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Research and Patterns of Rock Acid Pressure Corrosion Tests

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Abstract: In China, tight sandstone gas reservoirs are widely distributed, yet their development is hindered by issues such as low extraction efficiency and a monotonous extraction approach. To enhance the efficiency of tight sandstone gas extraction, this study investigates the internal fracture network characteristics of sandstone and its correlation with chemical solutions. Employing the sandstone acid fracturing technique, an experimental setup under gravitational conditions is established. Through this apparatus, fracturing experiments are primarily conducted on rocks utilizing the acid fracturing technique. The experimental findings suggest that the acid-fracturing coupling approach effectively induces rock fracturing. Uniaxial compression tests also indicate a noticeable alteration in the elastic-plastic behavior of rock samples after chemical solution corrosion, becoming more pronounced with increasing duration. The research demonstrates that this experimental setup significantly enhances the fracturing of sandstone and consequently improves the extraction of tight sandstone gas, holding crucial reference value.

1 Introduction

In recent years, with the continuous discovery of tight sandstone gas in basins such as Ordos, Tarim, and Sichuan, tight sandstone gas refers to a type of gas reservoir where natural gas is stored in sandstone with low porosity and permeability. The characteristics of this type of reservoir include the microscopic pore structure of sandstone rock, resulting in the difficulty of gas flow. The low porosity and permeability of the rock restrict the movement of natural gas in the rock matrix, making extraction relatively challenging. The development of tight sandstone gas requires the use of unconventional techniques, such as hydraulic fracturing and horizontal wells, to fracture the rock, increase permeability, and maximize gas release through multilayer development. Due to the vast potential reserves of this type of reservoir, the development of tight sandstone gas is strategically important for meeting energy needs, and acid pressure is one of the important methods for effectively developing such sandstone oil and gas reservoirs[1]. Acid pressure is a common reservoir modification technology, especially suitable for sandstone reservoirs. The core objective of this technology is to improve the physical properties of the reservoir by injecting acidic solutions, thereby increasing the oil and gas recovery rate. The main mechanism of acid pressure on sandstone reservoir development is through the injection of acidic solution, which reacts with minerals such as calcium carbonate and silicates in the reservoir rock, producing water-soluble products such as salts and carbon dioxide, thereby dissolving the reservoir rock, effectively increasing porosity and permeability. Additionally, the cleaning action of the acidic solution enables effective cleaning of reservoir pores, dissolving or flushing impurities such as clay particles and mud grains, enlarging effective pores, and further increasing permeability. Furthermore, the injection of acidic solution can generate pressure, inducing crack formation, which helps to increase the permeability of the reservoir, making it easier for oil and gas to flow through the reservoir and be extracted. Finally, the acidic solution has a dissolving effect on deposits, cements, or shales in the reservoir, preventing pore blockage and effectively enhancing the fluidity of oil and gas. Therefore, acid pressure technology comprehensively enhances the physical properties of sandstone reservoirs through multiple mechanisms, creating favorable conditions for increasing recovery rates.

Gong Wei optimized the acid solution formula and process to complete the technology for jet acid pressure transformation[2]. Guo Yanjie studied the acid pressure method for reservoirs to achieve difficult production transformation[3]. He Chunming et al. researched acid pressure technology suitable for deep-seated low-permeability fractured carbonate reservoirs[4]. Zhang Long et al. found through triaxial compression tests of acid-base chemical solutions that both acidic and alkaline solutions have a negative effect on sandstone[5]. Hou Bing et al. used the phase field method to simulate the phenomenon of hole chaining and found that acid pressure cracking is more effective in multiple hole chains to increase flood discharge area[6]. Guo Jianchun used stereoscopic acid pressure technology to improve the development of deep-seated rock oil and gas[7]. Youliang Chen and Peng Xiao studied the damage constitutive model of rocks under freeze-thaw-confining pressure and acid erosion and found the damage evolution of rock

