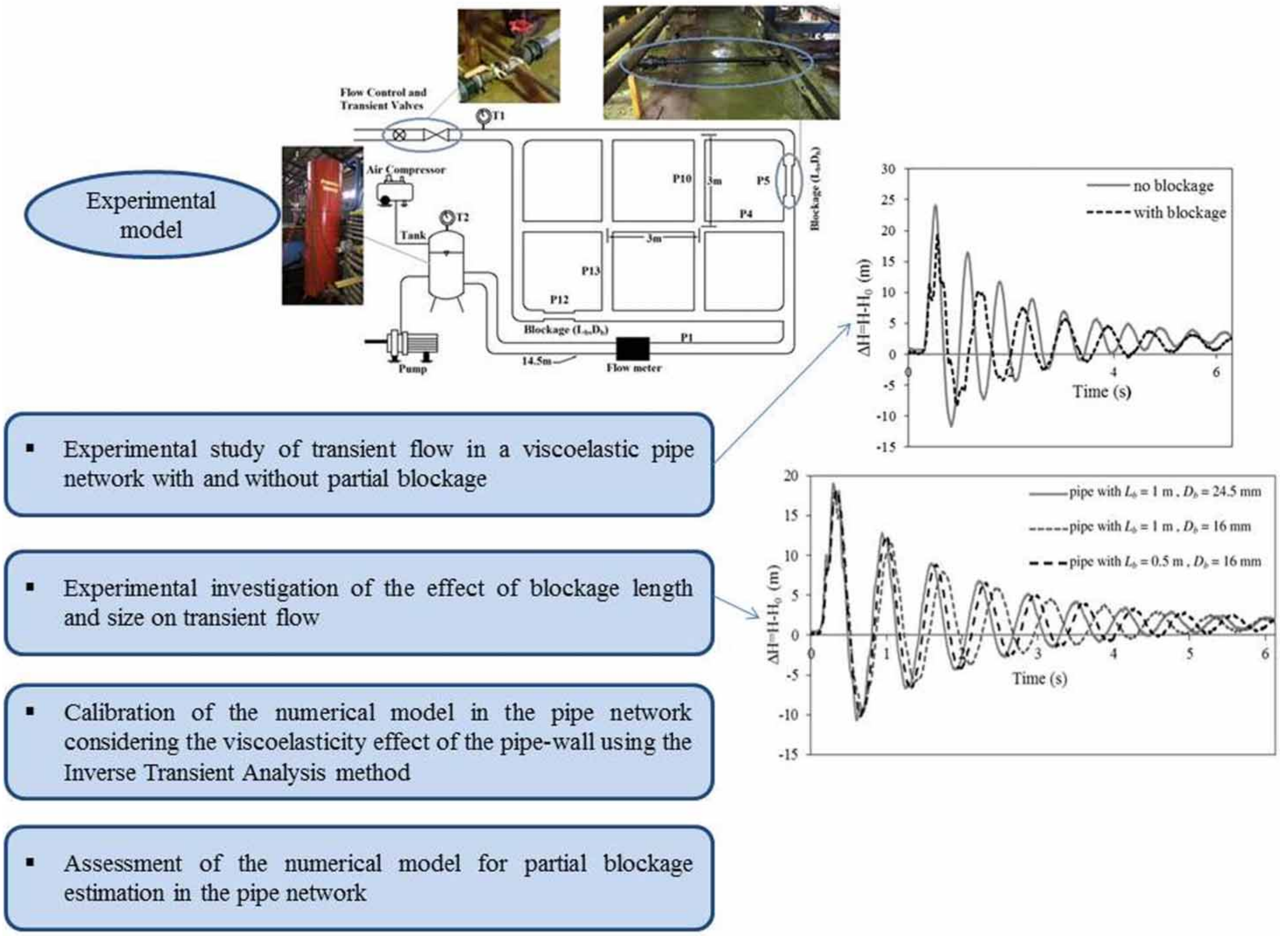
In this study, transient flow and partial blockage in polyethylene (PE) pipe network are investigated experimentally and numerically using the method of characteristics in the time domain considering pipe-wall viscoelasticity. The experiments were conducted on a PE pipe network with and without partial blockage. The experimental pressure signals were damped during a short period of time in the blockage-free case. The numerical model was calibrated by the inverse transient analysis (ITA). The hydraulic transient solver calibrated with one Kelvin–Voigt element showed good consistency with the experimental results. Partial blockages with different lengths and sizes were examined at different locations of the pipe network. Results reveal an increase in head loss, pressure signal damping, and phase shift with increase in blockage. In addition, the location and characteristics of blockages with different sizes were determined using the ITA in the pipe network.

Key words: partial blockage, polyethylene pipe network, transient flow, viscoelasticity

HIGHLIGHTS

- Experimental investigation of transient flow properties in a viscoelastic pipe network.
- The effects of blockage on transient flow were examined in a polymer pipe network.
- ITA was used to calibrate the numerical model.
- Determining the blockage characteristics in the pipe network.

