Research Article

A hydrate blockage detection apparatus for gas pipeline using ultrasonic focused transducer and its application on a flow loop

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Abstract
This paper introduces a novel apparatus and the analyzing method for hydrate blockage detection in natural gas pipeline using the ultrasonic focused testing technique. The apparatus mainly consists of three parts: an ultrasonic focused transducer, a supporting guide track and a positioning ruler for the transducer. It can be installed by fixing the guide track onto the pipe outer wall, and the distance of the transducer to the pipe wall can be adjusted with the positioning ruler. The reflection signals of hydrate surfaces can be then received and recorded by an oscilloscope. The hydrate thickness thus can be calculated by multiplying the ultrasonic velocity with the time difference between two reflections. A calibrating test using this apparatus certified that it can provide an accurate measurement of both the pipe wall thickness and the hydrate blockage thickness from outside of the pipe. A maximum hydrate thickness of 50 mm can be measured due to the high penetrability of the ultrasonic. The feasibility of applying this apparatus to the metal pipeline was verified with a carbon steel cylinder with ice attached on the inner wall. A 360° blockage profile around the cylinder was obtained with a step angle of 5°. The accuracy of measured thickness and cross-sectional area of the blockage can reach 96% and 91%, respectively. Finally, an application test was conducted on a full visible flow loop of 35 mm inner diameter and 49 m length. The test results showed that the hydrate blockage contour measurement can be achieved with this apparatus despite the gas and water flow in the loop. This hydrate blockage detection apparatus can be applied to gas-dominated pipelines in which hydrate mainly forms on the wall. Early warning of hydrate blockage can be further studied based on the measurement results using this apparatus.

Key Words
blockage contour, flow loop, gas-dominated pipeline, hydrate blockage, ultrasonic focused transducer

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1 INTRODUCTION

In the process of oil and gas exploitation with different geological characteristics and transport environments, the recovered oil and gas usually contain more or less saline water and heavy components of oil and gas fields.\textsuperscript{1-3} Blockage formed of deposition such as wax, asphalt and gas hydrate may cause safety problems and even lead to accidents.\textsuperscript{4-6} Flow assurance management is critical to the safe and economic operation of deep water oil and gas production and transportation.\textsuperscript{7-11} Due to the high pressure and low temperature in deep water pipeline, gas hydrate blockage often occurs in natural gas production and transportation lines. It was firstly found in pipelines of Russia (former Soviet Union) in 1934.\textsuperscript{12} From then on, the safety problems caused by gas hydrate blockage have become increasingly serious, and pose substantial threats of economic loss to the petroleum industry. For economic reasons, natural gas cannot be completely purified before transportation through long-distance pipelines. Natural gas (mainly methane) will form gas hydrate under favorable pressure and temperature. In addition, the pressure and flow rate of natural gas in the pipeline will change with extended distance. Consequently, gas hydrate will gradually separate out and accumulate continuously in the pipe resulting in a blockage of ever-expanding volume.\textsuperscript{13-15} When the blockage completely fills the pipeline, transportation capacity is subsequently lost. Therefore, it is particularly important to study the blockages caused by gas hydrate for flow assurance.

Over the past two decades, with the rapid development of microelectronics and signal analysis technology, object contour measuring instruments based on various principles have emerged, and their detection limits range from nanometers to millimeters.\textsuperscript{16-20} Among them, ultrasonic technology is widely used in machinery manufacturing,\textsuperscript{21} construction engineering,\textsuperscript{22} petrochemical equipment,\textsuperscript{23} and other fields.\textsuperscript{24-26} Therefore, the use of acoustic wave-guides to estimate blockage positions is a straightforward process. However, it is insufficient for blockage evaluation and subsequent removal to simply determine the blockage position, especially in partially blocked pipelines. To obtain more information, such as the contour shape and the cross-sectional area of the blockage,\textsuperscript{27} further detection and signal processing are required.

Some researchers have worked on blockage detection in pipelines by using frequency response analysis. Antonopoulous-Domis\textsuperscript{28} measured the axial resonant frequency of a duct with and without a blockage present to recover the cross-sectional area, and the location of the blockage employing a frequency domain technique. Qunli and Fricke\textsuperscript{29-31} used a similar method for a duct with a rigid termination and showed that similar results may be obtained using multiple axial resonant frequencies for closed-closed and closed-open duct geometries.

