A blockage detection model based on the pressure wave method for natural gas condensate pipelines

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Abstract. To address the precision constraints of conventional pressure wave models in complex subsea gas condensate pipeline environments, this research proposes an obstruction localization technique incorporating both wave speed adjustment and valve parameter refinement. The approach employs pressure transients induced by regulated valve depressurization at subsea manifolds. Through integration of the Method of Characteristics with comprehensive valve behavior simulation, a sophisticated computational framework is developed to concurrently execute wave transmission evaluation and blockage diagnosis. Experimental validation via a laboratory-scale flow loop demonstrates significant enhancement in detection precision through wave speed compensation. A key innovation lies in the algorithm's capacity to establish quantitative relationships between valve actuation duration and induced pressure wave magnitude, offering a robust and precise methodology for subsea pipeline integrity assessment.

Keywords: Pressure wave method; Blockage detection model; Method of characteristics.

1. Introduction

With the global energy sector's increasing focus on deepwater development, maintaining operational safety in subsea gas condensate pipelines has emerged as a critical concern [1]. These pipelines face particular challenges from hydrate formation under low-temperature, high-pressure conditions, creating substantial flow assurance risks that may result in serious production incidents [2]. Consequently, developing precise and reliable clog detection methodologies is paramount for ensuring pipeline integrity. Current detection approaches encompass several techniques: acoustic reflection analysis, frequency domain response evaluation, inverse transient examination, and pressure wave propagation analysis [3]. The pressure wave technique stands out for its superior detection precision and versatility across various blockage scenarios. This methodology generates pressure disturbances through rapid valve actuation or fluid pulsing, then identifies obstructions by examining wave propagation patterns and reflection signatures [4]. Nevertheless, traditional pressure wave models predominantly rely on ideal gas assumptions, neglecting crucial factors like multiphase flow interactions and thermo-pressure effects on wave speed [5]. Furthermore, current modeling frameworks inadequately characterize how valve operational dynamics influence pressure wave generation [6], thereby constraining detection performance.

To address these challenges, this study proposes a clogging detection method based on pressure wave propagation. A coupled algorithm for pressure wave propagation and clogging feature inversion is developed by combining wave velocity correction and valve parameters. In addition, the model quantifies the relationship between valve operation time and wave excitation amplitude, which improves the accuracy of clogging detection.

2. Model formulation

Transient flow in pipelines is governed by three fundamental principles of fluid dynamics and the associated constitutive relations (equations of state). In this study, the governing equations are simplified to a coupled system of continuity and momentum equations under the adiabatic assumption (ignoring wall heat transfer) in the case of a negative pressure wave induced by rapid valve closure, as detailed in equation (1).

$$\begin{cases} \dfrac{\partial \rho}{\partial t}+\dfrac{\partial(\rho u)}{\partial x}=0 \\ \dfrac{\partial(\rho u)}{\partial t}+\dfrac{\partial\left(\rho u^{2}\right)}{\partial x}=-\dfrac{f \rho u|u|}{2D}-\rho g \sin \alpha-\dfrac{\partial P}{\partial x} \end{cases} \tag{1}$$

The fundamental equations are first converted into ordinary differential equations through determination of their characteristic roots. Following this conversion, the equations undergo discretization into algebraic formulations to derive numerical solutions. Consequently, the system of characteristic equations that models the transient pressure wave can be expressed in the following manner:

$$\begin{cases} \dfrac{dM}{dt}+\dfrac{A}{a_T}\dfrac{dP}{dt}+\dfrac{fB^2 M|M|}{2DPA}+\rho g A \sin \theta=0, \dfrac{dx}{dt}=a_T \\ \dfrac{dM}{dt}-\dfrac{A}{a_T}\dfrac{dP}{dt}-\dfrac{fB^2 M|M|}{2DPA}-\rho g A \sin \theta=0, \dfrac{dx}{dt}=-a_T \end{cases} \tag{2}$$