GRAPHICAL ABSTRACT



ABBREVIATIONS

The following symbols are used in this paper:

A	pipe cross-sectional area
a	pressure wave speed
D_b	diameter of blockage
E_0	the elasticity modulus of the pipe-wall
E_k	the elasticity modulus of the spring of k element
f_s	the frictional loss coefficient of the steady-state
g	gravity acceleration
H	pressure head
H_0	steady-state pressure head
h_{fs}	steady frictional loss
h_{fu}	unsteady frictional loss
J	creep compliance function
J_0	the instantaneous creep compliance
J_k	creep compliance of the spring of k element
L_b	length of blockage
$ALSE$	the average least square errors
N	the number of elements in Kelvin–Voigt model
P	the ratio of the radial diffusion timescale to the pressure wave timescale
Q	flow rate

Re dimensionless Reynolds number
t time
V_0 steady-state velocity
x the coordinates of the pipe axis
ε the prediction error for blockage characteristics
ε_e instantaneous elastic strain
ε_r retarded strain
μ_k the viscosity of the dashpot of k element
τ_k retardation time of the dashpot of k element
σ stress

INTRODUCTION

Propagation of transient flow and estimation of maximum and minimum pressure waves are essential in water supply and design and operation of pipe network systems. Transient flows are initially formed due to changes in the boundary conditions of the system. The pressure wave signals are then measured and analyzed to assess the condition of the piping systems. Many researchers have studied transient flow and the head loss caused by unsteady flows (Brunone *et al.* 1991; Pezzinga 2000; Vitkovsky *et al.* 2000; Fathi-Moghadam *et al.* 2013; Duan *et al.* 2017b, 2018). Recently, the practice of polymer pipes such as polyethylene (PE) and PVC in water supply systems and pipe networks has attracted much attention due to their superior structural and hydraulic properties. Researches have been conducted on the dynamic behavior and viscoelastic effects of polymeric pipes under transient pressure oscillation. Brunone *et al.* (2000) examined the pressure wave damping in a PE pipeline considering unsteady friction; however, their study showed a significant difference between the numerical and experimental results due to their disregard for the viscoelasticity effects of polymer pipe-walls. Covas *et al.* (2004) also studied the dynamic behavior of PE pipes under transient pressure oscillation. Their numerical and experimental results showed that pressure waves in pipes are quickly damped, causing time delay and a sudden strong pressure drop immediately after a fast valve closure. In another study, Covas *et al.* (2005) developed a numerical model to calculate transient pressure in PE piping systems. Comparison of transient flow signals of the system with a classic model showed that their numerical model is able to predict the pressure fluctuations and circumferential strains in PE pipes.

The viscoelastic behavior of PVC pipes with the transient flow was investigated by Soares *et al.* (2008). The creep function of these pipes was calculated by the inverse transient analysis (ITA). The results showed that the damping, scattering, and shape of the transient pressure waves are fully described by taking into account the viscoelastic behavior of the pipe-wall in the developed numerical model. Carriço *et al.* (2016) showed that unsteady friction and viscoelasticity of PE pipe-walls have similar effects on transient signals and the effects cannot be simultaneously distinguished. The study by Duan *et al.* (2010) showed that the pressure head damping attributable to unsteady friction is comparable to the viscoelasticity of the pipe-wall during the initial transient wave stage. However, the contribution of the viscoelastic effect was greater both in terms of peak attenuation and phase shift in later stages. Evangelista *et al.* (2015) investigated the transmission and reflection of transient pressure waves in high-density polyethylene (HDPE) branched pipelines. Their results indicated a significant variation of transmission and reflection coefficients at pipe junctions compared to suggested coefficients by classic theory. The difference was due to the viscoelastic behavior of the pipe-wall materials. In their study, viscoelastic parameters of the pipe system were calibrated regardless of unsteady friction effects. Pan *et al.* (2020) presented an effective transient-based method to examine viscoelastic parameters of plastic pipes.

As one of the many problems faced in piping systems, leakage and blockage can be caused by different physical and chemical processes in pipelines and pipe networks, ultimately resulting in failure, energy loss, and reduced system efficiency. Transient flow and its application as a method of assessing the effects of leakage and blockage in piping systems can be found in Stephens *et al.* (2002), Adewumi *et al.* (2003), Haghighi & Ramos (2012), Meniconi *et al.* (2012), Tuck *et al.* (2013), Duan (2016, 2018, 2020), Duan *et al.* (2014, 2017a), Capponi *et al.* (2017, 2020), Zhao *et al.* (2018), Louati *et al.* (2018), Rahmanshahi *et al.* (2018), Keramat & Zanganeh (2019), Zouari *et al.* (2020), Zhang *et al.* (2020), and Pan *et al.* (2021). Stephens *et al.* (2002) conducted field investigations and used transient flows to identify the blockages in a long pipeline as part of a piping system composed of pipelines, branches, and loops. They reported that the identification accuracy was dependent on the length of the different segments in the pipe network. The length and diameter of the pipeline were 575 and 100 mm, respectively, within which four blockages with two different sizes were artificially created. The results from the ITA showed that the predicted values for the location and size of the blockages were close to the field measurements.

Adewumi *et al.* (2003) proposed a numerical method to determine the location and characteristics of extended blockages caused by the deposition of hydrates in gas pipelines. They showed that the system's internal conditions could be identified in the time domain by generating transient pressures and examining the pressure variations caused by the reflections from the blockages in the pipeline.