However, there are few studies on partial blockage contour measurement in natural gas pipelines because the high pressure and subsea environment limits the normal use of many apparatuses. In comparison, more studies focus on the measurement of methane hydrate phase equilibrium conditions with different concentrations and components.\textsuperscript{32-36} Most of the corrosion and deposition detections are easy to carry out inside the pipeline in non-operational condition without considering the influence of the flow conditions in the pipeline.\textsuperscript{37-39} On the contrary, hydrate blockage usually occurs in the pipeline transportation process and it needs to carry out in-situ detection in operational condition. However, to the best of the authors’ knowledge, there are few ultrasonic detection techniques which can be applied to hydrate blockage contour detection in the flow process of deep water natural gas pipeline. Therefore, the whole process of hydrate blockage contour detection in the pipeline must be carried out from the outside of the pipeline, which can not only ensure the normal operation of the pipeline, but also avoid the interference of the complex and changeable flow environment in the transportation. The purpose of this paper was to provide a subsea gas pipeline blockage contour measurement apparatus. Using an adopted portable mobile design, the apparatus is suitable for both offshore and subsea conditions. Based on time of flight calculations, the blockage profile of hydrate around a circle is determined after calibration by relocating around the pipe. The apparatus provides a new means of early warning of gas hydrate blockage and risk prevention\textsuperscript{40-45} for gas transportation.

The principle for ultrasonic measurement is based on the travel time of acoustic wave in material. The acoustic wave travels through the material and then reflected when it reaches the other surface of the material. The thickness is calculated based on the reflection time of the acoustic wave. Based on the design principle of the transducer, ultrasonic detection methods can be divided into two categories: contact and noncontact measurement. The most common use of ultrasonic transducer for material thickness measurement is to directly attach the transducer to the material surface with couplant, that is the contact method. The contact method has many limitations on the detection of the blockage contour in natural gas pipelines. For example, in most cases, the outer surface of some materials to be tested is blocked, and the transducer itself cannot directly contact with the object to be tested. It is hard to ensure the uniformity of the coated couplant on the pipe wall. For this work, the hydrate blockage is deposited on the inner wall of the pipe, the shielding of the pipe wall brings inconvenience to the contact measurement. Moreover, the direct contact causes strong reflection of the pipe wall which results in
great signal attenuation. Therefore, the noncontact method is necessary for this circumstance.

In this work, a noncontact ultrasonic measurement apparatus is presented for the blockage contour detection of natural gas pipeline. It utilizes the penetrability of ultrasonic to measure the thickness of hydrate blockage inside the pipe and effectively avoids the contact reflection attenuation along the pipe wall.

2 | APPARATUS AND MATERIALS

The main units of the apparatus and their operating principles are described in this section.

2.1 | Ultrasonic transducer

Figure 1 shows the ultrasonic transducer, which is one of the most important parts of this detecting system. Figure 1A describes the working principle of the focused ultrasonic transducer. This special design can effectively reduce the interference caused by diffraction and multiple reflection signals. Figure 1B, 1 show photographs of the transducer and the waterproof connector, respectively.

The verification tests for the contact and noncontact methods using the ultrasonic focused transducer were carried out previous to the apparatus development. A carbon steel pipe (the inner diameter is 10 cm, and the wall thickness is 1 cm) filled with ice was used to simulate the gas pipe with hydrate blockage. The pipe was put in a refrigerator, and the temperature was set to 272 K to prevent the ice melting. Figure 2A, 2 compare the ultrasonic signals obtained with the contact and noncontact method. As shown in Figure 2A, the ultrasonic wave reflects from the outer and inner wall of the pipe and produces strong multiple reflection signals because of the contact interface between the transducer and the wall. Therefore, the contact method may lead to the overlap of the target and interference signal. As shown in Figure 2A, it is difficult to confirm the location of the target signal directly and accurately. On the contrary, as indicated in Figure 2B, the noncontact method can generate a clear signal to distinguish the reflection of the pipe wall and the ice. This is because the actual distance between the transducer, and the pipe wall is gradually close to the focal length. The ultrasonic focused transducer makes the signal converge at the focal spot and generates much stronger reflection than the contact method, which results in an increase in signal intensity. However, this noncontact method has its disadvantage that it is only applicable to detect the hydrate formed on the inner wall of gas-rich pipelines. For oil-water pipelines, hydrate usually forms in water phase and mixes with water as slurry. There will be no clear interface.

Since the hydrate blockage can form at any point of the inner wall of the pipe, the ultrasonic transmission method can only indicate the presence or location of a blockage; it cannot provide the blockage contour, that is, the thickness of the blockage around the inner wall. Therefore, the ultrasonic reflection method is adopted in this paper. As shown in Figure 1, the ultrasonic transducer is a single-crystal longitudinal-wave transducer with a 1/4 wavelength layer that is acoustically compatible with water. This design provides a uniform coupled method with a quarter wavelength matched layer to strengthen the acoustic energy transmitted.

\[
d = \frac{1}{4} \lambda
\]

where \( \lambda \) is the wavelength and \( d \) is the thickness.

