Sand content calculation model based on characteristic analysis of sand-carrying oil flow acoustic signal

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Abstract. Aiming at the problem of sand production in oil wells during offshore oilfield exploitation, this paper presents a method for real-time monitoring and acquisition of sand production changes in oil wells. The acoustic signals of the sand-carrying oil flow impacting the inner wall of the pipeline is collected by acoustic sensor installed on the outside of the production pipeline. The characteristics of the signals are analyzed in time and Time-frequency domain to establish a sand content calculation model. The experiment design was based on the indoor simulation of sand production monitoring platform. The objective of this study is to investigate the relationship among the energy of sand-carrying two-phase flow impact acoustic signal, oil flow viscosity, sand particle size, and impact velocity. The characteristics of the acoustic signal in the time-frequency domain system are analyzed by the STFT. The results show that the sand content calculation model can effectively obtain the sand content in the pipeline on the characteristic frequency band of 21.9~22.1kHz of sand impact acoustic signal. The calculation error of the sand content is no more than 10%. The model can effectively reduce influence of fluid noise on the calculation of sand content. It can accurately monitor the sand content of sand production wells in real time, which provides technical guarantee for safe and efficient production of oil fields.

1. Introduction

Offshore oil and gas resources are of great significance to the global energy strategy, but oil well sand production is one of the major problems that urgently need to be resolved in the safe and efficient development of offshore oilfields\(^1\)\(^2\)\(^3\). The impact of sand production on the normal production of oil and gas wells is negative. It is mainly manifested in the serious harm to the bottom of the well and oil-gas layers, wellbore lifting equipment, and surface equipment\(^4\)\(^5\). These hazards not only increase the production cost of oil and gas wells, but also increase difficulty of oil and gas field management. The world generally believes that the development of a reasonable and effective sand production management system can achieve safe and efficient production in oil field\(^6\)\(^7\). The three factors that are critical to the sand production management system are sand production prediction, sand production acquisition, and sand production response. At present, during the oil field production process, the methods of sand production monitoring mainly include ER method, vibration measurement method,
etc., but there are problems such as the lag of monitoring results and the inaccuracy of sand content calculation. This research group conducted sand production monitoring based on the analysis of the acoustic signal characteristics of sand-carrying oil flow impacting the pipeline, and completed sand production monitoring tasks in multiple oil fields of the Bohai Sea.

This paper proposes a sand production calculation model and sand production monitoring device based on the analysis of the acoustic signal characteristics of the sand-carrying oil flow impacting the pipeline wall. The device consists of an acoustic sensor, a charge amplifier, a four-channel acquisition instrument and a computer with data acquisition software. The acoustic sensor is fixed at the 90° elbow of the circulating pipeline by non-implanted installation method. The acoustic signal of the sand-carrying oil flow impacting the elbow inner wall is collected by the acoustic sensor. A sand production calculation model is established through computer storage and analysis. The sand content in the circulating oil flow in the pipeline is obtained in real time based on the model. The advantages of the sand content calculation model and monitoring method of the sand-carrying oil flow proposed in this paper are real-time monitoring, accuracy and strong anti-noise interference ability.

2. Principle Overview

In the production process of oil wells, production wells with severe sand production frequently face the problem of erosion damage to pipeline. The sand-carrying oil flow flows in the pipelines at a certain flow rate. When passing through the elbow, the sand particle in the oil flow will impact the inner wall of the pipeline due to inertia, causing erosion of the production pipeline. The simulation diagram of the impact of sand particle with the inner wall of the pipeline when the sand-carrying oil flow passes through a 90° elbow is shown in figure 1(a). At the same time, the impact of sand particle will cause the inner wall of the pipeline to be subjected to impact pressure, as shown in figure 1(b). The impact pressure can be converted into the acoustic pressure that the acoustic sensor can collect:

\[ p = \frac{\eta \langle F(t) \rangle}{\Delta A} \]  

Where \( \eta \) is the efficiency of converting impact pressure into acoustic pressure. \( F \) is the impact force of sand particle on the inner wall of the pipeline in unit time \( t \), N. \( \Delta A \) is the contact area of sand particle impact the inner wall of the pipeline, m\(^2\). The acoustic pressure generated by the sand particle impacting the inner wall of the 90° elbow in the sand-carrying oil flow is direct proportional to the impact force by the sand particle impacting per unit time.