Meniconi *et al.* (2012) evaluated the effect of changes in the pipe cross-section on the behavior of transient wave in a visco-elastic series pipeline system. The results showed that pressure damping occurs over a long period, but the effect of discontinuities is only tangible in the initial phases of the transient flow. Moreover, each intense change in the pressure signal was found to be associated with the pressure wave passing through the measuring sections. Later, they compared the effects of partial blockage in two pipeline systems with elastic and viscoelastic materials (Meniconi *et al.* 2013). The blockage characteristics were determined using the ITA and found that the prediction error was probably due to the pipeline material, boundary conditions of the system, and blockage characteristics. In the same year, Tuck *et al.* (2013) compared the transient reactions in a pipeline with and without extended blockages and found the extended blockages change the period of oscillations depending on the length and severity of the blockage. Duan *et al.* (2014) placed an extended blockage in the pipeline and measured the transient reactions in the frequency domain. Their results showed that the blockage changes the resonant amplitudes and frequency locations, and that changing the frequency location can be used to identify the location of the blockage. Che *et al.* (2021) showed that a blockage in the pipe system affects the pressure heads. These changes may exceed the original transient design capacity and increase the risk of pipe system failure.

Previous studies have mostly focused on transient flow and blockage effects in simple systems such as the reservoir-pipe-valve system. The purpose of this study is to experimentally investigate the properties of transient flows and partial blockage effects in more complex PE piping networks. Using a genetic algorithm scheme and the ITA method, the numerical model in this study is calibrated for a pipe network in the absence and presence of blockage while considering the polymer pipe-wall's viscoelasticity. The location and characteristics of the pipe network blockages were determined by the ITA.

EXPERIMENTAL MODEL

Experimental setup

To conduct experiments for transient flow and blockage effects, a PE pipe network was assembled in the Hydraulic Laboratory of the Faculty of Water and Environmental Engineering at Shahid Chamran University of Ahvaz (Figure 1). The pipe network consists of six 3×3 m square loops. The pipes were HDPE with a nominal diameter of 50 mm, wall thickness of 5.5 mm, and nominal pressure of 16 bar. A 700 L pressurized tank was at the network upstream end to avoid the development of negative transient pressure waves. A ball valve at the network downstream end was used to generate the required transient pressure waves for analysis. A globe valve was placed downstream of the ball valve to control and adjust the steady flow for the experiments. The steady discharge in the system was measured using an ultrasonic flowmeter. Multiple-axial supports were used to anchor pipes to the ground and prevent the propagation of additional pipe-wall stress waves into transient pressure waves (Keramat *et al.* 2020). Experiments were performed with and without blockage at different steady-state flow rates of 0.86–1.5 L/s in a turbulent flow regime. Accordingly, the range of steady Reynolds numbers (Re) for this study is $(28\text{–}49) \times 10^3$. A programmable step motor was connected to the ball valve to close the valve automatically.

The transient pressure signals were measured upstream of the ball valve and top of the pressure tank (T1 and T2 in Figure 1) using calibrated WIKA S-11 pressure transmitters with a pressure range of 0.0–16.0 bar and a sampling frequency of 1,000 Hz. Smaller diameter pipes (D_b) with different lengths (L_b) were placed at different locations throughout the network to model blockage. The effects of blockage on transient flow signals in the pipe network were used to calibrate the numerical model and thereby characterize the blockage. A list of experiments with blockage location and characteristics are shown in Table 1.

Experimental investigation of the blockage impact on transient signals in the pipe network

In this section, experiments are conducted to examine the effects of blockage on transient pressure waves in a viscoelastic pipe network. In the first set of experiments, a smaller diameter pipe with $L_b = 1.0$ m and $D_b = 16$ mm was placed at P5 in Figure 1, and pressure signals were recorded upstream of the ball valve (transducer T1). Figure 2 presents a comparison of the overpressure transient signals ($\Delta H = H - H_0$, where H is the transient pressure head and H_0 is the steady-state pressure head) for the experiments with and without blockage at P5. Figure 2 reveals that in the no-blockage case, the initial pressure peak was damped over a short period of time. The pressure peaks and damping period of the transient wave were less in the pipe network relative to a long single pipeline of the same material as tested and reported in Fathi-Moghadam & Kiani (2020).