In the early blockage stage, hydrate particles gradually bedded on the pipe surface, and the deposition thickness is far less than the pipe wall. As a result, the propagation time of the ultrasonic wave in hydrate is much shorter than that in the pipe wall, which makes it difficult to identify the target signal. Therefore, we tried different frequencies to improve the signal recognition, since different frequencies have different propagation characteristics. The higher frequency signal has a higher resolution; however, the intensity is easily attenuated in the propagation medium. Therefore, it is of great significance to choose an appropriate ultrasonic frequency for measurement. Figure 1S provides a comparison of the signals for different frequencies. It can be found that the target signal of 5 MHz is easier to distinguish under the same experimental conditions. Thus, the frequency of the ultrasonic transducer used in the experiment was chosen to be 5 MHz. The received signal was digitized, amplified and then displayed on a digital phosphor oscilloscope (DPO 4034B; Tektronix Inc). The dynamic variation of the waveform was recorded by the computer for further analysis.

2.2 | Portable guide track

In practical operation, the transducer was fixed on a circular track to achieve free motion around the pipeline and realize the measurement of a 360° profile as illustrated in Figure 3. To satisfy the measurement requirements, a circular track was designed with the following functions: First, it can be applied to any gas pipe with different diameters. According to the international standard, natural gas pipeline diameters range from 9 to 25 cm. Based on this requirement, the two ends of the track are equipped with two flexible fixed bolts. By adjusting the screw advance distance of the bolts, the guide can be fixed on any pipeline with an outer diameter ranging from 9 to 25 cm. Second, the apparatus must be waterproof. The hydrate blockage
problem in natural gas pipelines mainly occurs underwater, since the low temperature environment in water is more conducive to the formation of gas hydrate. Therefore, the guide track is made of stainless steel to achieve anticorrosion performance. To consider the on-site test requirements, the size of the track should be as small as possible to ensure the overall portable characteristics of the apparatus. Third, to complete the 360-degree measurement, a rotated slider is designed to complete the free sliding without resistance around the pipe; meanwhile, the angle position relative to the center of the pipe can be determined by an angular scale plate installed on the guide track.

2.3 Precise localization

The accurate localization of the ultrasonic transducer is the precondition to complete the measurement of the blockage contour. Precise localization requires direct and rapid measurement of two dimensions, including distance and angle localization. Distance localization is the basis of blockage thickness measurement and wall thickness calibration. As shown in Figure 4. The black ruler is a key part for adjusting and reading distance information of the ultrasonic transducer. In the measurement process, the reflected signal received by the transducer can be acquired quickly, and the relative distance between the transducer and the pipeline can be controlled by adjusting the side knob of the ruler to obtain the best test effect. When the distance position is determined, the waveform data at this time are recorded to complete the measurement of the blockage thickness at this point. Angle positioning is the key to the measurement of the blocked section contour of the pipe. When the blocked thickness of a position is determined, the angle position information relative to the center of the pipe can be determined by the angular scale plate installed on the guide track. Then, the 360° plot of the blockage profile can be drawn by connecting these points.
Signal processing method

When the ultrasonic transducer can detect the blockage interface, the blockage thickness can be obtained by Equation (2)

\[ r = D - R - s \]  (2)

where \( r \) is the thickness of the hydrate blockage, \( D \) is the focal length of the transducer, \( R \) represents the thickness of the pipe wall, and \( s \) represents the vertical distance between the transmitter end of the transducer and the pipe wall. In an actual situation, the propagation of both the transmitted and reflected signals will pass through the water, metal pipe, and hydrate blockage. The movement of the transducer will change the travel distance in each separate medium during the measurement. When the transducer moves away from the pipe, the propagation distance in the water will increase, and the travel distance in the hydrate will decrease. Conversely, as the transducer moves closer to the pipe, ultrasonic waves travel shorter through the water and longer in the hydrate. Therefore, the actual focal length of the transducer will also change due to the difference in wave velocity and travel distance in different media. The theoretical calculation method of the actual focal length is as follows:

\[ D = D_0 \times \frac{V_{\text{water}}}{V_{\text{medium}}} \]  (3)

where \( D_0 \) is the original focal length, which is the inherent attribute of the transducer. The physical meaning of \( D_0 \) is the distance between the focus and the transmitting source when propagating in water, \( V_{\text{water}} \) is the wave velocity in water, and \( V_{\text{medium}} \) is the wave velocity in the actual medium. Integrating Equation (3) into Equation (2) leads to Equation (4):

