INTRODUCTION

The partial blockage due to solid deposits such as gas hydrate, wax, asphalt, and naphthenate is a major risk in hydrocarbon transportation systems.\(^1\) The continuous solid accumulation may lead to fire explosion, pollution, or other ecocatastrophes if not removed in time.\(^2\,5\) Efforts have been made to invent effective methods for blockage detection in pipelines. The acoustic technique was applied to blockage detection by Koyama et al.,\(^6\) yet with a major limitation on signal interference. The backpressure technique was applied by Scott and Satterwhite\(^7\) for blockage detection, but merely rough estimations were provided. The transient wave methods using energy analysis\(^8\,\text{–}\,11\) and wave-blocking interaction\(^12\,\text{–}\,14\) and

Pressure pulse wave attenuation model coupling waveform distortion and viscous dissipation for blockage detection in pipeline

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Abstract
Safety issues are always a major concern in the oil and gas transportation facilities. Equipment damages are frequently encountered due to solid deposition such as gas hydrate deposition. A fast and efficient detection of the location, length, and rate of the accumulating blockage will significantly help relieve the potential risk. Most existing pressure wave-based models suffer the difficulty to properly predict the blockage percentage arising from the ignorance of the wave attenuation. In the present work, an attenuation model to describe the transportation of the pressure pulse wave in gas is developed; the effects of waveform distortion and absorption as a result of the nonlinear effect and viscous dissipation are collectively considered for the first time. A simplified procedure to couple the wave attenuation in the model is proposed. The results show that the model can remarkably improve the prediction accuracy of blockage percentage by reducing the errors from \(-9.0\%\) to \(-4.2\%). Moreover, the attenuation process of the pressure pulse wave is determined to consist of three stages. The effect of waveform distortion on amplitude mainly occurs in the second stage, when our proposed model shows an improved prediction. The performance of the proposed model will help the early warning of the blockage in the pipelines and effectively avoid the potential injury and financial loss.

KEYWORDS
blockage percentage detection, nonlinear effect, oil and gas transportation, pressure pulse wave attenuation model, waveform distortion

1 INTRODUCTION

The partial blockage due to solid deposits such as gas hydrate, wax, asphalt, and naphthenate is a major risk in hydrocarbon transportation systems.\(^1\) The continuous solid accumulation may lead to fire explosion, pollution, or other ecocatastrophes if not removed in time.\(^2\,5\) Efforts have been made to invent effective methods for blockage detection in pipelines. The acoustic technique was applied to blockage detection by Koyama et al.,\(^6\) yet with a major limitation on signal interference. The backpressure technique was applied by Scott and Satterwhite\(^7\) for blockage detection, but merely rough estimations were provided. The transient wave methods using energy analysis\(^8\,\text{–}\,11\) and wave-blocking interaction\(^12\,\text{–}\,14\) and
frequency-response method\textsuperscript{15-17} were also applied to detect blockages in liquid pipelines which show a good performance, but no evidences have shown its feasibility in gas pipeline.

In recent years, the pressure pulse wave method has been considered as another promising method for an early detection of partial blockage on account of its short response time, small intrusiveness, economical cost, anti-interference ability, and high detection accuracy. The method involves the injection of a pressure pulse into the pipeline by a quick-acting valve and a following analysis of the reflected signal by the partial blockage. Adewumi et al\textsuperscript{18} proposed a model to describe the pressure pulse propagation through gas pipeline containing blockages and proved the feasibility of this method by a series of numerical studies. Chen et al\textsuperscript{19} performed laboratory experiments on the pressure wave propagation model and found that the blockage length and location could be predicted with acceptable accuracy. However, the detection distance was limited by the signal degradation and the percentage of the blockage was underestimated by almost 50% because of the wave-attenuation-induced energy dissipation. An effective way to achieve long-distance detection was to increase the amplitude of the incident wave; but the resulting nonlinear effect cannot be neglected.\textsuperscript{20} Thus, an accurate attenuation model is necessary for a good prediction. No model has been reported to accurately describe the attenuation process of pressure pulse wave with high amplitude prior to this work.

In this study, an attenuation model to predict the transportation of one crest pressure pulse wave in fluid is presented.

## 2 | MATHEMATICAL MODEL

As mentioned above, with the increasing wave amplitude, the nonlinear term in the equation becomes non-negligible. The exact solution one-dimensional nonlinear wave in an ideal fluid with zero viscosity was derived by Riemann and Earnshaw, respectively, in 1860 and 1858,\textsuperscript{20} which can be expressed as

\[ u = u_0 \exp \left( -\alpha \tau \right) \sin \left( \omega \tau - k x + \sigma \frac{u}{u_0} \right) \]  \hspace{1cm} (4)

where \( \alpha \) is the amplitude absorption coefficient. Then, Equation (4) can be rewritten as

\[ y = \exp \left( -\alpha X \sigma \right) \sin (\omega \tau + \sigma y) \]  \hspace{1cm} (5)

where

\[ \tau = t - \frac{x}{c_0}, y = \frac{u}{u_0} \]  \hspace{1cm} (6)