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under acid erosion and freezing-thawing and confining pressure, and derived the model parameters to reveal the reliability of the model[8]. Fanhui Zeng provided a method of acidifying rocks to reduce fracturing pressure, and the research results showed that acidification can reduce rock strength and critical stress intensity factor of cracks, thereby reducing crack pressure combination[9]. Jianchun Guo found through quantitative prediction models that the greater the acid concentration, the greater the rock damage variables and shear strength intensity[10]. Ahmadi, M.A., & Shadizadeh, S.R experimental investigation on the adsorption behavior of natural surfactants extracted from Zyziphus Spina Christi leaves onto shale sandstone reservoir rocks under static and dynamic conditions, with implications for chemical EOR applications[11]. Greibrokk conducted a study on the application of multi-stage supercritical fluid extraction in samples from Kimmeridge Clay and Posidonia shale formations, aiming to assess its potential as a substitute for liquid extraction of petroleum source rocks[12]. These studies indicate that most scholars use separate methods of chemical solution and gravity pressure to fracture rocks, and there are few models to simultaneously handle stress and chemical solution for rock fracturing.

This paper starts from the characteristics of the internal crack network of sandstone and the relationship between seepage flow to improve the production of tight gas. It establishes a model of a gravity-pressure-coupled test system for rock acid pressure under the gravity pressure, which integrates a corrosion simulation device, a gravity-pressure device, and an electrochemical detection device. Based on this model, the influencing factors such as solution dosage ratio and load value during the test process are analyzed, and then the optimized supporting devices are realized, providing theoretical support for the effective extraction of sandstone gas.

2 Overview of the Experimental Model

2.1 Overview of the Experimental Model

The experimental setup primarily consists of a gravity pressure apparatus and a corrosion simulation device, complemented by a working platform and pillars, creating a coupled rock acid-fracturing testing system. In essence, this apparatus simulates the subsurface environment by employing the gravity pressure apparatus and corrosion simulation device installed on the working platform. The setup includes sandstone specimens placed within the test chamber and a gravity pressure apparatus containing chemical solutions. The upper part of the rock specimen is connected to the pressurized container, enabling simultaneous application of chemical solutions and gravitational pressure on the rock sample. This system achieves the coupling of gravity pressure and chemical corrosion. Furthermore, an electrochemical workstation is connected to the rock specimen via conductive wires and linked to a computer through data cables, forming a closed circuit to monitor the electrochemical changes in the rock sample.

This experimental design facilitates real-time monitoring of the microstructural changes in shale under the combined influence of gravity pressure and chemical solution pressure. It is suitable for indoor investigations into the microscopic structural variations of rocks subjected to the simultaneous effects of pressure and acid corrosion, achieved through laboratory experiments and continuous monitoring. The equipment is designed for simplicity, featuring a clear operational procedure and user-friendly interface, with the advantage of straightforward instrumentation.

2.2 Design of the Experimental System Model

This apparatus primarily comprises a corrosion simulation device, a gravity pressure apparatus, and an electrochemical detection device to facilitate the experimental process. In the corrosion simulation device, the core operation involves the interaction between the rock sample, chemical solution within the container, and the transmitted load, occurring through a flexible board during pressurization. The gravity pressure apparatus applies pressure to the experimental setup by increasing the weight of the weights, allowing for the acquisition of electrochemical data as the load is continuously applied. The electrochemical detection device operates by inducing reactions through an electrochemical workstation, and the reaction data are then transferred to a computer via conductive wires. Consequently, the computer accurately receives and records data reflecting the internal changes in the rock specimen.

The specific system models are illustrated in Fig 1 and Fig 2.