\[ D_0 = R \times \frac{V_{\text{pipe}}}{V_{\text{water}}} + r \times \frac{V_{\text{hydrate}}}{V_{\text{water}}} + s \]  (4)

where \( V_{\text{pipe}} \) represents the wave speed in the metal pipe, and \( V_{\text{hydrate}} \) represents the wave speed in the hydrate blockage. Since \( D_0, R, V_{\text{pipe}}, V_{\text{water}}, V_{\text{hydrate}} \) are known constants that can be measured directly, the thickness can be calculated as follows:

\[ r = \frac{V_{\text{water}}}{V_{\text{hydrate}}} \left( D_0 - R \times \frac{V_{\text{pipe}}}{V_{\text{water}}} - s \right) \]  (5)

where \( s \) is a variable obtained during dynamic measurement using the black ruler depicted in Figure 4. The above-mentioned Equation (5) illustrates the signal processing in mobile measurements.

In addition to the mobile measurement method, the apparatus can also realize the traditional measurement of fixed transmission and reception. To distinguish it from the mobile measurement method described in Equations (2)-(5), we call it the fixed transducer measurement method. The significant difference from the traditional methods is that the measurement is also contactless. The calculation based on the received signal waveforms is shown in Equation (6):

\[ r = V_{\text{hydrate}} \times \frac{t_3 - t_2}{2} \]  (6)

where the travel times of \( t_2 \) and \( t_3 \) represent the reflection waveform on the inner surface of the pipeline and the blockage interface, respectively.
RESULTS AND DISCUSSION

3.1 Wall thickness calibration

Corrosion is inevitable for metal pipelines in long-term underwater environments, particularly electrochemical corrosion. Generally, corrosion will lead to changes in the thickness of the pipe wall, so the actual thickness of the pipe wall should be measured before blockage profile detection. Since the wall thickness is far less than the inner diameter, it can be approximately considered that the propagation speed of the ultrasonic wave in the metal pipe is a constant. The actual thickness of the pipe wall can be calculated by the following formula:

$$ R = V_{\text{pipe}} \times \frac{t_2 - t_1}{2} $$  \hspace{1cm} (7) 

where $t_1$ and $t_2$ represent the reflected signals at the inner and outer walls of the pipe, respectively, as depicted in Figure 5.

Figure 6 illustrates the calibration of the wall thickness with different thicknesses compared to the measured results. The black dots with error bars represent the measured results with a digital caliper, and the red dots are determined using our apparatus. Figure 6A, 6B, 6C, 6D illustrate the comparison of the measurement in metal material and the parity plots, while Figure 6B, 6C correspond to the plastic material. In consideration of the situation of submarine pipeline transportation, the calibration range is selected as 1-12 mm. According to the test results, the accuracy of carbon steel is higher than that of plastics, possibly because of the defects inside the plastics. However, when the thickness decreases to as low as 1 mm, the measurement accuracy will be significantly decreased. The reason for this result is that when the thickness is lower than the detection limit, it will enter the detection blind area, which is inevitably
caused by the design principle of the transducer. We believe that this disadvantage does not affect the practical application of equipment related to submarine pipeline transportation.

### 3.2 Blockage thickness calibration

Because the propagation characteristics in ice and hydrate are similar, we used ice instead of hydrate to carry out a series of verification experiments. It was found that the reflected signal could be observed when the blockage was in close contact with the inner surface of the pipe, but the energy attenuation when it passed through the interface and multiple reflections made it difficult to distinguish the travel time in many cases.

We first measure and calculate the blockage thickness using the fixed transducer method, which was outlined in the previous section. The waveforms of the reflected signals are depicted in Figure 7A. The arrows in the figure show the target signals reflected at the blockage interface of different thicknesses. It can be seen that the thickness is positively correlated with the travel time and inversely with the intensity, and this is because the increase of the thickness extends the travel time of the ultrasonic wave in the propagation medium; correspondingly, the attenuation also increases. When the thickness of the blockage exceeds a certain range, the target signal can no longer be distinguished. Then, we used the mobile transducer method to detect the blockage for comparison. The basic principle of this method is to increase the signal penetration through multiple interfaces and the relative intensity at the target interface depending on the convergence at the focus. The arrows in Figure 7B represent the reflected signal on the outer wall of the pipe, and the signal intensity here is the highest; The second reflected signal that is close to the highest one comes from the inner wall of the pipe. When the travel time reaches more than 0.12 ms, the intensity of the received signal remains high. Therefore, we believe that the mobile focusing measurement method has a larger
detection range than the traditional fixed transducer measurement method. It is also verified that this method can enhance the propagation of signals in complex transmission media.

