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Experimental research on supercritical CO2 true triaxial pneumatic fracturing

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Abstract: The application of supercritical CO$_2$ pneumatic fracturing technology to the development of shale gas and coalbed methane was explored. Experimental tests were conducted using the first true triaxial SC-CO$_2$ pneumatic fracturing experimental system, and the effects of initial air pressure and energy-accumulation agent dosage on pressure changes and the initiation and propagation of fracturing were studied. Through the analysis of the pressure curve, it is found that, at a certain volume, the efficiency of reaction pressurisation can be improved by appropriately increasing the amount of accumulator and increasing the initial air pressure; compared with hydraulic fracturing and SC-CO$_2$ fracturing, the process of pneumatic fracturing is more similar to that of blasting in rock. The reverse
The tensile stress wave generated in the process of pneumatic fracturing is the cause of the annular cracks; the cracks on the surface of the sample after the cracking exhibit fractal characteristics, with a good linear fit between the fractal dimension $F_d$ and the damage variable $w$, as defined by the cracked area. Since the fractal dimension can better describe the complexity of the crack, using the fractal dimension as the damage variable can better describe the degree of damage. The research provides a reference for the engineering problem of the new waterless fracturing technique of SC-CO$_2$ pneumatic fracturing in shale gas production.

**Keywords:** supercritical CO$_2$; Pneumatic fracturing; Fractal dimension; Damage variable

1 Introduction

The combination of horizontal wells and hydraulic fracturing technology has achieved great success in the shale gas exploitation and has significantly increased the production of shale gas (Gao et al. 2020; Wang et al. 2014; Zhou et al. 2016). At the same time, the shale gas revolution triggered by this in the United States has had a huge and far-reaching impact on the international energy structure (Vengosh et al. 2014). However, while using traditional hydraulic fracturing to extract shale gas, problems such as water pollution and water blocking effects are exposed (Middleton et al. 2014). Supercritical CO$_2$ fracturing technology is a new type of fracturing technique proposed against the background of people seeking more efficient, safe, and environmentally friendly shale gas extraction methods. The low viscosity and high diffusivity of supercritical CO$_2$ fluid have attracted the attention of scholars interested in shale gas development. To promote the improvement and progress of this technique, scholars have investigated CO$_2$ phase change fracturing in shale gas exploitation. Among them, compared with hydraulic fracturing, supercritical CO$_2$ fracturing technology has the following main advantages: (1) The
fracturing fluid has a low viscosity and high diffusivity, and is easily connected with natural fractures to form a more complex fracture network (Wang et al. 2019; Wang et al. 2012); (2) As a waterless fracturing technique, it saves water and reduces pollution (Zhang et al. 2018; Shi et al. 2007; Wang et al. 2015; Wang et al. 2018); (3) The initiation pressure is lower, and it is easier to produce shale gas from high-strength reservoirs (Ishida et al. 2014); (4) For the displacement of CH4, the adsorption of CO2 by the reservoir is stronger, making CH4 easier to resolve, thereby increasing the rate of shale gas extraction (Li et al. 2017; He et al. 2018); (5) The fast return of fracturing fluid effectively reduces the impact of water lock in the hydraulic fracturing process, that is, the expansion of clay is smaller, shale gas is easier to analyse, and the rate of extraction thereof is greatly improved (Chen et al. 2015). The research on the initiation and propagation of supercritical CO2 fluids is mainly embodied in the study of in-situ stress differences, the mechanical properties of the rock itself, primary fractures, bedding planes, and other influencing factors. Experiments have shown that the initiation pressure of supercritical CO2 fracturing is significantly lower than that of hydraulic fracturing. The main reason for this is that seepage allows the supercritical CO2 fluid to enter the primary fractures of the rock mass, resulting in an increase in pore pressure and a decrease in initiation pressure (Isaka et al. 2019; Haimson et al. 1969). Experiments show that when the difference between the maximum horizontal principal stress and the minimum horizontal principal stress is large, the initiating crack can pass through the bedding and along a direction perpendicular to the minimum horizontal principal stress. When it is small, the initiating cracks are connected to bedding and primary cracks (Wang et al. 2017). However, some other documents have found that the stress difference does not necessarily contribute to hydraulic fracturing, which depends on the nature of the interface and the shear stress on it (Gao et al. 2019; Gao et al. 2020). Compared with hydraulic fracturing, supercritical CO2 fracturing makes it easier for an initiated crack to connect with
bedding and primary fractures to form a complex network structure, indicating that supercritical CO\textsubscript{2} fracturing technology has more obvious advantages in layered rocks (Zhang et al. 2017). At the same time, the in-situ stress, reservoir temperature, and fluid temperature were analysed with injection speed and other factors. Compared with hydraulic fracturing, supercritical CO\textsubscript{2} has a lower viscosity and causes more complex fractures, which is conducive to fracturing, but the requisite large amount of CO\textsubscript{2} is expensive to prepare, and there is an urgent need to provide a more efficient and energy-saving new type of waterless fracturing technique.