The calculation of pressure wave propagation speeds in subsea pipelines initiates with comprehensive evaluation of thermodynamic conditions (temperature and pressure) and fluid phase characteristics. These variables serve as inputs for Equation (3) to derive phase-specific wave velocities. For homogeneous flow configurations (e.g., annular-mist flow), the system's effective wave speed is subsequently determined through Equation (4). Conversely, under phase-segregated flow conditions (exemplified by stratified flow), Equation (5) governs the computation of the composite wave velocity.

$$a_T=-\frac{V}{\sqrt{M_m}}\sqrt{\left(\frac{\partial P}{\partial V}\right)_S}=-\frac{V}{\sqrt{M_m}}\sqrt{\frac{c_P}{c_V}\left(\frac{\partial P}{\partial T}\right)_V\left(\frac{\partial T}{\partial V}\right)_P} \tag{3}$$

$$a_{T,M}=\left\{\left[\alpha\rho_G+(1-\alpha)\rho_L\right]\left(\frac{\alpha}{\rho_G a_{T,G}^2}+\frac{1-\alpha}{\rho_L a_{T,L}^2}\right)\right\}^{-\frac{1}{2}} \tag{4}$$

$$a_{T,M}=\left[\frac{\rho_G\rho_L}{(1-\alpha)\rho_G+\alpha\rho_L}\left(\frac{\alpha}{\rho_G a_{T,G}^2}+\frac{1-\alpha}{\rho_L a_{T,L}^2}\right)\right]^{-\frac{1}{2}} \tag{5}$$

where aT,M is the mixed wave velocity, m/s; α is the gas volume fraction.

The detection model for blockages incorporates various boundary conditions such as pipe specifications, obstruction properties, and valve pressure release settings. A fixed flow rate is applied at the pipe entrance, whereas the exit maintains constant pressure. Both pipe dimensions and blockage features modify fluid dynamics, consequently changing pressure wave speed. Valve operation dynamics play a crucial role in generating and transmitting pressure waves, which are mathematically represented through valve timing functions and opening coefficients to quantify wave excitation effects.

The venting flow rate q depends on several factors, including the operational characteristics of the pressure relief valve, existing backpressure conditions, and the fluid dynamics at the discharge outlet. Among these, the critical pressure ratio (CPR) plays a pivotal role as a determining factor. For the subcritical flow condition (occurring when P_a/P_L>CPR), the mass flow rate is computed using Equation (7). Under critical flow conditions (when $P_a/P_L \leq$ CPR), the flow rate is governed by the critical flow equation presented in Equation (8).

$$CPR = \left(\frac{P_a}{P_L}\right)_c = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{6}$$

$$q = C_d A_L P_L \sqrt{\frac{2kM_m}{(k-1)RT}\left[\left(\frac{P_a}{P_L}\right)^{\frac{2}{k}} - \left(\frac{P_a}{P_L}\right)^{\frac{k+1}{k}}\right]} \tag{7}$$

$$q = C_d A_L P_L \sqrt{\frac{kM_m}{ZRT_L}\left(\frac{2}{k+1}\right)^{\frac{k+1}{k-1}}} \tag{8}$$

3. Experimental verification

To validate the model's reliability, this research constructed a pressure wave-based pipeline blockage monitoring and early warning experimental platform (Fig. 1). The setup comprises four main components: a closed circulation circuit, drive equipment, measurement devices, and a signal collection system. Compressed air and deionized water served as the gaseous and liquid phases respectively. The test section was fabricated from 50.0 mm ID stainless steel tubing, extending 145 meters in total length. A high-speed solenoid valve (model 2W500-50, DN50 specification) featuring a 0-1.0 MPa pressure differential capacity and 5 ms actuation speed was mounted on the bypass line at the circuit's discharge section.