The sand-carrying oil flow impacting acoustic signal collected in this paper is a non-stationary signal. In order to be able to process this signal, traditional signal processing methods only study the statistical characteristics of the signal in the time or frequency domain. They cannot reveal the time-varying characteristics of the sand signal in the joint time domain. Therefore, this paper chooses short-time Fourier transform (STFT) to analyze the data. As the promotion and expansion of the discrete Fourier transform, STFT divides the signal into many small time intervals through a window function to
determine the frequency information of the signal in the time interval\[12\]. Given an unsteady continuous signal \(x(t)\) and a window function \(w(t)\) with a very narrow time width, \(w(t)\) will slide along the time axis. The STFT of the signal is defined as\[13\]:

\[
\text{STFT}_s(t, w) = \int_{-\infty}^{+\infty} x(\tau)w^*(\tau - t)e^{-j\omega \tau}d\tau
\]

Where \(x(t)\) is a continuous signal. \(w(t)\) is a window function.

The acoustic signal collected by sensor is a digital discrete signal, so the STFT is discretized. Assuming that the signal collected by the acoustic sensor from the sand-carrying oil flow impacting the pipeline wall is \(x(n)\), the window function is \(w(n)\), the window function moves on the time axis, and the window function length is \(N\), then the discrete form of the STFT transform is:

\[
\text{STFT}_s(n, k) = \sum_{m=0}^{N-1} x(n + m)w(m)e^{-j2\pi nk/N}
\]

Where \(x(n + m)w(m)\) is a short time sequence.

3. Experimental Equipment and Test Methods

3.1. Experimental equipment

According to the characteristics of sand-carrying oil flow, this paper designs a liquid-solid two-phase flow simulation monitoring experimental platform, as shown in figure 2. The experimental platform mainly includes key power components, multiphase flow mixing and circulation devices, sensor installation positions, circulating fluid temperature control systems, and acoustic signal acquisition systems. The screw pump provides the power to transport the liquid-solid two-phase flow, and the frequency converter can realize the circulation mode at different flow rates. The cooperation between two 90L liquid storage tanks can respectively realize a single loop and multiple stable loops of the entire experimental platform. The mixer at the mouth of the tank can ensure that the sand particle added and the fluid in the tank are evenly mixed. The power of the mixer is 0.12kW and the maximum speed is 1440r/min. The shaft is connected to the upper and lower propeller-type stirring impellers to meet the intensity requirements of the stirring.
The data acquisition system includes: an acoustic sensor, a charge amplifier, a four-channel acquisition instrument, and a computer with data acquisition software. The sensor is installed at the elbow of the circulating pipeline at twice the pipeline diameter. The actual installation diagram of the acoustic sensor is shown in figure 2(a). The charge amplifier and the four-channel acquisition instrument are integrated into one device, as shown in figure 2(b), which is used to obtain the real-time impact acoustic signal of the sand-carrying oil flow and transmit it to the charge amplifier to convert it into a voltage signal. It is collected by the data acquisition instrument, finally stored and analyzed by the computer.

![Acoustic sensor installation diagram](image1.png)

![Acoustic signal acquisition system](image2.png)

Fig. 3 Acoustic sensor and signal acquisition system

### 3.2. Experimental design

In the process of sand-carrying oil flow impacting the inner wall of the elbow, the signals collected by the acoustic sensor mainly include two types: oil flow impact acoustic signal and sand impact acoustic signal. First, the experiments of sand particle impacting the pipeline wall at different speeds and sand-free oil flow cyclically impacting the pipeline wall in the simulation monitoring experimental platform are carried out. The experimental process is as follows:

1. The acoustic signal acquisition experiment of the sand-free oil flow impacting the pipeline wall was carried out in the two-phase flow simulation monitoring experimental platform, and the impact velocity of the oil flow is set as 1.5 m/s, 2 m/s, 2.5 m/s and 3 m/s. Under 4 different oil flow velocities, the oil viscosity is set as 10 mPa·s, 20 mPa·s, 30 mPa·s, 40 mPa·s. Parameter design is shown in Table 1.