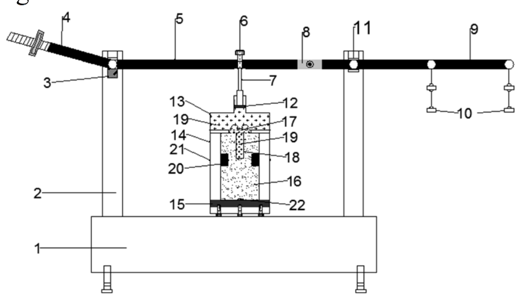

Fig. 1 Three-dimensional Schematic Diagram of the Experimental Structure

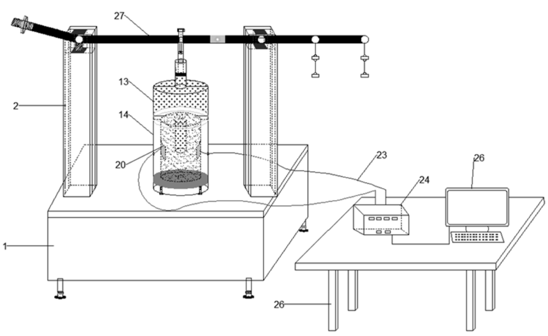

Fig. 2 Model's Corrosion-Pressurization Coupling Device Layout

2.3 Operation of the Experimental System Model

1)Device Installation: Initially, boreholes are drilled at the upper part of the rock sample, and the subsequently drilled rock sample is placed in a chemical solution for corrosion. The bottom of the test chamber accommodates the required rock specimens, adjusting the test chamber to an appropriate height. Subsequently, the gravity pressure container and baffle are connected through the test chamber, with the container holding the chemical solution connected to the pillar using a straight rod, thereby completing the installation of the gravity pressure apparatus.

2)System Calibration: The vertical rod is adjusted to a horizontal position using a horizontal adjustment balance weight. The adjustable pressure rod is then mounted on the vertical rod, and pressure loading is achieved by adding weights to the tray. Finally, the signals from the collected electrodes are transmitted to the electrochemical workstation via conductive wires.

3)Experimental Testing: Gradual pressure loading is applied by incrementally adding weights to the tray at different positions, assessing the compressive strength of the rock sample. The experimental data recorded by the electrochemical workstation are then analyzed to reveal the characteristics of crack development and the dynamic evolution process.

2.4 Acid-Fracturing Experiment on Sandstone

To investigate the impact of the sandstone acid-fracturing test apparatus on the reaction characteristics of sandstone, a simplified experimental procedure was devised based on the setup of the test apparatus. Two key factors, namely the primary acid concentration and corrosion time, were defined during the experiment to assess their influence on the reaction characteristics of sandstone,As shown in Table 1.The aim was to explore the temporal variations in sandstone under different pH values of chemical solutions, thereby validating the feasibility of the experimental apparatus design.

Table 1 Solution-Water Ratio Schemes for Chemical Solutions

Solution	Composition	Solution	pH
1	HCL	0.2	3
2	HCL	0.2	6
3	Distilled ---		7
4	NaOH	0.2	9
5	NaOH	0.2	12

The sandstone specimens, with a diameter of 50mm and a height of 150mm, were subjected to the chemical solution corrosion as outlined in Table 1.1 The specimens were divided into five groups based on different pH values of the chemical solutions. Subsequently, the corroded sandstone samples underwent boiling in distilled water to remove surface chemical residues. Afterward, the sandstone samples were dried in an oven and allowed to stand. Following this, the statically placed sandstone samples were introduced into the corrosion and pressure apparatus with chemical solutions of varying pH values. A constant load, provided by a 2kg weight, was applied for 30 days, 60 days, and 90 days to obtain sandstone samples at different corrosion time points, along with the corresponding chemical solutions post-treatment. The specimens, having undergone chemical interaction, were then subjected to uniaxial compression tests. The changes in stress-strain curves of the sandstone samples after acid-fracturing and the variations in the pH values of the chemical solutions were observed.

By establishing the experimental apparatus described above, the process of rock acid pressure corrosion can be observed clearly, allowing for a more detailed examination of the patterns of change in rocks under acid pressure corrosion conditions. This provides a novel approach to more efficiently extracting tight sandstone gas, thereby achieving increased production of tight sandstone gas.