For pressure pulse wave with one crest (suppose the waveform of the pulse wave with one crest is sine wave), we have.

\[ \omega \tau + \sigma y \in [0, \pi] \]  \hspace{1cm} (7)

To facilitate the calculation and the position of the discontinuity surface (the discontinuity surface is a thin layer where
the velocity of the fluid particle changed sharply, it was generated with shock wave), Equation 5 are written as

\[
h = \omega r = \begin{cases} \\
\arcsin \left[ \exp \left( aX_s \sigma \right) \right] - \sigma y \\
\arcsin \left[ \exp \left( aX_s \sigma \right) \right] - \sigma y + \pi 
\end{cases}, y \in \left[ 0, \exp \left( -aX_s \sigma \right) \right] (8)
\]

Equation 8 are plotted in Figure 1 when \( \sigma = 5 \). The figure indicates the generation of a shock wave. The curve ABCDE is the mathematical solution, and the curve ABDF is the real waveform. According to the mass conservation on each side of the discontinuity surface, the area encapsulated by DEF equals that of BCD, and therefore, the area of ABDF equals that of ABCDE. The area of ABCDE \( (S_{ABCDE}) \) can be calculated as

\[
S_{ABCDE} = \int_{0}^{\exp(-aX_s \sigma)} \left\{ -\arcsin \left[ \exp \left( aX_s \sigma \right) \right] - \sigma y + \pi \right\} dy
\]

\[
-\int_{0}^{\exp(-aX_s \sigma)} \left\{ \arcsin \left[ \exp \left( aX_s \sigma \right) \right] - \sigma y \right\} dy
\]

\[= 2\exp \left( -aX_s \sigma \right) \] (9)

If the length of FB is \( l \), the area of ABDF \( S_{ABDF} \) can be calculated as

\[
S_{ABDF} = \int_{0}^{l} \left\{ -\arcsin \left[ \exp \left( aX_s \sigma \right) \right] - \sigma y + \pi \right\} dy
\]

\[-l \left\{ \arcsin \left[ \exp \left( aX_s \sigma \right) \right] - \sigma l + \pi \right\}
\]

\[= \frac{1}{2} \sigma l^2 - \exp \left( aX_s \sigma \right) \cos \arcsin \left[ \exp \left( aX_s \sigma \right) l \right] + \exp \left( -aX_s \sigma \right) \] (10)

Because \( S_{ABCDE} = S_{ABDF} \), we can obtain

\[l = \frac{2\sqrt{\sigma \exp \left( -aX_s \sigma \right) - 1}}{\sigma} \] (11)

It should be noted that there are critical points of the position of discontinuity surface when \( l \) equals to \( \exp \left( -aX_s \sigma \right) \). And these points can be calculated by

\[l = \frac{2\sqrt{\sigma \exp \left( -aX_s \sigma \right) - 1}}{\sigma} = \exp \left( -aX_s \sigma \right) \] (12)

which can be simplified as

\[2\exp \left( aX_s \sigma \right) - \sigma = 0 \] (13)

Equation (13) is a transcendental equation with two real roots when \( 0 < aX_s \leq 1/2 \). These two roots can be represented by \( m_1 \) and \( m_2 \) \( (m_1 < m_2) \). When \( 0 < \sigma \leq m_1 \), the amplitude of the pressure pulse wave has not yet been affected by the discontinuity surface, and we have

![Figure 1](https://via.placeholder.com/150)

**FIGURE 1** Illustration of Equation (8) at \( \sigma = 5 \). The red and blue curves represent Equation (8a) (Which mean the first equation in equation [8]) and Equation (8b) (Which mean the second equation in equation [8]), respectively. The black line represents the discontinuity surface of the shock wave. Curve ABCDE is the mathematical solution, and curve ABDF is the real waveform

\[
p_{\max} = \frac{u_{\max}}{u_0} = \exp \left( -aX_s \sigma \right) = \exp \left( -ax \right) \] (14)

where \( p_{\max} \) is the amplitude of the pressure wave, \( p_0 \) is the amplitude of the incident wave, and \( u_{\max} \) is the maximum vibration velocity of fluid particle in the propagation process.

When \( m_1 < \sigma \leq m_2 \), the discontinuity surface swallows the crest in this stage, therefore,

\[
p_{\max} = \frac{u_{\max}}{u_0} = 2\sqrt{\sigma \exp \left( -aX_s \sigma \right) - 1} \] (15)

When \( \sigma > m_2 \), the influence of the shock wave faded away; in this stage, the value of \( p_{\max}/p_0 \) can be calculated by Equation (14) as well.

### 3 | EXPERIMENTAL RESULT AND DISCUSSION

To verify this attenuation model, a series of experiments have been performed in a stainless-steel pipeline with a 40 mm inner diameter and a 220 m length, as shown in Figure 2. Nitrogen was injected into the inlet with a high pressure. The pressure wave was generated by a solenoid valve. The transient dynamic pressure was measured by one static pressure transducer and three dynamic pressure transducers placed on the pipe marked as S1, D1, D2, and D3. In the partial blockage section, tubes with different diameters were placed in different positions to simulate the partial blockage with different percent blockage.

