Experimental Research and Numerical Analysis of the Attenuation Law of Ultrasound Propagating in Shale

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Abstract. To study ultrasound's attenuation law propagating in shale, we first tested the attenuation rate of ultrasound in air and shale by assembling an experimental device by ourselves. The experimentally measured ultrasonic attenuation coefficient in the air is close to the value obtained from most kinds of literature, so our self-assembled practical device is very reliable. By fitting the experimental data, we found that the average attenuation coefficient of ultrasound in the air is 0.0258 dB/m. The average attenuation coefficient in shale is 0.0657 dB/m. As the ultrasonic power increases, the attenuation coefficient of ultrasound gradually increases. Through calculation and analysis using the ultrasonic intensity formula, we found that the effective propagation distance of ultrasound in shale is about 1.2 m.

1. Introduction

Observed from the technological development of shale gas exploitation in recent years, shale gas exploitation still mainly uses hydraulic fracturing [1]. Although hydraulic fracturing technology can bring a good increase in production, there are still many problems used in shale gas production. First of all, shale gas exploitation areas are primarily located in mountainous regions, and water resources are scarce. The use of hydraulic fracturing technology requires a considerable amount of water and has potential environmental risks such as water pollution and geological structure damage. Secondly,
mountains are not conducive to the arrangement of hydraulic fracturing equipment. Large-scale hydraulic fracturing operations in mountainous areas will extend the construction period and increase development costs. Therefore, it is essential to explore a low-risk and easy-to-operate shale gas boost production technology.

Ultrasound is a high-frequency, high-energy mechanical wave that can produce mechanical vibration effects, cavitation effects, and thermal effects. All three effects can act on microscopic molecules to cause expansion, compression, and vibration. Based on the above characteristics, scholars in the United States and the former Union of Soviet Socialist Republics proposed using ultrasound to increase the production of oil reservoirs [2]. The field application shows that under the action of ultrasound, the production of oil wells has increased. Based on this application effect, in recent years, many scholars have also proposed applying ultrasound to shale gas exploitation to cope with the low porosity and low permeability characteristics of shale gas reservoirs.

The uses of ultrasound can be roughly divided into two categories [3]. The first type is the use of ultrasound energy to change certain states of materials. This effect requires the generation of more extensive energy ultrasounds, which is generally called power ultrasound. For example, ultrasonic cleaning, ultrasonic oil extraction, and ultrasonic processing are all power ultrasound applications in industrial production. The second type is the use of ultrasound to collect information, especially the information inside the material. Since ultrasound has the characteristic of being able to penetrate almost any material, for some other materials that cannot be penetrated by radiant energy, ultrasound shows usability in this respect, such as ultrasonic flaw detection and ultrasonic diagnosis. The use of ultrasound to increase shale gas production is exactly the first type of use based on ultrasound.

There is little research on the application of ultrasound to shale gas exploitation, but the theoretical research of applying it to coalbed methane exploitation has achieved specific results. Sun et al. [4] used a self-assembled experimental device to study the desorption effect of different gases under ultrasonic treatment. The study results show that the adsorption capacity of coal-rock for different gases is carbon dioxide, methane, and nitrogen in descending order. After ultrasonic treatment, the gas desorption rate increases by 70%, and the desorption capacity increases by 20%. Through experimental research, Yi et al. [5] found that the Langmuir adsorption isotherm equation can describe the gas adsorption characteristics of coal-rock under ultrasound action. The parameters in the equation are linearly related to the sound intensity of ultrasound. Zhao et al. [6] conducted experiments on the adsorption-desorption law of coalbed methane under the action of ultrasound. Experimental results show that with the increase of ultrasonic power, the adsorption capacity of coal-rock decreases and the gas desorption rate increases.

Judging from the above research situation, ultrasound can indeed have a significant effect on increasing the production of unconventional natural gas. Therefore, the combination of ultrasound and shale gas exploitation is a technology worthy of research and advancement. To combine ultrasound with shale gas exploitation, it is first necessary to understand the attenuation law of ultrasound propagation in shale and lay the first theoretical basis for an ultrasound to promote shale gas desorption. This paper takes the problems mentioned above as the research goal. By assembling the experimental device by ourselves, we first tested the attenuation coefficients of ultrasonic waves of different frequencies in the air and compared the experimental results with the attenuation coefficients obtained from most literature reliability of the experimental device. Secondly, this paper tests the attenuation coefficients of ultrasound of different frequencies in shale. It combines the test results with
the sound intensity formula to obtain the attenuation law of ultrasound propagating in shale.