2. When the two-phase flow circulation device is closed, under 4 different impact heights, 4 different sizes of sand particle freely fall in the air. The acoustic signal of particle impact the pipeline wall collection experiment was carried out. Parameter design is shown in Table 2.

| Flow velocity / (m/s) | Viscosity / (mPa·s) |
|----------------------|---------------------|
| 1.5                  | 10                  |
| 1.5                  | 20                  |
| 1.5                  | 30                  |
| 1.5                  | 40                  |
| 2                    | 10                  |
| 2                    | 20                  |
| 2                    | 30                  |
| 2                    | 40                  |
| 2.5                  | 10                  |
| 2.5                  | 20                  |
| 2.5                  | 30                  |
| 2.5                  | 40                  |
| 3                    | 10                  |
| Flow velocity /(m/s) | Viscosity/(mPa·s) |
|---------------------|-----------------|
| 3                   | 20              |
| 3                   | 30              |
| 3                   | 40              |

Table 2  Parameter design of sand particle impact experiment

| Sand particle size /(μm) | Impact height/ (cm) | Impact velocity /(m/s) |
|--------------------------|---------------------|------------------------|
| 180                      | 10                  | 1.40                   |
| 180                      | 20                  | 1.98                   |
| 180                      | 30                  | 2.42                   |
| 180                      | 40                  | 2.80                   |
| 150                      | 10                  | 1.40                   |
| 150                      | 20                  | 1.98                   |
| 150                      | 30                  | 2.42                   |
| 150                      | 40                  | 2.80                   |
| 106                      | 10                  | 1.40                   |
| 106                      | 20                  | 1.98                   |
| 106                      | 30                  | 2.42                   |
| 106                      | 40                  | 2.80                   |
| 75                       | 10                  | 1.40                   |
| 75                       | 20                  | 1.98                   |
| 75                       | 30                  | 2.42                   |
| 75                       | 40                  | 2.80                   |

4. Experimental Results and Analysis

4.1. Characteristic analysis of oil flow impact acoustic signal

The acoustic signal generated by the sand-carrying two-phase flow impacting the pipeline wall is composed of the stronger acoustic signal produced by the oil flow and the weaker acoustic signal produced by the sand particle. The acoustic signal time-domain diagram of sand-free oil flow impacting the pipeline wall under 10mPa·s, 20mPa·s, 30mPa·s, and 40mPa·s at a flow rate of 2.0m/s is shown figure 4. Figure 4 shows that as the viscosity of the oil flow changes, the time domain amplitude of the impacting the inner wall of the elbow acoustic signal in the pipeline changes less. In order to further reveal the time-frequency domain characteristics of the acoustic signal generated by the oil flow impacting the pipeline wall, the STFT method is used to analyze the acoustic signal in the time domain.

The two-dimensional time-frequency spectrum diagram of the acoustic signals of sand-free oil flow impacting the inner wall of the elbow under 4 different viscosities at a flow rate of 2m/s is shown figure 5. Figure 5 shows that the acoustic signal frequency distribution of the oil flow of 4 different viscosities impacting the inner wall of the elbow is uniform. There is no obvious characteristic main frequency band in the entire analysis frequency band of 0-50kHz. Therefore, the energy of the oil flow impulse acoustic signal in the unit frequency band is basically the same in the analysis of the entire frequency band.
The time domain diagram of oil flow impacting the pipeline wall acoustic signal under velocity of 1.5m/s, 2m/s, 2.5m/s and 3m/s at the 20mPa·s oil flow viscosity is shown figure 6. Figure 6 shows that as the impact velocity of the oil flow increases, the time domain amplitude of the oil flow impact acoustic signal generated by the sensor increases significantly. Similarly, in order to obtain the characteristics of the impact acoustic signal of the oil flow at different flow velocity in the time domain, two-dimensional time-frequency spectrogram of the acoustic signals of the sand-free oil flow impacting the pipeline wall under the four flow velocity at 20 mPa·s oil viscosity is shown figure 7. The frequency amplitude of the acoustic signal of the sand-free oil flow impacting the pipeline wall increases with the oil flow velocity in the entire analysis frequency band. Combining the above analysis, the time domain amplitude of the acoustic signal of the sand-free oil flow impacting the pipeline wall increases with the impact velocity in the time domain system. It is not affected by the oil viscosity. Based on the analysis frequency band of 0-50kHz, the frequency amplitude of the acoustic signal of the sand-free oil flow impacting the pipeline wall increases as the flow rate of the sand-free oil flow velocity increases in the time domain system. It is not affected by the oil flow viscosity.
4.2. Characteristic analysis of sand particle impacting acoustic signal