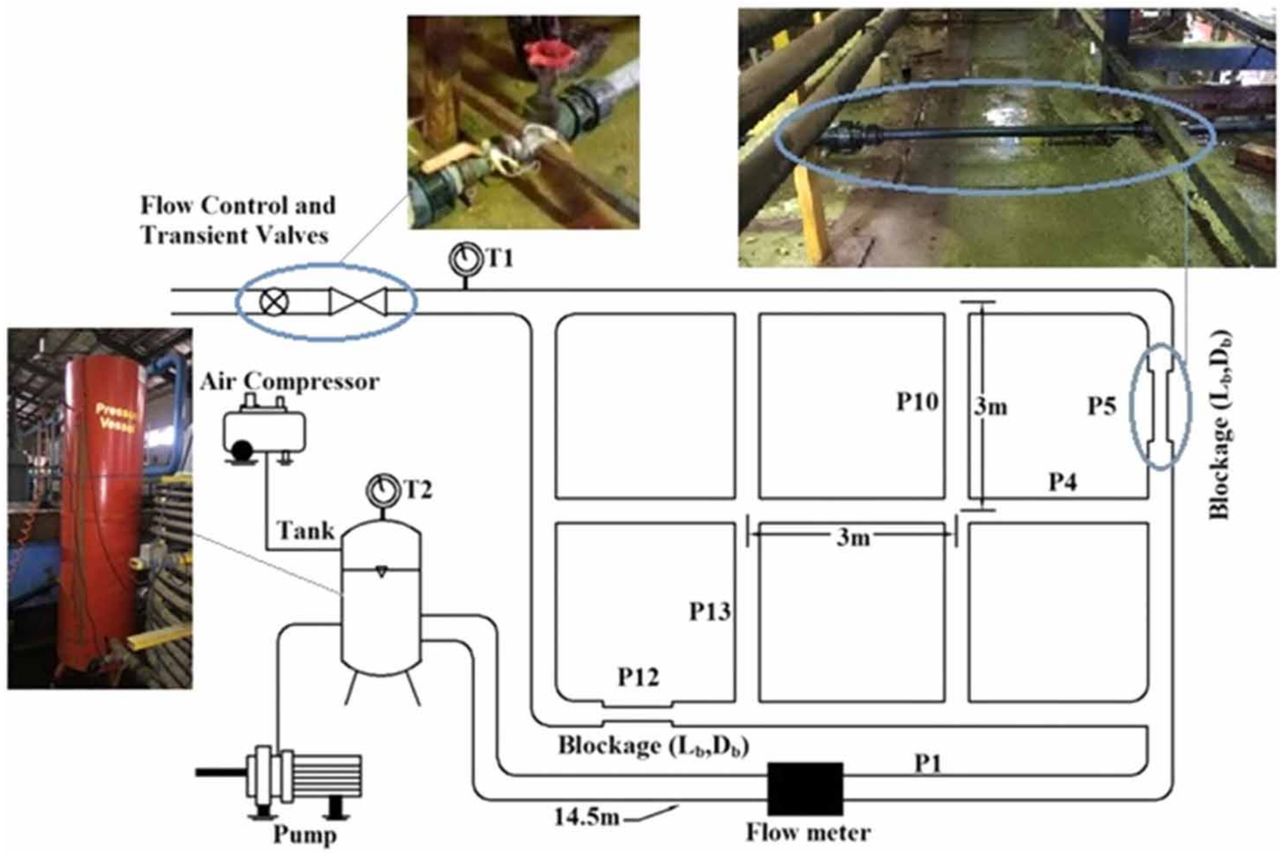


Figure 1 | Schematic of the tested pipe network and position of the blockages.

Table 1 | Specifications of the tested blockages in the pipe network

Blockage	Location	L_b (m)	D_b (mm)
Blockage 1	P5	1	16
Blockage 2	P5	1	24.5
Blockage 3	P12	1	16
Blockage 4	P12	1	24.5
Blockage 5	P12	0.5	16

This means that the intensity of pressure damping is greater in a pipe network. However, blockage in the pipe network changes the maximum and minimum transient pressure heads and causes damping of the transient flow signal in comparison with the no-blockage case. The effect of pressure reflection from the blockage in the network increases the intensity of the initial pressure peak damping of the transient wave signal in a shorter period of time. Also, the comparison of cases with and without blockage shows that the presence of blockage in the pipe network causes more phase shifts of the pressure signal and changes the time of pressure peaks. Moreover, the pressure reflection produced by a blockage in the network also transforms the transient signal. Meniconi *et al.* (2012) pointed out that changes caused by blockage are more noticeable in the early pressure cycles of the transient wave signal. This is also confirmed here in the magnified first 3 s of signals in Figure 2.

In order to investigate the effect of blockage length and size on transient pressure waves in the network, pipes with lengths of $L_b = 0.5$ and 1 m and diameters $D_b = 16$ and 24.5 mm were placed in the P12 branch (Figure 1) and pressure signals upstream of the ball valve were recorded in Figure 3. Results reveal greater pressure damping and phase shift for higher

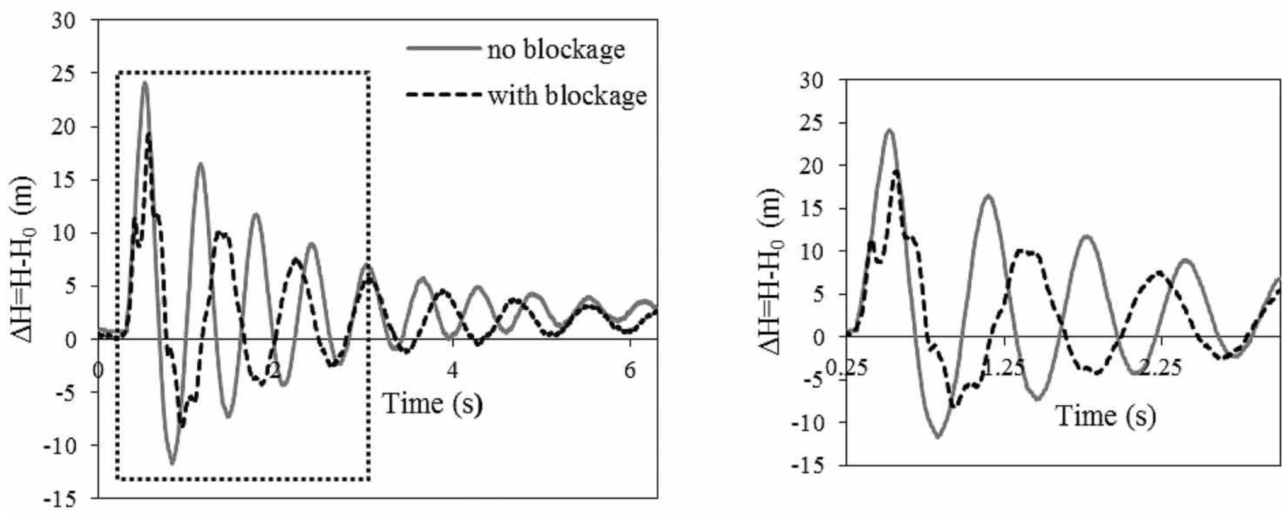


Figure 2 | Comparison of transient signals with and without blockage for discharge of 1.5 L/s; and magnification of transient signals in the first 3 s of pressure oscillation.