Firstly, the pressure wave attenuation tests were performed in the pipeline without any blockage. The experimental
results and the calculation results are shown in Figure 3. According to the developed model, the pressure wave attenuation process can be divided into three stages. In stage one ($0 < \sigma \leq m_1$), although the waveform distortion had already been occurring and the discontinuity surface had formed when $\sigma = 1$, the amplitude of the pressure wave was not significantly affected. The amplitude change can be accurately calculated by Equation (14). When $\sigma = m_1$ (the critical point 1), the discontinuity surface moved to the position of the wave crest.

In the following stage two ($m_1 < \sigma \leq m_2$), the discontinuity surface swallowed the crest (as shown in the small figure in the insert of Figure 3) reducing the amplitude of the pressure wave. Comparing to Equation 14, the calculations of amplitude ratios by Equation (15) are more accurate. The calculation difference between the two equations due to the waveform distortion term can be as large as 13.2%.

When $\sigma = m_2$ (the critical point 2), the discontinuity surface moved to the position of the wave crest again. In stage three, when $\sigma > m_2$, the influence of the discontinuity surface weakened, so the amplitude ratio can again be accurately calculated by Equation (14).

Overall, the first set of experiments verified the feasibility of the proposed model to describe the attenuation of the pressure wave in the case of waveform distortion. Our proposed model provided an accurate result and overcame the difficulty of the conventional models in wave attenuation.

Secondly, a series of blockage detection tests with 6 different blockage percentages were performed to further test the predicting accuracy of the proposed model, details of experimental results see Figures S2-S7. The location of the blockage was at 172.3m and 182.6m ($4.8 < \sigma < 6.0$) where the pressure wave attenuation process is at stage two. The predictions of the blockage percentages with and without considering waveform distortion were calculated based on the amplitude difference between the incident wave and reflected wave of blockage. The calculation errors relative to the actual values are shown in Figure 4. Each blockage percentage was tested with four different amplitudes of incident pressure wave (range from 50kpa to 90kpa). Comparing to the model without considering the waveform distortion, our model remarkably improved the accuracy and reduced the errors. Over the tested blockage percentages, the errors on average reduced from −9.0% to −4.2%. The error reduction was more pronounced at higher blockage percentages. When the blockage rate equals 0.938, the prediction error could considerably reduce from −6.4% to −1.6%. The results further demonstrate the advantages of the new model in terms of predicting the blockage percentage with the necessary consideration of the wave distortion.

In addition, the detection distance range mainly depends on the propagation distance of the pressure pulse wave. After calculation, the propagation distance of pressure pulse wave in this study is 3-5 kilometers. For in situ pipelines, the propagation distance of pressure pulse wave is longer than that in laboratory due to the higher static pressure and greater wave amplitude in pipelines. According to the experimental data shown in Figure 3, the proposed model is in good agreement with the experimental results in the stage 1 and stage 2 where the propagation distance $x$ is relatively close. Unfortunately, there is no experimental data in stage 3 where the propagation distance $x$ is relatively long due to the limited length of

**FIGURE 2** Schematic diagram of the blockage detection pipeline experimental system. The total pipe length was 220m, the static pressure transducer $S_1$ and dynamic pressure transducer $D_1$ were close to the solenoid valve, the distance between $D_1$ and $D_2$ was 76 m, and the distance between $D_1$ and $D_3$ was 189.1 m.

**FIGURE 3** Comparison between the models with and without considering waveform distortion in the pressure wave propagation process. The wave attenuation test was performed in the pipeline without blockage (details of experimental result see Figure S1). The static pressure of this test was 2.4 MPa, the amplitude of incident wave $p_0$ was $-103.1$ kPa with the 13.8 ms width, the calculated result of effective absorption coefficient $\alpha$ was 0.0022, and $m_1$ and $m_2$ were 2.5 and 28.8. The small figures on the top right represent the waveform of the experimental results and the model calculations of the incident wave and the wave when $\sigma = 4.6$.
the experimental pipelines. So the applicability of the proposed model in the stage 3 or long detection distance needs further verification, which is our next work.

4 | CONCLUSION

In conclusion, our pressure pulse wave model with introduction of a dissipation term shows a potential to significantly help detect the solid deposition in the pipelines and avoid the potential equipment damages. Our new model also shows a good performance in balancing the theoretical derivation and engineering availability. The viscous dissipation of the medium in the pressure wave propagation process was simplified to exponential attenuation in our model, making it much more convenient in the engineering applications; yet it might introduce errors. Therefore, it is an acceptable choice to obtain the numerical solution of the governing equation which considered the effects of viscous dissipation, boundary conditions, and wall friction, and these are what we would like to do in the future. Besides, in the gas transport pipelines, there are branch pipes, different blocking substances, and irregular blocking shape, which will have varying degrees of impact on the blocking detection. Limited by the length of this article and the limitation of the experimental platform, this paper did not discuss these issues, which are our future works too.

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CONFLICT OF INTEREST

The authors declare no competing financial interest.

AUTHOR CONTRIBUTIONS

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