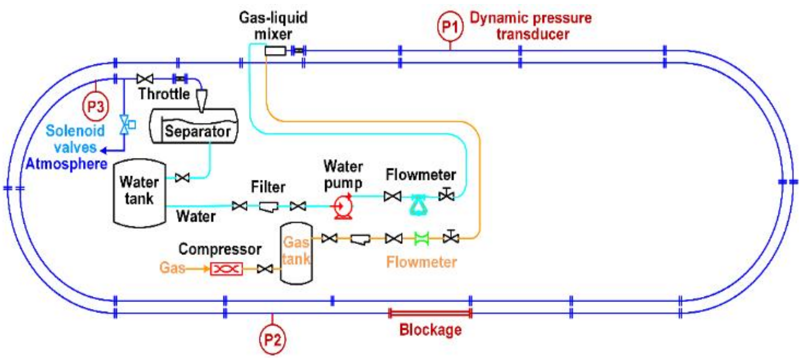

Figure.1. Schematic of experimental system

For capturing pressure fluctuations during wave transmission, three high-precision Keller PA-25Y pressure sensors (1 MPa full scale, 0.1% precision, 1 kHz bandwidth) were strategically positioned along the pipeline. The initial sensor (P1) was placed 19.2 m from the intake valve, followed by the secondary sensor (P2) at a 44.5 m interval from P1, and the tertiary sensor (P3) positioned 120.8 m downstream from P1. A safety valve was installed 0.5 m beyond P3. Data recording was accomplished using an NI PCI-6229 high-performance acquisition card, featuring 18-bit resolution, 16-bit precision, and 2 kHz sampling capability.

Following data conditioning procedures involving signal filtration, noise reduction, and feature identification, the acquired experimental measurements are systematically evaluated against numerical simulation outputs using combined time-domain and frequency-domain analytical methods. The model's predictive performance is assessed by statistically analyzing discrepancies in transient pressure profiles and pressure wave reflection characteristics, which enables comprehensive evaluation of error patterns, practical engineering relevance, and model precision. Table 1 summarizes the specific test parameters employed for the pressure wave-based blockage identification experiments.

Table 1 Table of experimental operating conditions

Case	Liquid holdup / %	Blockage length / m	Blockage location / m	Severity / %
1	0	1.5	74.1	75
2	10	1.5	74.1	75
3	0	1.5	32.6	50
4	10	1.5	32.6	50

The experimental results of blockage detection are presented in Fig.2. Investigation of pressure wave propagation in gas-liquid two-phase systems demonstrates substantial signal attenuation caused by liquid-phase components. Under equivalent blockage conditions, the pressure gradient signal amplitude in the liquid-containing cases (Case 2) decreases to 3.64 kPa, representing a 43.5% reduction compared to the pure gas-phase cases (Case 1, 6.44 kPa). Similarly, Case 4 shows a 56.2% amplitude attenuation relative Case 3. Notably, liquid-phase components not only reduce the characteristic signal amplitudes (with an average attenuation exceeding 40%) but also shorten the pressure gradient curve relaxation times by approximately 60.19% (e.g., the signal stabilization times for Cases 3/4 occur 2.56 s earlier than those for Cases 1/2). These results suggest that two-phase media significantly alter pressure wave propagation dynamics due to enhanced energy dissipation mechanisms. Three primary mechanisms are identified: (1) increased viscous dissipation due to liquid-phase properties, (2) energy dispersion through interfacial reflections, and (3) signal broadening from reduced wave velocities coupled with flow turbulence. The results emphasize the necessity for developing enhanced detection methodologies that account for gas-liquid coupling effects to compensate for signal degradation in two-phase systems.