The sand particle impacting acoustic signal is analyzed in the time domain system. The time-domain diagram of the acoustic signal of 106μm sand impacting the pipeline wall at 4 different heights is shown figure 8. Figure 8 shows that the domain amplitude of sand impacting the pipeline wall acoustic signal increases significantly as the impact height (impact velocity) increases. The time-domain diagram of the acoustic signal of four different sand particle impacting the pipeline wall under the impact height of
20cm is shown figure 9. Figure 9 shows that the time-domain amplitude of the sand impacting the pipeline wall acoustic signal increases significantly as the sand particle size increases.

Fig.8  Time-domain diagram of particle impacting the pipeline wall acoustic signals at different heights

Fig.9  Time-frequency domain diagram of different size particle impacting the pipeline wall acoustic signals

In the sand-carrying oil flow, the sand particle impacting the pipeline wall acoustic signal which is difficult to capture is weak compared to the fluid impacting acoustic signal. Therefore, the determination of the main frequency of the sand impacting acoustic signal is important for the analysis of the sand
impacting energy. The main frequency of the acoustic signal generated by the sand particle in the sand oil flow impacting the pipeline wall depends on the length of the contact time between the sand particle and the wall. The longer the time from the sand particle contacting the wall to the maximum deformation of the wall and the final restoration of the deformation, the lower the main frequency of the sand particle impacting pipeline wall acoustic signal. On the contrary, the higher the main frequency of the acoustic signal generated by the sand particle impacting the pipeline wall. In order to obtain the main frequency of the sand particle impacting the pipeline wall acoustic signal, take the acoustic signal data of 106 μm sand particle impacting the pipeline wall in a free fall under a height of 40cm as an example, the STFT three-dimensional time-frequency spectrum diagram is shown figure 10.

Figure 10 shows that the main frequency of the sand particle impacting the pipeline wall acoustic signal is around 22kHz, but the main frequency exact value cannot be accurate in the three-dimensional time-frequency spectrogram. Therefore, the high-frequency peak around 22kHz is independently analyzed. With 22kHz as the center and 0.1kHz as the step size, 21 frequency points are selected. The average amplitude of multiple frequency points at a specific resolution of around 22kHz in a whole acquisition period is obtained and compared. The 21 frequency profile curves of the high frequency part of the signal are shown figure 11.

The average amplitude of the frequency points represented by the 21 frequency profile lines during the acquisition time period is shown table 3. The normalized amplitude histogram of 21 frequency points
is shown figure 12. Figure 12 shows that the average amplitude of the 22kHz frequency point is the highest among the 21 frequency points when 106μm sand particle impact the pipeline wall under impacting height of 40cm, followed by 22.1kHz and 21.9kHz. Therefore 21.9~22.1kHz is selected as the characteristic frequency band of sand impacting the pipeline wall acoustic signal. This is selected as the research frequency band of this paper.

![Histogram of normalized amplitude at 21 frequency points](image)

Fig.12  Histogram of normalized amplitude at 21 frequency points

5. Calculation Model of Sand Content in Sand-carrying Oil Flow

5.1. Energy analysis of liquid-solid two-phase in sand-carrying flow

Based on the above characteristic analysis of the liquid-solid two-phase flow impacting signal, the liquid-solid two-phase energy in the sand-carrying oil flow is calculated. The energy of the signal that the liquid-solid two-phase flow impacts the pipeline wall is expressed by \( VE \), and its calculation formula is as follows[14]:

\[
VE = \frac{1}{T} \int_{0}^{T} v^2(t) \, dt
\]

Where \( T \) is the acoustic signal data sampling time length involved in the calculation. \( v(t) \) is the voltage value after signal processing at time \( t \).