3 Results Analysis

3.1 Analysis of Acid-Fracturing Test Results

3.1.1 Variation Patterns in Rock Mass Over Time

Acid-Fracturing experiments induce chemical erosion on sandstone samples, resulting in a loss of mass. The Mass Loss Rate serves as a quantitative indicator to measure the extent of this loss. Calculating the difference between the initial and final masses allows determining the numerical value of the mass loss rate, reflecting the sandstone samples' erosion resistance in acidic solutions. Thus, to better illustrate the changes in sandstone mass in chemical solutions, the Mass Loss Rate (Q) is defined as follows:

$$Q=\frac{S_t-S_0}{S_0}\times 100\% \tag{1}$$

Where: S_0 is the initial mass of the rock sample; S_t is the mass of the rock sample after t time of interaction with the chemical solution

The Mass Loss Rate curve effectively depicts the extent of the rock's interaction with the chemical and aqueous solutions. By incorporating the initial mass of the rock sample and the mass obtained after corrosion with the chemical solution into Equation (1), followed by data processing and graphical representation using software, as shown in Fig 3. the trend can be analyzed.

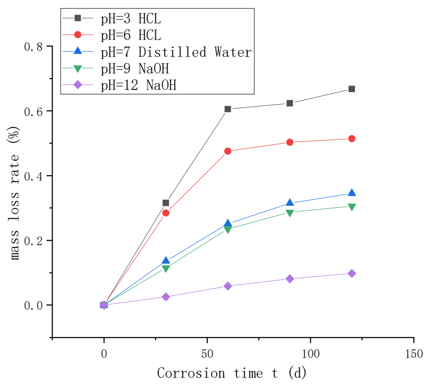

Fig. 3 Sandstone Mass Loss Dynamics Across Varied pH Over Time

(1) The mass loss rate of sandstone gradually increases with the extension of corrosion time. Overall, the trend indicates that in the early stages of corrosion, the degree of mass change in sandstone is higher, while in the later stages, the mass change becomes more gradual.

(2) Under various pH conditions and corrosion time levels in chemical solutions, sandstone exhibits different degrees of mass loss. In the presence of chemical solutions, the mass loss rate of the rock increases gradually with the extension of corrosion time, reflecting a continuous deterioration of rock mass. During the initial corrosion in chemical solutions, sandstone experiences the fastest corrosion in HCl solution with pH=3 and NaOH solution with pH=6, showing higher degrees of mass loss rate change, approximately 0.38% and 0.26%, respectively. As the corrosion progresses into the middle and later stages, the mass change of sandstone in HCl solution with pH=3 and NaOH solution with pH=6 stabilizes, and the mass loss rate gradually tends to stabilize, maintaining at 0.67% and 0.57%, respectively. The results demonstrate that the higher the concentration of hydrogen ions in the chemical solution, the faster the corrosion of sandstone, leading to a greater mass loss rate. Conversely, as the concentration of hydrogen ions decreases, the mass loss rate gradually stabilizes. For distilled water with pH=7, sandstone exhibits minimal mass change, and the mass loss rate steadily approaches a slow, stable state, remaining below 0.1%.

Based on the observed patterns, it can be seen that sandstone is more effectively corroded under chemical solutions with pH values of 3 and 12, leading to more significant mass loss. Therefore, using high-concentration chemical acid solutions can better corrode sandstone, thereby achieving increased production of tight sandstone gas.

3.1.2 Effect of Acid Pressure Corrosion Time on Different pH Values of Chemical Solutions

In the acid pressure corrosion experiment, sandstone samples were used as experimental materials. During the corrosion process of sandstone samples with chemical solutions, certain substances inherent in the sandstone could interact with the dissolved substances in the chemical solution, leading to changes in the pH value of the chemical solution over time. As shown in Figure 4. Therefore, the degree of pH reaction detected can explicitly indicate the effectiveness of the interaction between sandstone samples and chemical solutions.

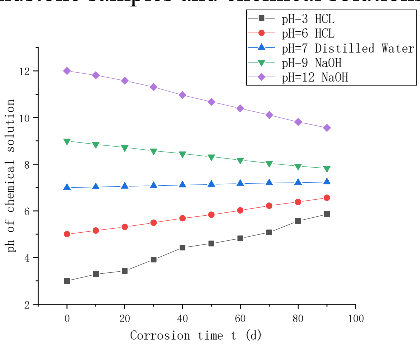

Fig. 4 pH Variation During Acid Pressure Corrosion

Figure 4 shows the variation of different pH values of solutions with acid pressure corrosion time：

(1) As the corrosion time progresses, the pH values of the solutions slowly approach neutral values.