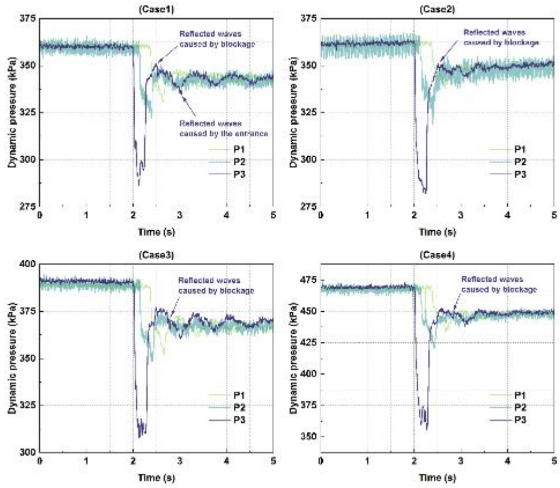

Figure.2. Results of the experiment

The comparative analysis between numerical simulations and experimental measurements is presented in Fig.3. Results demonstrate excellent agreement in pressure wave characteristics during valve operations. Specifically, for Case 1, the experimental pressure wave amplitude (-72.63 kPa) shows merely 2.77% deviation from the simulated value (-74.64 kPa). Wave velocity measurements (329.37 m/s experimentally vs 335.75 m/s numerically) yield a minimal 1.94% relative error. Characteristic reflection waves from both blockages and inlet disturbances exhibit remarkable temporal alignment. However, pressure recovery phases reveal notable differences: while simulations completely return to outlet pressure, experiments maintain a 15.43 kPa residual pressure difference attributable to unmodeled wall friction and fluid compressibility effects. Error quantification confirms the model maintains <5% accuracy in both wave velocity and amplitude predictions, satisfying engineering precision standards.

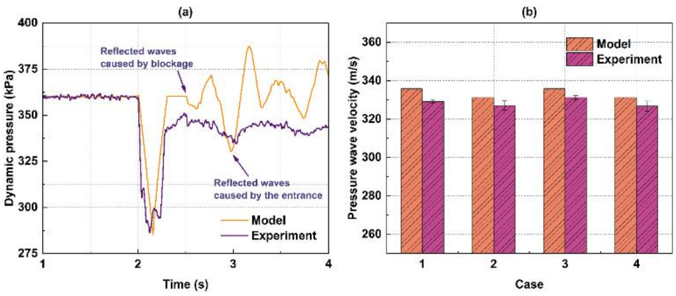

Figure.3 Comparative results of models and experiments

4. Summary

This research develops a blockage diagnosis model integrating wave velocity correction and valve parameters for detecting obstructions in submarine natural gas condensate pipelines. Experimental validation confirms the model's strong applicability in pressure wave excitation and wave velocity estimation, offering reliable data support for subsea pipeline blockage detection.

References

[1] Kapelan, Z., Savic, D., & Walters, G. (2004). Incorporation of prior information on parameters in inverse transient analysis for leak detection and roughness calibration. Urban Water Journal, 1(2), 129–143. https://doi.org/10.1080/15730620412331290029

[2] Wang, J., Meng, Y., Han, B., Liu, Z., Zhang, L., Yao, H., Wu, Z., Chu, J., Yang, L., Zhao, J., & Song, Y. (2023). Hydrate blockage in subsea oil/gas flowlines: Prediction, prevention, and remediation. Chemical Engineering Journal, 461. https://doi.org/10.1016/j.cej.2023.142020

[3] Li, C., Zhang, Y., Jia, W., Hu, X., Song, S., & Yang, F. (2024). Blockage detection techniques for natural gas pipelines: A review. Gas Science and Engineering, 122, 205187. https://doi.org/10.1016/j.jgsce.2023.205187

[4] Adeleke, N., Ityokumbul, M. T., & Adewumi, M. (2013). Blockage Detection and Characterization in Natural Gas Pipelines by Transient Pressure-Wave Reflection Analysis. SPE Journal, 18(02), 355–365. https://doi.org/10.2118/160926-pa

[5] Adewumi, M. A., Eltohami, E. S., & Solaja, A. (2003). Possible Detection of Multiple Blockages Using Transients. Journal of Energy Resources Technology, 125(2), 154–159. https://doi.org/10.1115/1.1525002

[6] Chu, J., Yang, L., Liu, Y., Song, Y., Yu, T., Lv, X., Li, Q., & Zhao, J. (2020). Pressure pulse wave attenuation model coupled waveform distortion and viscous dissipation for blockage detection in pipeline. Energy Science and Engineering, 8(1), 260–265. https://doi.org/10.1002/ese3.435