2. Attenuation coefficient test

2.1. Experimental equipment

Figure 1 shows the schematic of the ultrasonic attenuation test device. Figure 2 is the physical diagram of the ultrasonic attenuation test device. The experimental device mainly includes an ultrasonic generator, piezoelectric Ceramic Transducer, virtual oscilloscope, and computer.

![Figure 1 Schematic of the ultrasonic attenuation test device](image1)

![Figure 2 Physical diagram of the ultrasonic attenuation test device](image2)

2.2. Experimental principle

Figure 3 shows the principle diagram of the ultrasonic attenuation test.

![Figure 3. Principle diagram of the ultrasonic attenuation test](image3)

The 0 point in Figure 3 is the location of the ultrasound source. The incident wave of the ultrasound propagates in the x direction. The wave equation of ultrasound is shown in Equation 1:
\[
\begin{cases}
\text{Incident: } y_1 = A_0 e^{i(wt - \gamma x)} \\
\text{Reflected: } y_2 = RA_0 e^{i(wt + \gamma(x - 2x_0))}
\end{cases}
\]  \hspace{1cm} (1)

where \( A_0 \) is the initial amplitude of the ultrasound, m; \( R \) is the reflection coefficient; \( \gamma \) is the propagation coefficient of the ultrasound; \( w \) is the frequency of the ultrasound, Hz.

In the interval between the incident point 0 and the ultrasonic receiving point \( X \), the incident wave and the reflected wave will superimpose each other, and the wave equation of the composite wave formed after superposition is:

\[
y = y_1 + y_2 = A_0 e^{i(wt - \gamma x)} + RA_0 e^{i(wt + \gamma(x - 2x_0))}
\]  \hspace{1cm} (2)

Each point of the composite wave is made of simple harmonic vibration, and its amplitude distribution can be calculated using Equation 3:

\[
A = A_0 \sqrt{e^{-2\alpha x} + R^2 e^{-2\alpha(x - x_0)} + 2Re^{-2\alpha x_0} \cos 2k(x - x_0)}
\]  \hspace{1cm} (3)

where \( \alpha \) is the attenuation coefficient of the ultrasound.

If the ultrasonic receiver is used as the reflecting surface, the composite wave amplitude received by the ultrasonic receiver is:

\[
A = A_0 (1 + R) e^{-\alpha x}
\]  \hspace{1cm} (4)

Because the ultrasonic generator and receiver are made of the same material, there is:

\[
\frac{A}{A_0} = \frac{U}{U_0}
\]  \hspace{1cm} (5)

where \( U \) is the voltage value displayed by the virtual oscilloscope, mv; \( U_0 \) is the voltage value output by the ultrasonic generator, mv.

Assuming that the voltage value \( U_i \) displayed by the virtual oscilloscope when the ultrasonic receiver is at any peak position \( x_i \), there is:

\[
U_i = U_0 (1 + R) e^{-\alpha x_i}
\]  \hspace{1cm} (6)

Measure the position coordinates \( x_i \) and voltage values \( U_i \) at multiple peaks respectively and record them in the experiment table. Fit the experimental data to get the attenuation coefficient of ultrasonic \( \alpha \).

2.3. **Reliability verification**

To verify the self-assembled experimental device's reliability, we first tested the attenuation of ultrasound in the air. The relationship curve between the recorded voltage and the position is shown in Figure 4.
Figure 4 Attenuation curve of ultrasound in air

It can be seen from Figure 4 that when the power of the ultrasound is 50 W, the attenuation coefficient of the ultrasound in the air obtained by fitting is 0.0197 dB/m. When the ultrasound's power is 110 W, the ultrasound's attenuation coefficient in the air received by fitting is 0.0318 dB/m. Take the average of the two experimental results as 0.0258 dB/m as the attenuation coefficient of ultrasound in the air. The test result is consistent with the result (0.02 dB/m) described in most literature. Therefore, our self-assembled experimental device has high reliability.

2.4. Analysis of experimental results
The fitting curve of the attenuation coefficient of the ultrasound in the shale measured by the experiment is shown in Figure 5.