Through the experimental analysis in section 3, the following conclusions are obtained:

① In the time domain system, the time domain amplitude of the oil flow impacting the pipeline wall acoustic signal increases as the oil flow velocity increases.

② In the time domain system, the time domain amplitude of sand particle impacting the pipeline wall acoustic signal increases with the increase of sand particle size. The time domain amplitude of sand impacting the pipeline wall acoustic signal increases with the increase of sand particle impact velocity.

③ In the time-frequency domain system, based on the 0-50kHz analysis frequency band, the frequency amplitude of the oil flow impacting the pipeline wall acoustic signal is uniformly distributed, and the energy in the unit frequency band is basically the same.

④ In the time-frequency domain system, the characteristic main frequency of sand impacting the pipeline wall acoustic signal is 21.9~22.1kHz. The impactting energy of sand particle is the largest in the frequency band of 21.9~22.1kHz.

Based on the above conclusions of ① ③, the energy of the sand-free oil flow impact on the pipeline wall acoustic signal is related to the impact velocity of the oil flow, and it is not affected by analysis and
filtering frequency bands. In order to more easily capture the acoustic signal of sand impacting the pipeline wall, the frequency band with the largest sand impacting energy is selected as the research frequency band. Therefore, 21.9~22.1kHz band-pass filtering is performed on the oil flow impulse acoustic signals under different flow rates, and the time domain data of filtered oil flow impulse acoustic signal is used to calculate energy of oil flow impact elbow under different flow speeds through formula (4). The relationship between the average impacting energy and the flow velocity is shown in figure 13. The average impacting energy of the fluid is recorded as $FE(\nu, f)_{\text{fluid}}$, and the impacting energy of oil flows under four different flow velocity is fitted by cubic polynomial. The calculation expression of the impacting energy relationship of the sand-free oil flow is:

$$FE(\nu, f)_{\text{fluid}} = a_0 + a_1\nu + a_2\nu^2 + a_3\nu^3$$  \hspace{1cm} (5)$$

Where $\nu$ is the oil flow velocity, m/s. $f$ is the filtering frequency band, Hz. The polynomial coefficients after fitting are shown in table 3.

![Impact energy results of oil flow at different flow rates](image)

**Table 3** The coefficient in formula (5)

| Subscript | 0   | 1   | 2   | 3   |
|-----------|-----|-----|-----|-----|
| value     | 30.31 | -49.98 | 24.02 | -2.02 |

Based on the above conclusions of ○○, the acoustic signal data of four different sizes particle impacting the pipeline wall is subjected to 21.9-22.1kHz band-pass filtering, and the filtered acoustic signal data is used to calculate the relative impacting energy by formula (5). The relationship between the impacting energy and impact velocity of the four different sand particle is shown in figure 14. The impacting energy of sand particle is recorded as $SE(\nu, f, d)_{\text{sand}}$, and the impacting energy curves of 4 kinds of sand particle are fitted by third-order polynomial to obtain the calculation expressions of the relative average impacting energy and impact velocity of sand grains of different particle sizes:

$$SE(\nu, f, d)_{\text{sand}} = (b_0 + b_1\nu + b_2\nu^2 + b_3\nu^3)$$  \hspace{1cm} (6)$$

Where $\nu$ is the impact velocity of the sand particle, m/s. $f$ is the filtering frequency band, Hz. $d$ is the sand particle size, μm. The energy values of the four kinds of sand particle impacting the pipeline wall under different flow rates are brought into formula (6). The third-order polynomial fitting coefficients are shown in table 4.
Fig. 14 Impacting energy results of sand particle

Table 4 The coefficient in formula (6)

| Subscript | 0  | 1  | 2  | 3  |
|------------|----|----|----|----|
| 180μm      | -63.0 | 99.70 | -51.08 | 8.88 |
| 150μm      | -63.33 | 99.72 | -50.98 | 8.83 |
| 106μm      | -57.29 | 89.72 | -45.71 | 7.93 |
| 75μm       | -51.69 | 80.60 | -41.09 | 7.17 |