3.3 | Blockage contour

Figure 8 illustrates the blockage contour measurements outside a 12-cm-diameter carbon steel pipe. The 360° rotation around the pipe can be realized by manual control. In this experiment, to facilitate the observation of the actual blockage contour, the metal cylinder is used instead of the real pipe. Figure 8A shows a photograph of the cylinder. The ice deposits on the inner wall of the pipe are the blockages to be measured. Since the ice is close to the hydrate in physical properties, it is easier to simulate hydrate blockage with homogeneous solid blocks of ice. Furthermore, in combination with the actual situation that hydrate particles

**FIGURE 9** CCD photographs showing the blockage profile inside a visual flow loop in operation and the contour plot results together with the relative amplitude data, (A, B) before hydrate deposition, (C, D) after hydrate deposition. (E) General plane layout of the visual flow loop, the arrow shows the test position.
start to form and deposit in the visual circulation pipeline, ice blocks are very close to the real situation of pipeline blockage. Figure 8B-D show the measured results of the blockage profile. The blue short dashed lines represent the actual blockage contour directly measured from the inside of the metal cylinder. The red dots indicate the test results using our apparatus. The black dashed lines obtained by connecting the red data points are the prediction of the blockage contour profile. To investigate the impact of test points and interval angle on the results, Figure 8B-D illustrate the measurement with interval angles of 45°, 30°, and 15°, respectively. Correspondingly, the number of data points represented by red dots are 8, 12, and 24, respectively. The comparison indicates that more data points create a contour plot closer to the actual contour. Therefore, the measurement accuracy is positively correlated with the number of measurements. Theoretically, it is impossible to measure the blockage profile of every point in the circumference of the cylinder with a finite number of passes. When the interval angle is reduced to a certain extent, the slight improvement in precision will lead to the multiplication of time consumed. Therefore, practical measurements should be considered comprehensively according to the specific situation.

3.4 Validation on a full-length visible flow loop

The novel ultrasonic test apparatus has already been demonstrated to be effective regardless of the traditional fixed transducer or mobile transducer method. However, the apparatus is designed for the on-line detection of hydrate blockages. The compatibility with loop systems must also be tested. In this section, quasi-field-scale experiments were conducted on the visual circulating flow loop for blockage contour detection. Since the blockage occurs inside the pipe and the test results cannot be verified by direct methods, we monitor the blockage by combining the intuitive images captured by the CCD camera outside the pipe. Figure 9E depicts the general plane layout of a 49 m full-length visible flow loop, and the red row shows the test position. Figure 9A, 9 show the blockage profile inside the visual flow loop in operation before and after the partial blockage captured by the CCD camera. The main advantage of the apparatus is that it can detect the partial blockage contour in the early stage of hydrate accumulation in the pipe. Thus, the apparatus is also applicable for early warning of oil and gas pipeline transportation blockages. In addition, the operation can ignore the working conditions in the pipeline, such as gas pressure and flow rate. Figure 9B, 9 show the measurement results which correspond to the hydrate-free (Figure 9A) and hydrate-deposited state (Figure 9C), respectively. The red dashed lines indicate the contour test results, while the blue dashed lines represent the relative amplitude data. Since in the hydrate-free state, the target signal does not exist, so the measured relative amplitude data are just the baseline. At this time, all data points are zero as shown in Figure 9B. We artificially changed the gas pressure and flow rate in the flow loop during the experiment, and the test results did not show any significant fluctuations which show that our method and results are stable and reliable.

4 CONCLUSIONS

This paper provides a novel detection apparatus for hydrate blockage of submarine gas pipelines. The portable mobile design enables the apparatus to be installed on any longitudinal position of the pipe. The noncontact method provides a new dimension for measurement. Based on time of flight calculations, the blockage thickness of the hydrate inside the pipeline around the circle is determined by the inversion calculation of the signal. A 360° detection of the blockage can be realized by moving around the pipe.

The noncontact method is adopted in this paper, which makes use of the penetration characteristics of ultrasonic. The appropriate frequency is successfully selected through waveform comparison, which effectively eliminates the strong reflection interference caused by the contact interface and avoids the shielding of the pipe wall.

Quasi-field-scale experiments are conducted on a visual flow loop for blockage contour detection. The apparatus provides a new means of detection and safety prevention for oil and gas pipeline safety transportation regardless of the operation conditions in the pipe. Furthermore, the apparatus provides an early warning method for gas transportation before the pipe is completely blocked.

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CONFLICT OF interest

None declared.

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SUPPORTING INFORMATION
Additional supporting information may be found online in the Supporting Information section.

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