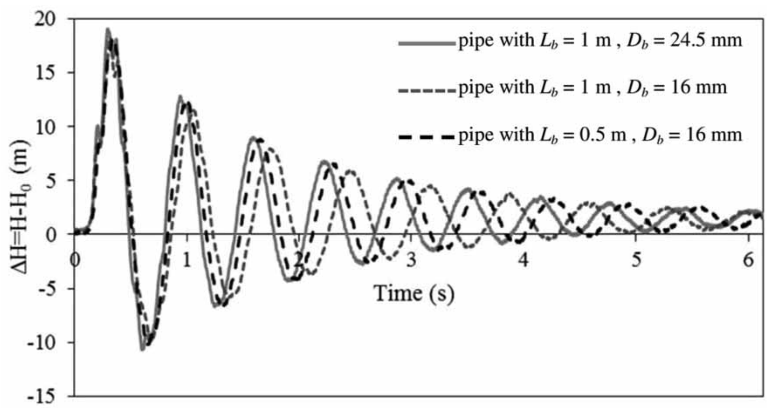


Figure 3 | Comparison of transient signals for different blockage lengths and diameters (discharge of 1.2 L/s).

blockage length ($L_b = 1$ m) and size ($D_b = 16$ mm) due to more pressure loss. Also, the results show that the change in the blockage diameter has more effects on the amplitude and phase of transient pressure wave than blockage length. Therefore, it can be assumed that a numerical model will be able to estimate blockage diameter more accurately than blockage length. This issue is further discussed in the 'Numerical model' section.

NUMERICAL COMPARISON AND DISCUSSION

Numerical model

The governing equations for transient flow in pipes are continuity and momentum equations (Equations (1) and (2)) as discussed in Covas *et al.* (2005). These equations are used in this study for the viscoelastic effect of the pipe-wall.

$$\frac{dH}{dt} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} + \frac{2a^2}{g}\frac{d\varepsilon_r}{dt} = 0 \tag{1}$$

$$g\frac{\partial H}{\partial x} + \frac{1}{A}\frac{dQ}{dt} + g(h_{\mathrm{fs}} + h_{\mathrm{fu}}) = 0 \tag{2}$$

where x is the coordinates of the pipe axis, t is the time, H is the pressure head, Q is the flow rate, a is the pressure wave speed, g is the gravity acceleration, A is the pipe cross-sectional area, h_{fs} is the steady frictional loss, h_{fu} is the unsteady frictional loss, and ε_r is the retarded strain.

The continuity and momentum equations in the pipe network are solved using the method of characteristics (MOC; Covas & Ramos 2001). The pressurized tank with fixed head and the transient valve (Figure 1) are considered as upstream and downstream boundary conditions in the numerical model along with junctions' boundary conditions (as discussed in Chaudhry (2014)). The steady-state head loss is calculated by the Darcy–Weisbach equation. To calculate the steady loss coefficient, the Hagen–Poiseuille equation (Equation (3)) is used for laminar flow conditions, and the Blasius equation (Equation (4)) is used for turbulent flow and smooth pipe-wall.

$$f_s = \frac{64}{\text{Re}} \tag{3}$$

$$f_s = 0.316\text{Re}^{-0.25} \tag{4}$$

where f_s is the frictional loss coefficient of the steady-state and Re is the dimensionless Reynolds number.

The results of Duan *et al.* (2010) indicate that accurate physically based unsteady friction models are required if the ratio of radial diffusion timescale to the pressure wave timescale is of order 1 or less, defined by parameter P as

$$P = \frac{2D/fV_0}{L/a} \tag{5}$$

where V_0 is the initial flow velocity. Since the parameter P is calculated to be greater than 1 in this study, the effects of unsteady friction loss are assumed negligible and only the viscoelastic effect of the pipe-wall is considered in the numerical model.

In PE pipes, the strain is divided into instantaneous elastic strain (ε_e) and retarded strain (ε_r) (Covas *et al.* 2005):

$$\varepsilon(t) = \varepsilon_e + \varepsilon_r(t) \tag{6}$$

and the strains caused by continuous applying of a stress $\sigma(t)$ can be linearly added according to the Boltzmann Superposition Principle, and the total strain is calculated as follows (Aklonis *et al.* 1972):

$$\varepsilon(t) = J_0\sigma(t) + \int_0^t \sigma(t-t')\frac{\partial J(t')}{\partial t'}dt' \tag{7}$$

where J_0 is the instantaneous creep compliance and $J(t')$ is the creep function at t'.