CO\textsubscript{2} phase change fracturing technology is an emerging fracturing technique: the concept was first proposed by the British Cardox company in the 1950s to achieve rock fracturing through a CO\textsubscript{2} fracturing tube (Ke et al. 2019). It involves heating liquid CO\textsubscript{2} through use of a heating agent to make it absorb heat and expand, and through the rupture of the CO\textsubscript{2} fracturing tube, release high-energy CO\textsubscript{2} fluid (in a supercritical state) to achieve the purpose of breaking rocks and cleaning boilers. In addition, compared with the rapid loading rate of traditional blasting techniques and low loading rate used in hydraulic fracturing, the loading rate of supercritical CO\textsubscript{2} phase change fracturing technology is relatively moderate, making it more suitable for rock fracturing. Therefore, after the introduction of CO\textsubscript{2} blasting fracturing to China in the 1990s, several applications have been developed for use in coalbed methane mining to overcome the problem of low permeability prevalent in China’s coal seams. This technology improves the mining efficiency of coalbed methane mainly by fracturing and enhancing the permeability of coal. Many scholars have conducted extensive research into this technique. Fan et al. (2020) studied the application of CO\textsubscript{2} phase change fracturing to promote gas drainage, and revealed the working principle of Liqued CO\textsubscript{2} phase change fracturing (LCO\textsubscript{2}-PTF): the fracturing pipe, under the shock wave from high-pressure gas, generates many cracks in the coal, which improves gas drainage.
He et al. (2018) established a numerical method of calculation of the range of influence of permeability based on mine field experiments to determine the hole spacing and gas flow after fracture. Kang et al. (2018) used numerical simulation to simulate the propagation of stress waves and the development of damage, and calculated the effective fracture radius of the coal and rock masses around the blast hole, comparing them it with the results of field experiments. In an exploratory experiment using supercritical CO\textsubscript{2} in coal, Yan et al. (2021) found that coal fractures after supercritical CO\textsubscript{2} fracturing were more complicated compared to hydraulic fracturing fractures. Due to the similarity between the phase change fracturing process and the traditional blasting technique, the current research on the crack initiation and crack propagation mechanism of supercritical CO\textsubscript{2} phase change fracturing is based more on the theory of rock breaking in blasting to analyse stress waves and high pressures. Other work focuses on the influence of a fluid on crack initiation and crack propagation (Donze et al. 1997; Kutter et al. 1971; Nilson et al. 1985). Zhang et al. (2019) established a cyclic dynamic model of rock fracture, and shows that supercritical carbon dioxide phase change fracturing is the result of stress wave. Goodarzi et al. (2015) performed numerical simulation on the rock-fracturing process under high-energy gas fracturing and concluded that the gas pressure has a greater influence on the length of the crack, while the stress wave has a smaller influence thereon. These studies have promoted the development of waterless fracturing techniques in CO\textsubscript{2} phase change fracturing.

However, when the traditional repetitive CO\textsubscript{2} fracturing device detonates, the high-pressure gas in its body cannot fracture the expansion tube and can only be discharged in the direction of the end of the liquid storage tube. The force in other directions exerted by the liquid storage tube is small, which has certain limitations. Disposable CO\textsubscript{2} crackers are extremely dangerous and are prone to explosion and flying tubes, therefore, some countries prohibit their use. In view of the hidden safety hazards of
traditional CO\textsubscript{2} phase change expansion fracturing, Hu et al. (2019) proposed a new type of CO\textsubscript{2} static pneumatic fracturing process, which mainly uses the large amount of heat released by the combustion of intrinsically safe CO\textsubscript{2} accumulators under voltage excitation to achieve CO\textsubscript{2} phase transition, using the gas shock wave and quasi-static gas pressure to cause the rock to expand and rupture along the primary fracture, thus forming new fractures: because the accumulator is only a heat supply and not an explosive product, it is safer and more controllable. The application of this new CO\textsubscript{2} pneumatic fracturing technology in shale gas exploitation has good prospects. At present, there is a lack of in-depth research into fracturing and the effects of CO\textsubscript{2} pneumatic fracturing techniques. In the present work, a series of laboratory tests were conducted through the pioneering true triaxial SC-CO\textsubscript{2} pneumatic fracturing experimental system to study the influence of initial air pressure and energy accumulation agent on the pressure curve and the initiation and propagation of fracturing fractures. Fractal analysis is performed on the surface cracks of the sample, and a linear fit is performed between the fractal dimension $F_d$ and the damage variable $w$ as defined by the cracked area. It is found that the fractal dimension (as a damage variable) can better describe the degree of damage. The research provides a reference for the engineering problems faced when using the new waterless fracturing SC-CO\textsubscript{2} pneumatic fracturing technique in shale gas production.