5.2. Sand content calculation model

Using the corresponding impacting energy converted from the acoustic signal of the liquid-solid two-phase impact on the pipeline wall, the calculation model of the sand content in the sand-carrying oil flow is established. The sand content calculation model proposed in this paper is mainly divided into two steps:

① Noise reduction processing of impact signal of sand-carrying oil flow. Before the calculation relationship between the impacting energy and the sand content established, it is necessary to perform noise reduction processing on the monitored acoustic signal. During the monitoring process, the acoustic signal collected by the sensor includes the oil flow impact noise signal and the effective acoustic signal of sand impact, so it is necessary to subtract the collected original monitoring signal energy from the sand-free oil flow impact signal energy at the same flow rate to obtain signal energy value after noise reduction:

\[
VE(v, f, d)_{\text{fluid-sand}} - VE(v, f)_{\text{fluid}} = \frac{1}{T} \int_0^T V^2(t) dt - \left( a_0 + a_1 V^2 + a_2 V^4 \right)
\]

Where \(VE(v, f, d)_{\text{fluid-sand}}\) is the impacting energy of the sand-carrying oil flow.

② Calibration of sand production rate. Divide the noise-reduced oil-sand two-phase flow signal energy value by the sand impact signal energy at unit mass flow rate to obtain the sand production flow rate:

\[
q_{\text{sand}} = \frac{VE(v, f, d)_{\text{fluid-sand}} - VE(v, f)_{\text{fluid}}}{SE(v, f, d)_{\text{fluid}}} = \frac{\frac{1}{T} \int_0^T V^2(t) dt - \left( a_0 + a_1 V^2 + a_2 V^4 \right)}{b_0 + b_1 V^2 + b_2 V^4} / Q
\]
Where $q_{\text{sand}}$ is the sand flow rate, g/s. $SE(\nu, f, d)_{\text{Sand}} \mid (1g/s)$ is the sand impact signal energy per unit mass flow rate. $Q$ is the sand mass flow rate in the sand impact experiment, g/s. Using the sand production rate $q_{\text{sand}}$ multiplied by the monitoring time $T$ is the total sand production $S$ of the oil well during the entire monitoring process:

$$S = q_{\text{sand}}T \quad (9)$$

With 150μm sand particle, 64 indoor simulated sand production monitoring experiments at four different sand contents under four different flow rates of 1.5, 2.0, 2.5, 3.0m/s were carried out. The sand ratio is calculated using the sand content model, and the calculation result is shown in figure 15. It can be seen from figure 15 that the error between the theoretical sand mass flow rate and the real sand mass flow rate is not more than 10% by the collected sand monitoring acoustic signals and the sand content calculating model. The results show that the sand content calculation model based on the analysis of the acoustic signal characteristics of the sand-carrying oil flow can reduce the impact of fluid noise on the sand production monitoring results, and the calculated sand content in the pipeline has a higher accuracy.

![Fig.15 Calculation results of sand flow rate under different flow velocity](image)

**6. Conclusion**

This paper studies on the sand production monitoring and sand content calculation of oil wells based on the analysis of the acoustic signal characteristics of the sand-carrying oil flow impacting the pipeline wall by the signal analysis method. Design experiments through indoor simulation of sand production monitoring platform, the research shows that the time domain amplitude and energy of the oil and sand two-phase impactting acoustic signals increase with the increase of sand particle size and impact velocity. The STFT method is used to analyze the characteristics of the acoustic signal in the time-frequency domain system. The characteristic frequency band of sand particle impact is determined to be 21.9~22.1kHz, and the sand content calculation model is established based on the oil-solid two-phase impactting energy relationship in the sand-carrying oil flow under the characteristic frequency band. The monitoring results error between the theoretical sand mass flow rate and the real sand particle mass flow rate under different flow rates is not more than 10%. Therefore, the sand content calculation model proposed in this paper can effectively reduce the influence of fluid. This monitoring method can accurately monitor the sand content of sand producing oil wells in real time, which provides technical guarantee for safe and efficient production of oil fields.
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