(2) In the initial stages of corrosion, the pH values of chemical solutions at different initial pH values exhibit both upward and downward trends, repeating these fluctuations with prolonged corrosion time. Significant variations are observed in the chemical solutions with initial pH values of 3 and 12. The chemical solution with an initial pH of 7 shows smaller pH variations and eventually exhibits weak alkalinity.

(3) In the acidic solutions with pH values of 3 and 6, as the corrosion time increases, the pH of the chemical solution gradually shifts towards neutral. The former undergoes faster changes, stabilizing around 4.7 in the later stages of the experiment, while the latter stabilizes around 6.8.

(4) In the alkaline solutions with pH values of 9 and 12, the pH of the chemical solution gradually shifts towards weak acidity with increasing corrosion time. The effect is more pronounced in the early stages, with a more significant decrease in pH. In the later stages, both solutions maintain nearly the same rate of decrease, stabilizing around 7.6 for pH=9 and 9.3 for pH=12.

(5) Analyzing the results of the corrosion of sandstone samples by chemical solutions at different pH values, the pH of the chemical solution gradually tends towards neutralization with increasing corrosion time. The solution with an initial pH of 3 tends to neutralize the fastest, followed by pH=12, pH=6, pH=9, and pH=7. These observations suggest that acidic solutions have a more pronounced impact on the pH system of chemical solutions during the sandstone pressure corrosion experiment compared to alkaline and neutral solutions. Additionally, the analysis indicates that minerals present in the sandstone samples interact with the ions in the chemical solution during corrosion, causing the partial decomposition of minerals and resulting in the chemical solution trending towards a neutral state.

Based on the observed patterns, it is found that during the process of acid-pressure corrosion over time, the intense reaction of sandstone gradually diminishes into a slower process. It can be analyzed that with the prolongation of acid-pressure corrosion time, sandstone is continuously corroded, leading to a continuous change in the chemical solution. Therefore, prolonging the corrosion time can more effectively corrode the rock, thereby reducing the difficulty of extracting tight sandstone gas and achieving increased production of tight gas.

3.2 Sandstone Uniaxial Compression Test Result Analysis

During the acid pressure corrosion experiment, sandstone samples were extracted for uniaxial compression testing in cycles of 30 days. The TestExpert software corresponding to the rock creep apparatus was employed for parameter control and setup. The experiment data obtained were used to create stress-strain curve graphs using the software. Finally, stress-strain curve features for samples

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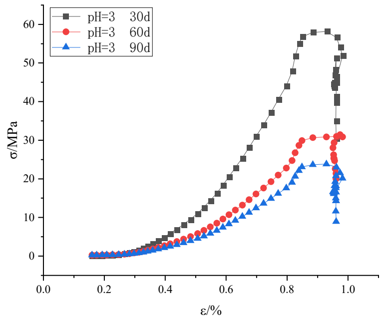
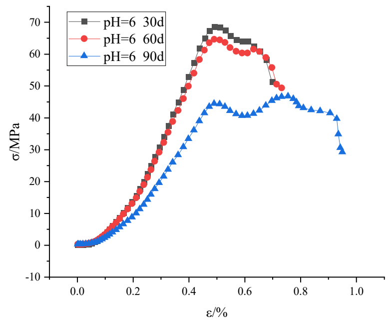
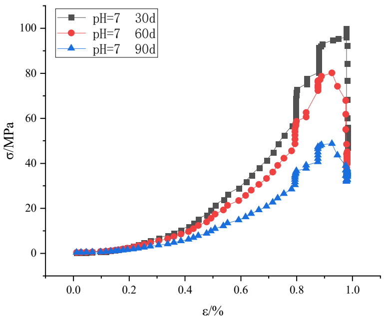
with the same pH values extracted at 30, 60, and 90 days were analyzed. As shown in Fig 5.Among them, Fig (a), (b), (c), (d), and (e) represent stress-strain curves at different pH values