2 Experimental work

2.1 Instruments

As shown in Fig. 1, SC-CO\textsubscript{2} pneumatic fracturing experiments were conducted in a true triaxial fracturing system. The true triaxial fracturing system includes a two-cylinder pump system, a true triaxial hydraulic loading device, a detonator and a pressure monitoring system. The gaseous CO\textsubscript{2} from the CO\textsubscript{2} cylinder enters the double-cylinder pump through a gas pipe with a pressure reducing valve and
a filter. The water bath system of the double-cylinder pump reduces the gas temperature to 0 °C, and the pressure is increased by the double-cylinder pump before gas is injected into the pump. The initial pressure and temperature can be displayed on the software interface, and the gas pressure in the fracturing tube can be recorded in real time through a pressure sensor. Confining pressure can be applied independently in the X, Y, and Z-directions by three hydraulic pumps, and applied to the specimen in each direction through the loading plate and steel plate. The maximum size of the specimen in this system is 200 mm × 200 mm × 200 mm, and the maximum confining pressure applied in each direction can reach 20 MPa.

2.2 Sample preparation

All samples were made of high-strength cement in the form of 200mm×200mm×200mm man-made cube samples, which are regarded as homogeneous. The water-cement ratio of high-strength cement is 0.11, and the sample is cured for 4 weeks. The mechanical properties of the sample were obtained through compression and tensile experiments. The uniaxial compressive strength is 100.95 MPa, the permeability is 46.40 md, the Poisson’s ratio is 0.13, and the elastic modulus is 21.74 MPa (Table 1).

Initially, a 150 mm long and 50 mm diameter PVC tube was inserted into the center of the uncured sample to prefabricate the hole for the fracturing cylinder. The fracturing tube used was made of Q235 steel with a height of 100 mm and a diameter of 50 mm. It is composed of an ignition head, a heating agent, an air inlet, and a detonating agent, as shown in Fig. 2.

After filling enough CO₂, we use the detonator to detonate the detonator. The detonator burns to ignite the heat-generating agent. The CO₂ in the fracturing tube is heated rapidly and the temperature and pressure rises to the rupture pressure, and the fracturing tube ruptures. After the cracking tube
ruptures, a large amount of gas leaks out and impacts and compresses the surrounding cement, causing cement damage in the vicinity.

2.3 Experimental procedure

The aim is to study the influences of initial air pressure and the amount of accumulating agent on the pressure curve and the initiation and propagation of fracturing fractures. In the experiment, three initial air pressures (15 MPa, 18 MPa, and 21 MPa) and three amounts of accumulating agent (15 g, 18 g, and 21 g) were used. Sample assembly and loading: we put the fracturing cylinder into the prefabricated hole and then plug the orifice with quick-drying cement. After waiting two hours for the quick-drying cement to solidify, we placed the assembled sample on the true triaxial loading frame, the wellbore horizontal orientation lay in the y-direction. The stress on the specimen is independently applied in the X, Y, and Z-directions. All experiments were conducted under the same stress state, \( \sigma_V = 8 \text{ MPa}, \sigma_h = 6 \text{ MPa}, \) and \( \sigma_H = 5 \text{ MPa}. \)

The carbon dioxide supplied by the gas cylinder is cooled to 0 °C using a water bath, pressurised by a booster pump, and then injected into the fracturing cylinder. The critical pressure and temperature of carbon dioxide are 7.38 MPa and 31.1 °C, and the CO\(_2\) in the fracturing cylinder is liquid. Pneumatic fracturing: during the pressurization process, the pressure sensor begins to record the pressure change in the fracturing cylinder. Due to the compressibility of carbon dioxide, it is difficult to measure and control its flow rate, therefore, in the process of carbon dioxide pressurisation, the valve is closed after maintaining the pressure for a period of time when the pressure reaches the target value. After the sample is broken, unload the triaxial confining pressure, take out the sample, and spray white paint evenly on the surface of the sample. Use the camera to take pictures of the six sides of the sample, perform a jigsaw puzzle, and observe the path of cracks on the surface of the sample. After taking the picture, peel off the
sample along the broken traces and observe the internal conditions of the cracks.

3 Results

3.1 Analysis of the experimental pressure curve

The pressure curve shown in Fig. 3 was recorded by the sensor in the fracturing experiment. According to observations, the curve can be divided into the following stages:

(1) In segment OA, during the excitation phase, the pressure curve gradually increases from parallel to a concave curve, but the whole process is relatively slow, lasting a total of 0.212 s. This process is excited by the connected voltage pulse. The energy-accumulating agent in the chamber burns and breaks the excitation chamber to drive other energy-accumulating agents inside the fracturing tube to start burning. In this process, most of the CO$_2$ did not start to undergo a phase change, but is only the result of the heat transfer of the energy accumulator upon combustion. At this time, the CO$_2$ inside the tube is in a state where gas and liquid coexist.