The creep function for viscoelastic materials is defined as follows using the generalized Kelvin–Voigt mechanical model (Aklonis *et al.* 1972):

$$J(t) = J_0 + \sum_{k=1}^{N} J_k(1 - e^{-t/\tau_k}) \tag{8}$$

where J_0 is the creep compliance of the first spring, defined as $J_0 = 1/E_0$; E_0 is the elasticity modulus of the pipe; J_k is the creep compliance of the spring of k element in the Kelvin–Voigt model, defined as $J_k = 1/E_k$; E_k is the elasticity modulus of the spring of k element; τ_k is retardation time of the dashpot of k element, defined as $\tau_k = \mu_k/E_k$, where μ_k is the viscosity of the dashpot of k element; and N is the number of elements in the Kelvin–Voigt model.

Inverse transient analysis method

There are several methods for calibration and defect detection in the pipeline systems (Che *et al.* 2021). In this study, the ITA is used to estimate the system's unknown parameters. One of the advantages of the ITA is its application to pipe systems with complex topography and configurations (Che *et al.* 2021). ITA uses the data collected from the real systems to predict the unknown parameters. The difference between the collected data and computational values is minimized by the optimization algorithm, and then the unknown parameters are estimated. In this study, the unknown parameters are wave speed, creep function parameters, location, and characteristics of the blockage in the pipe network. The collected pressure signals upstream of the ball valve (T1) were used in the ITA, and the genetic algorithm was used as the optimization method. The objective function of the optimization algorithm is defined by the average least square errors ($ALSE$).

$$ALSE = \frac{\sum_{i=1}^{M} [H_i^* - H_i]^2}{M} \quad (9)$$

where H_i* is the pressure head values collected from the experimental model, H_i is the pressure head values computed by the numerical model, and M is the number of measurements.

Calibration of numerical model

The numerical model was calibrated and verified using experimental pipe network data in the intact pipe network. The transient flow equations were discretized using the finite-difference method. The minor losses in the network were assumed negligible as suggested by Chaudhry (2014) and Fathi-Moghadam & Kiani (2020). In addition, the sample size used in the ITA was considered to be 6 s. To calibrate the model for the viscoelastic effect of the pipe-wall, only the steady-state friction was considered, and calibration parameters were estimated. In this case, the calibrated parameters were wave speed (a), retardation time (τ_k), and creep coefficient of Kelvin–Voigt element (J_k).

In the study by Fathi-Moghadam & Kiani (2020) on the same experimental pipe network, it was shown that some viscoelasticity effects on pressure wave damping and dispersion are less in the short viscoelastic pipes of the considered network. Their study showed the optimal number of Kelvin–Voigt elements for the viscoelastic pipe network with short pipes is one. In this paper, a sensitivity analysis was performed on the model with 1, 2, and 3 elements. Results showed that there is no clear difference between these three cases. Therefore, the optimum number of Kelvin–Voigt elements for the pipe network was selected as one for further analysis. Moreover, wave speed, creep compliance coefficient, and retardation time of Kelvin–Voigt element were simultaneously calibrated using the ITA, and the following values were estimated: $a = 329$ m/s, $J_1 = 26 \times 10^{-11}$ Pa^{-1}, and $\tau_1 = 0.048$ s. The pressure oscillation results collected from the upstream of the ball valve (T1) and model computed results with one Kelvin–Voigt element are shown in Figure 4 for steady flow discharge of 1.5 L/s. Considering the viscoelastic effect of the pipe-wall, Figure 4 shows good agreement between the numerical and experimental results. Consequently, the viscoelastic model is able to properly predict the transient pressure damping and phase shift.

The creep compliance function for PE pipe network of the present study was determined using the ITA method and the pressure oscillations upstream of the ball valve (T1). Using calibrated values of the creep coefficient (J_1) and retardation time (τ_1) in Equation (8), the creep function was calculated and plotted in Figure 5. The creep function in the viscoelastic pipe network with one Kelvin–Voigt element approaches constant value over a short period of time. This result is consistent with the study by Fathi-Moghadam & Kiani (2020).

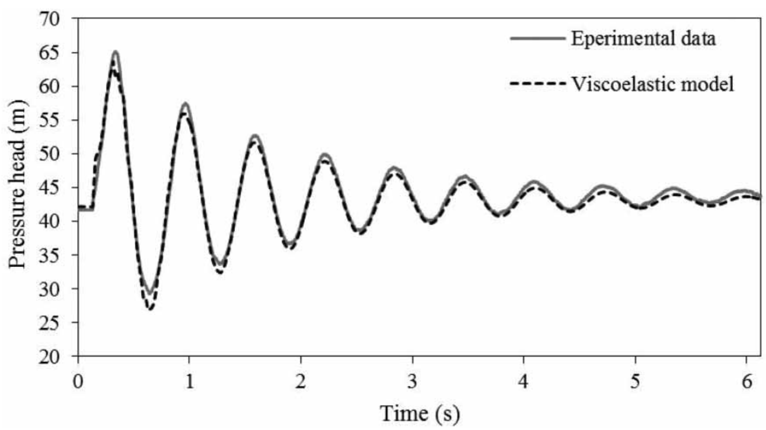


Figure 4 | Comparison of the experimental and numerical results of the viscoelastic model with one Kelvin–Voigt element.