Figure 5 Attenuation curve of ultrasound in shale

It can be seen from Figure 5 that when the power of the ultrasound is 50 W, the attenuation coefficient of the ultrasound in the shale obtained by fitting is 0.0764 dB/m. When the ultrasound's power is 110 W, the ultrasound's attenuation coefficient in the shale received by fitting is 0.0807 dB/m. Take the average of the two test results (0.07 dB/m) as the attenuation coefficient of ultrasound in shale. The experimental results also show that the attenuation coefficient of ultrasound will increase with the increase of its power.
3. Numerical analysis

After the attenuation coefficient of the ultrasound is obtained, the ultrasound's sound intensity during propagation can be calculated according to Equation 7, and the amplitude of the ultrasound during propagation can be calculated according to Equation 6.

\[ J = J_0 e^{-2\alpha l} \]  

(7)

Assuming that the initial amplitude is 1 mv and the initial sound intensity is 1 dB/mm, the calculated attenuation data of ultrasound propagating in air and shale is shown in Table 1.

The data in Table 1 shows that when the ultrasound propagates 1.2 m in the air, its amplitude attenuation is 44.9% of the initial value, and the sound intensity attenuation is 20.2% of the initial value. When the ultrasound propagates 1.2 m in the shale, its amplitude attenuates to 2.3% of the initial value, and the sound intensity attenuates to 0.1% of the initial value. The calculation results show that the effective propagation distance of ultrasound with a frequency of 24 kHz and a power of 50 W in shale is about 1.2 m. Considering that the experimental device is relatively simple and there are certain human errors, the propagation distance of ultrasound in shale should be greater than 1.2 m.

Table 1. Calculated attenuation data of ultrasound propagating in air and shale

| Distance (mm) | Attenuate in the air | Remarks     | Attenuate in the shale | Remarks     |
|---------------|----------------------|-------------|------------------------|-------------|
|               | Amplitude (mv)       | Intensity (mv) |                        | Amplitude (mv) | Intensity (mv) |
| 5             | 0.995                | 0.990       | —                      | 0.977     | 0.954       | — |
| 10            | 0.990                | 0.980       | —                      | 0.954     | 0.910       | — |
| 20            | 0.980                | 0.961       | —                      | 0.910     | 0.828       | — |
| 40            | 0.961                | 0.923       | —                      | 0.828     | 0.686       | — |
| 80            | 0.923                | 0.852       | —                      | 0.685     | 0.470       | — |
| 150           | 0.861                | 0.741       | —                      | 0.492     | 0.243       | — |
| 300           | 0.819                | 0.670       | —                      | 0.389     | 0.151       | — |
| 450           | 0.741                | 0.549       | Intensity attenuated by half | 0.242 | 0.059       | — |
| 600           | 0.670                | 0.449       | Intensity attenuated by half | 0.151 | 0.023       | — |
| 750           | 0.606                | 0.368       | —                      | 0.094     | 0.009       | — |
| 900           | 0.549                | 0.301       | —                      | 0.059     | 0.003       | — |
| 1050          | 0.496                | 0.246       | —                      | 0.037     | 0.001       | — |
| 1200          | 0.449                | 0.202       | —                      | 0.023     | 0.001       | — |
4. Conclusion
In this paper, the attenuation characteristics of ultrasound propagating in shale are researched through experiments and numerical analysis. The main conclusions obtained are as follows:

1) The average attenuation coefficient of the ultrasound in shale is 0.0657 dB/m.
2) As the ultrasonic power increases, the attenuation coefficient of the ultrasound gradually increases.
3) Effective propagation distance of ultrasound in shale is about 1.2 m.

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References
[1] Ross, D.J.K., Bustin, R.M. (2008) Characterizing the shale gas resource potential of Devonian-Mississippian strata in the Western Canada sedimentary basin: application of an integrated formation evaluation. AAPG Bull., 92 (1): 87-125.
[2] Wang, Z., Xu, Y. (2015) Review on application of the recent new high-power ultrasonic transducers in enhanced oil recovery field in China. Energy., 89: 259-267.
[3] Yuan, J., Luo, D., Feng, L. (2015) A review of the technical and economic evaluation techniques for shale gas development. Appl. Energy., 148: 49-65.
[4] Sun, R., Ji, Y., Lin L. (2015) On the effect of ultrasonic stimulation on the desorption of coalbed metaane. Journal of Experimentalal Mechanics., 30 (1): 94-100.
[5] Yi, J., Jiang Y., Xian, X. (2008) A numerical simulation of coalbed methane desorption and diffusion enhanced by ultrasound heating, Journal of Chongqing Jianzhu University., 30 (4): 99-104.
[6] Zhao, L. (2016) Experiment on CBM adsorption-desorption rules under the effect of ultrasonic pressure waves. Natural Gas Industry., 36 (2): 21-25.