(2) At section AB, during the violent stage of the reaction, the curve increases sharply, and the curve changes to a linear rise with a certain slope. The action time is short, about 0.127 s. During this process, the chemical reaction of the energy accumulator generates a significant amount of heat and involves the absorption of CO$_2$, the CO$_2$ gas inside the tube body enters a supercritical state after reaching a critical value, and the temperature and pressure increase, which is a state where gas, liquid, and supercritical states coexist.

(3) In section BC, in the slowly rising stage, the curve gradually changes from a straight line to a convex curve (at about 0.385 s). Since most of the CO$_2$ gas enters the supercritical state during the endothermic process, the gasification process is basically completed, and the slope of the curve decreases. At this time, most of the accumulators have done their work. Due to the large temperature difference, CO$_2$ is also continuously endothermic and pressurised, but there is still a small part of the CO$_2$ transformed from the conventional gaseous state to the supercritical state, and the fracturing tube undergoes continuous expansion.

(4) In section CD (an endothermic pressure rise), the curve starts from the original upward convex state and tends to rise steadily until it reaches the peak. The secant slope of this curve is as small as 5.27. The time elapsed in this process is 1.347 s. The CO$_2$ inside the fracturing tube has undergone the phase change and entered the supercritical state; however, due to the extreme temperature difference between
the CO₂ fluid and the accumulator, the CO₂ is still absorbing heat, making the pressure of the CO₂ (39.69 MPa) continue to rise until it reaches the peak pressure (46.53 MPa).

(5) In segment DE (the rupture stage), the curve starts to drop steeply from the peak until it reaches a low level. This stage lasts for 0.133 s. The CO₂ fluid destroys the weak layer fracturing the sample. At this time, the pressure of the CO₂ fluid inside the pipe body far exceeds the strength limit of the high-strength cement sample. The sample is instantly fractured, and the CO₂ fluid penetrates the micro-cracks and is released outwards. Due to the large amount of CO₂, with the outflow of the fluid, the pressure dropped sharply to 6.25 MPa.

(6) In section EF (the residual pressure release stage), F is not marked in the figure. Due to the large difference of this process, it lasted 23 s in total under these experimental conditions. To make the main characteristics of the curve more obvious, the figure is not shown. At point F, this curve describes that after the release of most of the CO₂ fluid, the cracks in the rock have closed to a certain extent. The CO₂ gas fills the micro-cracks again and slowly discharges, and the pressure is finally reduced from 6.25 MPa to the atmospheric pressure of 0.1035 MPa. Under different experimental conditions, there is a big difference in this section.

3.2 Analysis of aerodynamic pressure curves of different energy accumulations under the same initial pressure

The aerodynamic pressure curves under different energy-gathering dosages and initial pressures were recorded by the sensor in the fracturing experiment. The breakdown pressure of different samples is obtained from the peak value of the pressure curve. The aerodynamic pressure curves of different energy-accumulation doses under the same initial pressure were compared in Fig. 4, and the slope K₁ of section BC in the slow-rising phase of the curve and the slope of section CD during the endothermic pressure rise were obtained. K₂ can be seen in Table 2. Through comparison, it is found that the fracture pressure (peak pressure curve) of the fracturing tube is maintained at about 50 MPa under different energy accumulation doses and initial pressures. The peak pressure is related to the weak link strength of the fracturing tube. When comparing the slopes, it is found that under the same initial pressure, the
more the added dose, the faster the reaction; because the accumulator participates in the reaction during
the exothermic reaction, the greater the dose, the more sufficient the contact between the reactants. By
comparing Table 2, it is found that this change has a greater effect on the P-T curve. The following
conclusions can be drawn: 1) Appropriately increasing the energy-accumulating agent dosage to a
sufficient amount can effectively increase the secant slopes K1 and K2 of section AB, and at the same
time improve the efficiency of the combustion process; 2) The entire CO₂ pneumatic fracturing process
is a dynamic fracturing process. Due to the influence of triaxial stress, the peak pressure of supercritical
CO₂ will exceed the yield strength of the fracturing tube.

After fracturing, we sprayed paint on the surface of the sample to allow observation of the crack
morphology. Fig. 5 shows the fracture surface during fracturing with different energy-accumulation
doses under the same initial pressure. There are both similarities and differences between the test pieces
with different doses under the same initial pressure.

In previous studies, supercritical carbon dioxide fracturing fractures are found to be more
complicated compared with hydraulic fracturing fractures. Hydraulic fracturing fractures have only one
double-wing fracture, while supercritical carbon dioxide fracturing fractures have more branches
(Bennour et al. 2015; Binui et al. 2014).