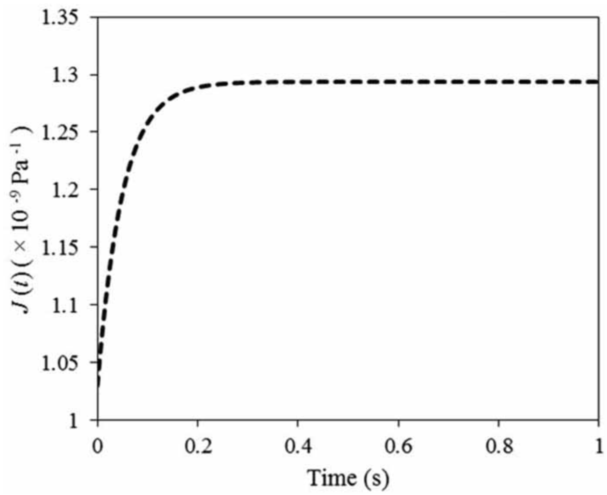


Figure 5 | Calibrated creep function for viscoelastic pipe network.

Assessment of the model for partial blockage estimation in the pipe network

As discussed before, blockage in a viscoelastic pipe network causes damping, phase shift, and transformation of the transient signal. According to the previous studies, defects in piping systems can be located and characterized based on the resulting changes in the transient waves (Mohapatra *et al.* 2006; Lee *et al.* 2008; Duan *et al.* 2012, 2014; Sun *et al.* 2016; Yan *et al.* 2020; Che *et al.* 2021). In this section, the aim is to assess the model for determination of blockage location and characteristics in a pipe network because of their effects on transient pressure waves. During the process, it is assumed that the number of blockages in the system is unknown. First, ITA is run for at least two candidate blockages in the system. This is required for the model to show its ability to differentiate blockages from normal network pipes. If the model estimates a diameter close to the normal network pipe diameters for one candidate blockage and a diameter significantly smaller for the other candidate blockage, then it can be concluded that there is one blockage in the system. However, if the model diameter estimates for both blockage candidates are significantly smaller than the normal network pipes diameters (i.e., shows that there might be more than two blockages in the system), the number of candidates should be increased. This procedure repeats until one of the blockage candidates does not reveal a significant diameter difference relative to the normal pipe network. In this study, pipes of length $L_b = 1$ m and diameters $D_b = 16$ and 24.5 mm were placed in different parts of the experimental model to simulate blockage. Experiments with these two blockages were carried out with different steady-state flow rates, and pressure signals were recorded for model assessment. A constant wave speed was assumed throughout the pipe network in both scenarios with and without blockage. It should be noted that the numerical model accounts for the calibrated creep function in the intact pipe network. According to Duan *et al.* (2010) and Pan *et al.* (2020), the viscoelastic parameters are a function of the pipe-wall material properties and not the flow conditions. Therefore, the calibrated viscoelastic parameters are applicable to any other test cases in the same system. In this case, the only unknown parameters will be location and characteristics of the blockages in the pipe network. First, to determine the effective signal range for prediction of pipe network blockage, a sensitivity analysis was carried out on the required number of experimental signal cycles for the analysis. Optimization was performed using the ITA and the genetic algorithm, and the best blockage locations and other characteristics were found in the first two cycles. Then, the numerical model was assessed for different blockage scenarios using the first two signal cycles and characteristics of candidate blockages were determined. The results for all scenarios with two candidate blockages showed that one of the blockage candidates has a diameter close to the normal network pipe size (which means one blockage in each scenario). All the numerical model findings for the unknowns are shown in Table 2. It is worth noting that the prediction error for the estimated length and diameter were calculated from Equation (10) and are tabulated in Table 2.

$$\varepsilon = \frac{|\text{Estimated value} - \text{Real value}|}{\text{Real value}} \times 100 \tag{10}$$

Table 2 | Model estimated blockages' characteristics and errors

Blockage	Q (L/s)	Model estimated location	L_b (m)	ε_{length} (%)	D_b (mm)	$\varepsilon_{diameter}$ (%)
Blockage 1	0.86	P4	1.5	50	12	25
Blockage 2	0.88	P10	1.6	60	17.4	29
Blockage 3	1.2	P12	1.2	20	14.2	11.3
Blockage 4	1.2	P13	1.3	30	21.4	12.7