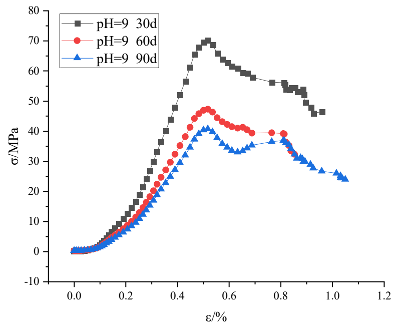
(a) ph=3



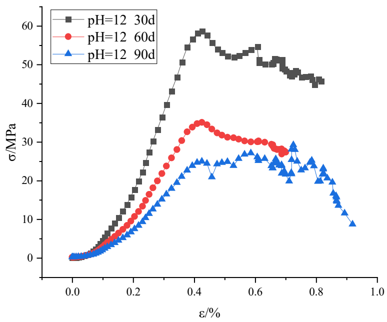
(b) ph=6



(c) ph=7



(d) ph=9



(e) ph=12

Fig. 5 Stress-Strain Curves at Different pH Values Corresponding to Days

Based on Fig 5, the stress-strain curves under corrosion conditions exhibit four main stages, with the following patterns:

(1)Initial Uniaxial Fracture Stage: In this stage, the sandstone sample, subjected to axial stress, initially experiences the closure of the original tensile cracks and micro-fissure structures. This leads to a compaction process, resulting in the early nonlinear deformation shape, represented by an upward concave curve on the stress-strain curve graph (Fig 5). Notably, the higher acidity levels demonstrate a more pronounced concave curve, indicating a more significant impact of chemical solution corrosion. As time progresses, the softening of the sample increases, and the strain compaction point becomes significantly higher. Analysis suggests that, under axial stress, the chemical solution induces greater changes in the internal porosity of the sandstone sample, leading to an extended compaction time. This reflects the more apparent development of porosity in the sandstone sample due to the corrosion by the chemical solution.。

(2)Initial Uniaxial Fracture Stage: In this stage, the sandstone sample, subjected to axial stress, initially experiences the closure of the original tensile cracks and micro-fissure structures. This leads to a compaction process, resulting in the early nonlinear deformation shape, represented by an upward concave curve on the stress-strain curve graph (Fig 5). Notably, the higher acidity levels demonstrate a more pronounced concave curve, indicating a more significant impact of chemical solution corrosion. As time progresses, the softening of the sample increases, and the strain compaction point becomes significantly higher. Analysis suggests that, under axial stress, the chemical solution induces greater changes in the internal porosity of the sandstone sample, leading to an extended compaction time. This reflects the more apparent development of porosity in the sandstone sample due to the corrosion by the chemical solution.

(3)With the continuous application of axial stress, new cracks develop in the sandstone sample. The stress-strain curve in Figure 5 shows a fluctuating trend due to the repeated rupture of new cracks. Notably, the plastic curve for the solution with a pH of 7 indicates a direct descending trend without the observed fluctuation. In contrast, solutions of different concentrations show varying degrees of fluctuation. The peak value on the stress-strain curve represents the deformation when the sandstone reaches failure. A higher peak value indicates a more significant corrosion effect on the sandstone sample, with a more pronounced decrease in the value, suggesting a more apparent softening effect as the corrosion time extends. The sandstone sample gradually exhibits flexible characteristics during this stage.

(4)Ultimate Failure Stage: After reaching the peak axial stress, internal damage occurs in the sandstone sample. In this stage, cracks propagate rapidly, and the load-bearing capacity of the sample decreases rapidly but does not reach zero, indicating that the sample still retains some load-bearing capacity. Figure 5 shows a reverse growth trend in the curve during this stage, with an overall descending trend.