Although the mechanism of CO₂ deflagration fracturing can be applied to the theory of blasting of
rock, it is difficult to form the power needed for blasting of rock (up to tens of thousands of megapascals)
under this ratio in the test. Therefore, it may not necessarily be formed as it would when blasting. The
crushing area of the rock does not produce a fractured surface. Combined with this experiment, S4, S5,
and S8 formed obvious fractured areas. Due to the excessive amount of the agent and the insufficient
CO₂, many energy accumulating agents failed to react, which eventually resulted in no cracks in the
sample 9.

In the nine sets of tests, with the increase of the peak pressure of fracturing, the development of the
fracture network of the samples became more complicated, and the opening and fracture degree of the
fractures also showed an increasing trend (except for the formation of a fracture zone in samples S4 and
S9 where no fracture surface is formed), which is conducive to application in engineering practice.
Nine CO\textsubscript{2} pneumatic fracturing tests were undertaken in this work. The main fracture propagation direction of two tests is not that of the maximum principal stress (tests S8 and S9, respectively). The fracture propagation direction in test S8 is the outlet of the fracturing tube pressure relief piece (as with the other tests). Test S9 does not form a fracture surface and thus its interior cannot be observed. It is consistent that the propagation direction of the main crack should extend in the weaker azimuth itself, which has a large dispersion, and the main stress is 5, 6, and 8 MPa. However, the stress difference of 1 MPa cannot distinguish the principal stress directions well, so more experiments need to be designed and carried out. The sample may be subject to damage smaller cracks, but these cracks are not long enough to penetrate the sample. At the moment when the high-energy CO\textsubscript{2} fluid cracks, these gases are more likely to crack toward these tiny cracks, but as the peak stress applied increases, the azimuth of the pressure relief port is more important, because the sidewall of the pressure relief port is the first area to bear the impact pressure.

To quantify the complexity of induced cracks, Hao et al (2019) used an electronic image-analysis method to calculate the trace length of the cracks on the surface of the specimen. The fracture mark length (L\textsubscript{f}) is defined as the total length of the fracture marks on the surface of the sample (citing this document), which can be calculated by using the following formula:

\[ L_f = \sum_{i=1}^{n} l_i \]  

(1)

Among them, L\textsubscript{f} is the length of the traces broken on all surfaces of the sample; l\textsubscript{i} denotes the length of the broken traces on the surface, as shown in Fig 8; n is the number of traces (n = 7 when three wings are broken, n when four wings are broken is 9).

The better to describe the cracks in a quantitative manner, digital image processing methods are used to threshold the image through MATLAB™ software, the image is binarised, and the area of the crack is calculated by measuring pixels and then converting into proportions thus:

\[ A_f = \sum_{i=1}^{6} A_i \]  

(2)

where, A\textsubscript{f} is the area of fractured cracks on all surfaces of the sample; A\textsubscript{i} is the area of fractured cracks on the ith surface, as shown in Fig. 9.

The area of cracks on the surface of each sample obtained by calculation is listed in Table 3.
3.4 Fractal analysis of fractures after fracturing

Fractal theory was developed by Mandelbrot (1983) in the 1970s, and its research object is the disordered, self-similarity or statistically self-similar system that exists widely in nature. So far, there have been many definitions and methods of calculation of fractal dimension, including the Hausdorff dimension $D_H$, information dimension $D_i$, similar dimension $D_s$, box-counting dimension $D_B$, correlation dimension $D_c$, capacity dimension $D_c$, spectral dimension $D_p$, and Lyapunov dimension $D_l$. The box-counting dimension (CBD) is relatively simple to calculate and its physical meaning is relatively intuitive, so it is widely used.

Consider a binary image of $M \times N$ pixels. Black pixels indicate that the pores divide the image into grids with side length $\delta_k$. The number of grids with black pixels is $N \delta_k^2$. When $\delta \to 0$, $-\lg N \delta_k^2 / \lg (1 / \delta) \to D_B$. Therefore, for a decreasing sequence ($\delta_k$), the least squares method can be used to fit the data points ($-\lg \delta_k, \lg N \delta_k^2$) in the double logarithmic coordinate system. When the correlation coefficient is large, the slope approximates to the fractal dimension. Usually the decreasing sequence $\{ \delta_k \}$ is obtained by the bisection method, $\{M, M/2, M/4, M/8, M/16, \ldots \}$.

As shown in Fig. 7, the fracture image obtained by the experiment is binarised, a reasonable segmentation threshold is determined, and the binarised image is obtained. The fractal dimension of the image is then calculated. By changing the size of the box, a different number of covered boxes is generated, and the fractal dimension of the image calculated.