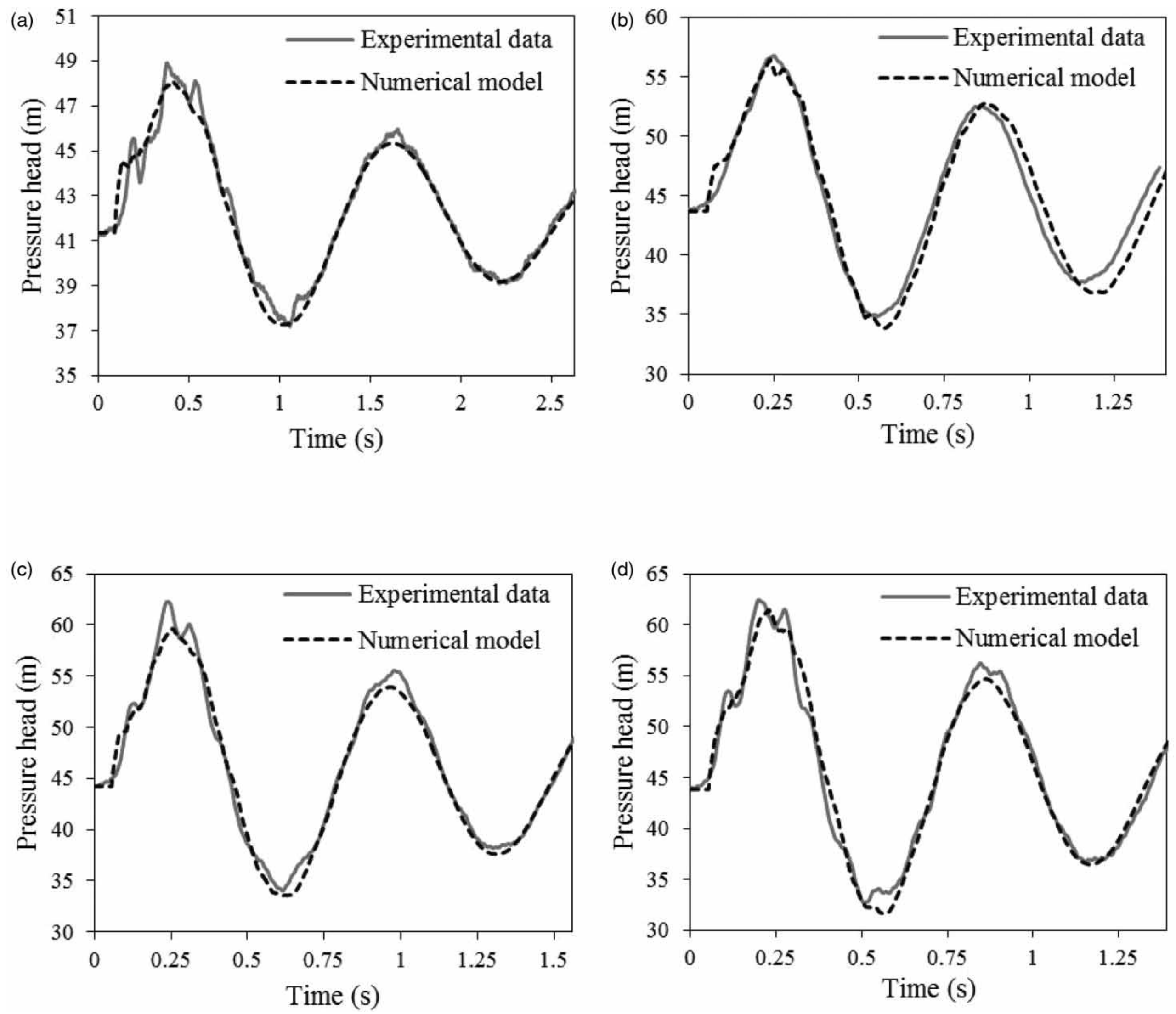


Figure 6 | Comparison of the experimental and numerical results for the blockage scenarios in Tables 1 and 2: (a) blockage 1, (b) blockage 2, (c) blockage 3, and (d) blockage 4.

Figure 6 compares the numerical and experimental results for the blockage scenarios in this study. For the cases in Table 1, the ITA has estimated the real blockage location or a value close to the real situation in the pipe network. The results are relatively suggestive of accuracy for the estimation of blockage location, length, and diameter in the vicinity of the ball valve where pressure reflection effects are more pronounced in the transient flow signal. The blockage farther from the ball valve causes lower accuracy in estimation of the blockage location and characteristics due to an increase in the number of in-between fittings and branching effects on the transient signal. Thus, the compatibility between the numerical and experimental signals is also reduced. In cases with a less severe blockage (Blockage 2 and Blockage 4), the model estimated results are less accurate. Also, the results in Table 2 indicate that for all cases, the maximum prediction error for the blockage diameter is 29% while the prediction error for the blockage length is higher, which reveal the prediction of the blockage diameter is more accurate than the blockage length. This result shows that the ITA is more sensitive to the blockage diameter than blockage length. In general, sources of errors in the estimation of blockage location and characteristics in this study are: small ratio of length to diameter of pipe elements in the experimental network, effects of branching-fitting-anchoring on pressure signals, measuring-recording device errors, and the uncertainties associated with the numerical model calculations. These errors and uncertainties have considerable effect on determination and characterization of the blockages in pipe networks as also stated in Duan (2016) for extended blockage detection in water pipeline systems. Considering the limitations and very low information available for evaluation of transient flow in the pipe network, further studies are suggested in order to acquire higher accuracy for application of the adopted method.

CONCLUSION

Experiments on a viscoelastic pipe network are conducted to calibrate and verify an adopted numerical model for determination of blockage in the system using the ITA method in the time domain. The governing equations were discretized by the MOC considering the viscoelasticity of polymer pipe-wall effect. The recorded transient pressure signals showed that the initial wave pressure peaks were damped during a short period of time, and increase of blockage length and size causes increase of damping and phase shift of the pressure signals. Using pressure signals, the unknown numerical model parameters, including wave speed and creep function parameters, were obtained. Results showed that the numerical model is capable of simulating transient signals using only viscoelastic effect and one Kelvin–Voigt element. Four scenarios of blockage in the pipe network are estimated by the calibrated numerical model for location, length, and diameter of blockage, and compared with the experimental results. As the pressure drop is more sensitive to the blockage diameter than blockage length, estimation of blockage diameter is more accurate than the blockage length. In addition, the characteristics of blockages closer to the source of transient are estimated more accurately compared to blockages farther in the network.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

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