In summary, under the corrosion of different chemical solutions, there are similarities in the stress-strain curves. Figure 5 illustrates that, under the corrosion of chemical solutions with higher pH values, the curve characteristics of the sandstone sample become more pronounced. With an increase in the duration of chemical solution exposure, both the elastic and plastic deformation stages exhibit significant changes. The curves in the plastic stage are more apparent than those in the elastic stage, with more significant peak values. As the corrosion time lengthens, the curves show a descending trend, indicating the gradual manifestation of flexible characteristics in the sandstone sample. During the uniaxial compression process, it is also evident that under conditions of higher chemical solution concentration, the stress variation of sandstone is more pronounced. Furthermore, with the prolongation of corrosion time, the internal stress variation of sandstone becomes more noticeable. Therefore, under conditions of higher concentration and longer corrosion time, it is more suitable for extracting tight gas from sandstone, thus effectively achieving increased production of tight gas.

4 Conclusions

This study employed a self-developed acid pressure corrosion test apparatus to assess the impact of chemical solutions with varying pH values on sandstone samples. The evaluation encompassed measurements of rock mass loss, variations in solution pH post-reaction, and subsequent uniaxial compression experiments following acid pressure corrosion. The feasibility of the acid pressure corrosion apparatus was verified through these experiments, yielding the following conclusions:

(1)Verification of Rock Acid Pressure Corrosion Design:Conducting indoor experiments validated the design for rock acid pressure corrosion. Relevant indicators were monitored during the sandstone's reaction with chemical solutions. The results indicated a gradual increase in rock mass loss rate during the acid pressure corrosion process. Notably, the mass loss rate escalated more rapidly with higher concentrations of chemical solution pH.

(2)Evolution of Solution pH and Rock Behavior:After a certain duration of corrosion, the pH of the solution within the container gradually approached weakly acidic or weakly alkaline conditions, trending towards a neutral value. In acidic and alkaline chemical solutions, the chemical reaction intensity of the rock in acidic solutions was stronger than in alkaline solutions. It can be inferred that ions in alkaline solutions react with ions in the sandstone sample, leading to dissolution or precipitation, resulting in a reduction in sandstone mass and a tendency for the solution's pH to approach neutrality.

(3)Uniaxial Compression Testing and Stress-Strain Curve Evolution:Uniaxial compression tests were conducted on rock samples subjected to chemical solution and gravity pressure. The evolution of stress-strain curves was observed. Over time, the strain at the peak point gradually increased on the curve, indicating a slow reduction in peak intensity and elastic modulus. In contrast, curves representing peak intensity and elastic modulus exhibited a gradual decline.

In summary, the experiments provided valuable insights into the behavior of sandstone under acid pressure corrosion conditions. The study successfully verified the feasibility of the acid pressure corrosion apparatus and highlighted the influence of chemical solution pH on rock mass loss and mechanical properties.

(1)In general, this study conducted experimental verification using a self-developed acid pressure corrosion test apparatus. It involved subjecting rock samples to corrosion experiments with chemical solutions of varying pH values, observing the resulting mass loss of the rocks, and subsequently conducting uniaxial compression tests after acid pressure corrosion. The experimental findings are as follows:

(2)During the acid pressure corrosion process, the mass loss rate of the rock gradually increases with the duration of chemical solution corrosion, with a faster increase observed with higher concentrations of solution pH.

(3)After a certain period of acid pressure corrosion, the pH value of the solution gradually approaches neutrality. In acidic and alkaline solutions, the chemical reactions within the rocks are more pronounced under acidic conditions, leading to a reduction in rock mass, while the solution pH tends towards neutrality.

Uniaxial compression tests indicate that with prolonged chemical solution corrosion time, the peak strain of the rock gradually increases, while the peak strength and elastic modulus exhibit a declining trend.

These patterns suggest that the properties of rocks under acid pressure corrosion conditions are influenced significantly by both the pH value of the chemical solution and the duration of corrosion, thereby affecting both the mass loss and mechanical performance of the rocks. Moreover, under conditions of high concentration chemical solutions and prolonged corrosion time, the enhancement of tight sandstone gas production can be more pronounced.

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