The fractal dimensions obtained by calculation are listed in Table 3.

In the fractal fitting, the value of $R^2$ is always greater than 0.99, indicating that the fractal characteristics of the fracture are obvious, and the calculated fractal dimension can describe the complexity of the fracture.

4 Discussion

4.1 Fractal dimension describes the damage to the rock

Rock damage refers to the phenomenon whereby microcracks and micropores in the rock gradually initiate and expand under the action of external load or environment, which causes the degradation of the overall macro-mechanical properties of coal and rock. The definition of damage variables is the core
of the study of coal and rock damage is to establish the damage evolution equation, construct the initial
and boundary value problems of the damage, and then solve the stress field, deformation field and
damage field of the coal and rock mass. The basis for solving these problems is the determination of
coal and rock damage variables. Using the total area of the cracks obtained as indicative of the severity
of damage, we define the damage variable as:

$$w = \frac{A_f}{A_s}$$  \hspace{1cm} (3)

Where, $A_f$ is the area of cracks on all surfaces of the sample; $A_s$ is the surface area of the sample,
that is, the total area of all six surfaces.

The damage variables of each sample can be obtained by calculation as shown in Table 3:

The acquisition of the fractal dimension is more advantageous in describing the complexity of each
fracture. Fig. 8 shows that the change in fractal dimension is contrary to that in the total area of the
fracture. As shown in Fig. 9, the fractal dimension can be obtained by linear regression. The linear
relationship between the number and the damage variable defined on the basis of the damaged zone is:

$$w = -0.632F_d + 1.1946$$

It is useful to use fractal dimension as damage variable to describe damage: compared with the
damage variable $w$ defined by damaged area, using the fractal dimension as a damage variable can better
capture the details of the cracking pattern.

4.2 The formation of annular micro-cracks

As shown in the Fig.10, in the experiment, after the sample is broken, circumferential microcracks
are generated on the four principal stress planes parallel to the fracturing tube. Unlike hydraulic
fracturing and SC-CO$_2$ fracturing, CO$_2$ pneumatic fracturing the process is more similar to the theory of
blasting rocks with traditional explosives.

Rock blasting theories can be divided into three types according to different perceptions of the main
causes of rock blasting cracking. The first is the tensile failure theory of the explosive stress
wave(Kumao et al. 1954). It is believed that the explosive stress wave is the main cause of rock fracture.
The initial failure and rock displacement are caused by the encounter of the stress wave and the free
surface, and the influence of the blasting gas is negligible. The shock wave generated by the explosion
will propagate from the hole wall until it reaches the free surface and is reflected as a tensile stress wave.
When the peak value of the tensile stress is greater than the tensile strength of the rock, the rock will spall. The second type of rock blasting theory is the theory of blasting gas expansion (Langefors et al. 1963), which is based on blasting stress waves only affecting crack propagation, while rock rupture is mainly caused by the expansion pressure of the blasting gas. Blasting gas has the characteristics of high temperature and high pressure, which will cause initial cracks in the well wall, and the quasi-static stress field and gas compression will further expand the cracks. The third type of rock blasting theory is that involving the combined action theory of blasting stress wave and blasting gas (Persson et al. 1970). It is believed that rock failure is the result of the combined action of blasting stress wave and blasting gas.

At present, the combined action theory of blasting stress wave and blasting gas has been accepted by most researchers because it comprehensively considers the effects of blasting stress wave and blasting gas in the process of rock destruction. The stress wave and blasting gas are viewed from the characteristics of explosion-induced action (Zhu et al. 2008). The combined action theory believes that the stress wave caused by blasting is a dynamic action and is considered the main initiator of rock fracture. The effect of blasting gas is deemed to be quasi-static, which further enlarges some cracks formed by the stress wave caused by blasting. Using this theoretical basis, researchers hope to quantify the destructive effects of stress waves and blasting gas caused by blasting, and further enrich the theory of rock blasting (Li et al. 2006).

According to the theory of combined action of blasting stress wave and blasting gas, rock blasting fracture is divided into three stages: the first stage corresponds to the process of impact pressure and its action on the centre of rock blasting to produce initial cracks, before decaying with outward propagation as stress waves. This encapsulates the process of dynamic rock breaking; the second stage corresponds to the process in which the stress wave meets the free gate to reflect, and it also encapsulates the process of dynamic rock breaking; the third stage corresponds to the stretching caused by high-energy CO$_2$ fluid fractured rock and impact pressure. The process of stress coupling propagation of radial cracks is a quasi-static rock breaking process at this stage. However, SC-CO$_2$ pneumatic fracturing cannot reach the gas pressure of explosive blasting, which is different from traditional drilling and blasting blasting.

The stage of ring-crack generation aligns mainly with the second stage of blasting of the rock. The stress wave propagates from the hole wall to the sample surface. During this process, the stress wave is continuously compressing the test surface. Due to the different wave impedances when encountering the free gate, the stress wave is reflected and forms a reverse tensile stress wave, generating tensile stress
on the surface of the rock. The tensile strength of the rock is much lower than its compressive strength, so it is easy to form a broken ring on the surface, but because the energy is constantly attenuated, this form of damage only occurs in the area close to the surface of the rock, forming flakes from the centre to the periphery.

4.3 Discussion of fracturing energy

The energy calculation of CO₂ phase change fracturing in coalbed methane mining (Yang et al. 2019; Bai et al. 2020), gas drainage (Hua et al. 2018), and seismic source exploration (Wang et al. 2020), all use the following formula:

\[ E_g = \frac{PV}{K-1} \left[ 1 - \left( \frac{P_1}{P} \right)^{\frac{K-1}{K}} \right] \]  \hspace{1cm} (4)

where, \( P \) is the rupture pressure of the fracturing tube, which is the peak pressure as measured; \( P_1 \) is the standard atmospheric pressure (101,325 Pa); \( V \) is the volume of CO₂ in the fracturing tube, m³; and \( K \) is the adiabatic index of CO₂, which is 1.295.

The explosion energy will increase with the increase of the pressure peak. However, in the experimental results, the experimental group with the initial pressure of 18 MPa and the initial pressure of 21 MPa both showed anomalies. Although the rupture pressure increased, the damage area of the rock is even greater: to explain this phenomenon, we undertook the following analysis:

1. Although we assume that the volume of CO₂ is constant, in the experiment, due to the different amounts of accumulator, the volume of CO₂ decreases as the amount of accumulator increases. From Eq. 4, the relationship between \( V \) and \( E_g \) is proportional, which can explain why the peak pressure in test S9 is high but the cracking effect is not good. The volume occupied by the energy-accumulating agent (using a mass of 18 g thereof) is relatively large. After the test, the remaining energy-accumulating agent in the fracturing tube is weighed and it is found that there is a problem in the reaction. There is no response at 9 g, and the actual additive dose is only 9 g.

2. Zhou Keping et al. (2017) believes that the traditional calculation formula for fracturing energy is derived from the ideal gas equation. The thermodynamic properties of liquid CO₂ are very special; generally speaking, the ideal gas state equation is often wrong near the critical point or when the pressure is high. Here the pressure is larger, so the real gas equation of state must be used. Combining the Span and Wagner equation of state, from the perspective of thermodynamics, the accuracy of calculating the explosion energy of the liquid CO₂ blasting system can be improved.
In 1996, Span and Wagner published the Span-Wagner equation of state, which is specially used for the calculation of the physical properties and phase equilibrium of pure carbon dioxide (Mondéjar et al. 2011). For the calculation of the physical properties of pure carbon dioxide, the Span-Wagner equation of state is more accurate, and the error is within engineering tolerance. We used the Span-Wagner equation to study the physical properties of carbon dioxide where \( \phi(\delta, \tau) \) is the Helmholtz free energy, which is affected by two independent variables of temperature and density, including that in an ideal fluid \( \phi^o \) and residual fluid \( \phi^r \).

\[
A(\rho, T) / RT = \phi(\delta, \tau) = \phi^o(\sigma, \tau) + \phi^r(\sigma, \tau)
\]  

(5)

The ideal gas is calculated as:

\[
\phi^o(\delta, \tau) = \ln(\delta) + a_1^o + a_2^o \tau + a_3^o \ln(\tau) + \sum_{i=4}^{8} a_i^o \ln\left[1 - \exp(-\tau \theta_i^o)\right]
\]  

(6)

The real gas part is calculated as:

\[
\Delta = \{(1 - \tau) + A_i \left[(\delta - 1)^2 - \left(\frac{1}{2}\right)^2\right]\} + B_i [(\delta - 1)^2]^k
\]

\[
\phi^r = \sum_{i=1}^{7} n_i \delta_i^d \tau_i^e e^{-\delta_i^o} + \sum_{i=5}^{39} n_i \delta_i^d \tau_i^e e^{-\delta_i^o} \tau_i \left(\delta_i - \gamma_i\right)^{2} - \beta_i (\tau - \gamma_i)^{2} + \sum_{i=40}^{42} n_i \Delta_i \delta_i \tau_i \left(\delta_i - 1\right)^{2} - D_i (\tau - 1)^{2}
\]  

(7)

In actual engineering calculations, the input parameters are pressure and temperature, and the output parameters are density, enthalpy, specific heat, etc. In the experiment, the gas temperature at the moment of fracture tube rupture must be collected.

5 Conclusion

A series of tests were carried out on cement specimens through the pioneering true triaxial SC-CO\(_2\) pneumatic fracturing system to understand the influences of SC-CO\(_2\) pneumatic fracturing on the generation and propagation of induced fractures under different initial air pressures and accumulator additive doses. The key conclusions are as follows:

1. SC-CO\(_2\) pneumatic fracturing pressure curve can be divided into an excitation phase, violent reaction phase, slow rise phase, endothermic pressure-rise phase, rupture phase, and a residual pressure phase. The peak pressure is related to the strength of the weak link of the fracturing tube. The pressure peak can be controlled by controlling the processing accuracy.
(2) Both the initial air pressure and the amount of accumulating agent affect the pressurisation efficiency of pneumatic fracturing. Appropriately increasing the amount of accumulating agent and increasing the initial air pressure can improve the efficiency of reaction pressurisation.

(3) The fissures produced by SC-CO\textsubscript{2} pneumatic fracturing are different from the fractures produced by hydraulic fracturing and SC-CO\textsubscript{2} fracturing, including: radial fissures, annular fissures, fissure bifurcation, and surface shedding. In SC-CO\textsubscript{2} pneumatic fracturing, the cracking process is more like that seen when blasting rock. Stress waves are generated during the pneumatic fracturing reaction, and the stress waves are reflected to form a reverse tensile stress wave, which generates tensile stress on the surface of the rock, so that the samples move from the centre to the fractures formed on the periphery are broken and ring-shaped cracks are generated.

(4) The cracks on the surface of the sample after cracking have fractal characteristics, and through comparison, it is found that the larger the damage variable defined by the crack area, the smaller the fractal dimension; linear fitting is used to obtain the fractal dimension and the damage variable. The functional relationship between them is: \( w = -0.632F_d + 1.1946 \); since the fractal dimension can better describe the complexity of the fracture, using the fractal dimension as the damage variable can better describe the degree of damage.

(5) The error in the formula derived from the ideal gas equation in the SC-CO\textsubscript{2} pneumatic fracturing energy calculation is greater than that when using the Span-Wagner equation of state. Considering the influence of temperature on the fracturing energy, a temperature acquisition system should be established in any future experiments. The gas temperature upon fracturing is also to be recorded.
CRediT authorship contribution statement

Xiaofei Wang: Data curation, Writing-review & editing. Enyuan Wang: Conceptualization, Investigation. Shaobin Hu: Conceptualization, Methodology.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Table 1

<table>
<thead>
<tr>
<th>Physical and mechanical properties of the specimens.</th>
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<tbody>
<tr>
<td>Density (g/cm³)</td>
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<tr>
<td>----------------</td>
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Table 2
### Table 3: Value of specimen fissure area fractal dimension, damage variable

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Initial pressure/MPa</th>
<th>Heating agent(g)</th>
<th>Fissure area (mm²)</th>
<th>Fractal dimension</th>
<th>Damage variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>15</td>
<td>12</td>
<td>5220.95</td>
<td>1.855</td>
<td>0.0218</td>
</tr>
<tr>
<td>S2</td>
<td>15</td>
<td>15</td>
<td>6243.62</td>
<td>1.844</td>
<td>0.0260</td>
</tr>
<tr>
<td>S3</td>
<td>15</td>
<td>18</td>
<td>8963.36</td>
<td>1.828</td>
<td>0.0373</td>
</tr>
<tr>
<td>S4</td>
<td>18</td>
<td>12</td>
<td>10302.50</td>
<td>1.802</td>
<td>0.0429</td>
</tr>
<tr>
<td>S5</td>
<td>18</td>
<td>15</td>
<td>9994.59</td>
<td>1.828</td>
<td>0.0416</td>
</tr>
<tr>
<td>S6</td>
<td>18</td>
<td>18</td>
<td>8440.99</td>
<td>1.863</td>
<td>0.0352</td>
</tr>
<tr>
<td>S7</td>
<td>21</td>
<td>12</td>
<td>4962.55</td>
<td>1.852</td>
<td>0.0207</td>
</tr>
<tr>
<td>S8</td>
<td>21</td>
<td>15</td>
<td>12468.13</td>
<td>1.825</td>
<td>0.0520</td>
</tr>
</tbody>
</table>
Fig. 1 True triaxial supercritical carbon dioxide combustion explosion fracturing experimental system

Fig. 2. Schematic diagram of sample and fracturing tube.
Fig. 3. P-T curve of blast fracture

Fig. 4. 3 experimental groups under the same initial pressure
Fig. 5. Schematic diagram of sample crack

Fig. 6. Schematic diagram for calculating the fracture area
Fig. 7. Schematic diagram of calculation principle of fractal dimension of box counting method

Fig. 8. Fractal dimension and damage variable change trend graph

Fig. 9. Fractal dimension and linear fitting of damage variable
Fig. 10. Schematic diagram of annular fissure