Liquid CO$_2$ phase transition fracturing technology and its application in enhancing gas drainage of coal mines

Yingchun Fan, Botao Qin, Qun Zhou, Quanlin Shi and Dong Ma
Key Laboratory of Gas and Fire Control for Coal Mines, China University of Mining and Technology, Ministry of Education, Xuzhou, China
School of Safety Engineering, China University of Mining and Technology, Xuzhou, Jiangsu, China
Jiahao Wu
School of Resources and Earth Science, China University of Mining and Technology, Xuzhou, Jiangsu, China

Abstract
Liquid CO$_2$ phase transition fracturing (LCO$_2$-PTF) is an effective and economical technology used to improve the permeability of rock and coal. In this study, the working mechanisms of LCO$_2$-PTF were analysed and relevant equipment was designed to develop and promote the application of this technology. It utilized phase transition equipment (PTE) consisting of a liquid gas container, control unit for the current and gas volume, heating tube, and other components. LCO$_2$ blasting experiments were conducted in an airtight container to investigate the released energy, pressure, and other technical parameters. The application of LCO$_2$-PTF for enhancing gas drainage in coal mines was then evaluated. The results of a blasting experiment showed a maximum energy of 947.12 kJ and revealed that the releasing pressure could be easily changed by varying the plate and heat tube. The releasing pressure remained unchanged within an initial distance and then decreased exponentially. The blasting products were gaseous CO$_2$ and water vapor, with no sparks or flames. The surface temperature of the PTE ranged from 269.32 to 277.96 K. Application of LCO$_2$-PTF in coal mines with low permeability showed gas drainage 3.38

Corresponding author:
Botao Qin, School of Safety Engineering, China University of Mining and Technology, No. 1, Daxue Road, Xuzhou, Jiangsu 221116, China.
Email: btqincumt@163.com

Creative Commons CC BY: This article is distributed under the terms of the Creative Commons Attribution 4.0 License (https://creativecommons.org/licenses/by/4.0/) which permits any use, reproduction and distribution of the work without further permission provided the original work is attributed as specified on the SAGE and Open Access pages (https://us.sagepub.com/en-us/nam/open-access-at-sage).
times higher than that achieved with conventional technologies, with methane concentration increasing from 55 to 89%. The attenuation coefficient of gas emissions dropped by 94% and the gas permeability coefficient of the coal body increased more than 23 times after fracturing. The shockwave of the high-pressure gas promoted the development and extension of cracks. The influence radius of the pre-cracking coal seam was 8.1 m, which is 6.75 times that of the original coal seam. The experimental results and the engineering applications indicate that LCO₂-PTF is a safe and effective technology to enhance gas drainage in coal mines.

Keywords
Carbon dioxide, phase transition, low permeability, gas drainage, coal mine

Submission date: 24 August 2019; Acceptance date: 14 July 2020

Introduction
Coal mine gas is a by-product of coal production in mines, and is a clean energy source (Hamawand et al., 2013; Karacan et al., 2011; Moore, 2012). However, gas also represents a threat to the safe mining of coal. As coal mines extend deeper underground, the pressure of gas in coal seams increases, and the risk of coal and gas outburst disasters also increases (Aguado and Nicieza, 2007; Noack, 1998; Wang et al., 2013). To mitigate gas disasters and improve the energy supply, pre-drainage and utilisation of gas is strictly implemented in coal mines (Liu et al., 2011; Lu et al., 2014; Wang et al., 2012; Zhou et al., 2015). However, the low permeability of coal seams limit the gas drainage at large depth. From a technical perspective, mining of protective seams has been considered the most effective measure in mines with coal seam groups (Jiang et al., 2015; Jin et al., 2016). On the other hand, in mines with a single mineable seam, other stimulative measures are also required. Currently, hydraulic slotting, hydraulic fracturing, and dynamite blasting are widely implemented to enhance permeability (Bell and Brannon, 2011; Bunger et al., 2005; Colmenares and Zoback, 2007; Sharma et al., 2011). Though hydraulic technologies have the significant effect, they have also generated public concerns because they consume larger amounts of water and pose potential threats to the environment. In addition, conventional blasting operations are dangerous in coal mines and the blasting materials are heavily regulated. Therefore, these stimulative measures are often limited by their practical applications.

In recent years, gas fracturing technology has garnered public attention because of its potential efficiency in enhancing coal seam permeability. N₂, CO₂ and air fracturing techniques have been tested in the field and show considerable capabilities for enhancing gas recovery (Zhou et al., 2018; Zhu et al., 2016). As a typical strategy for carbon capture and storage, CO₂ fracturing not only can reduce greenhouse gases but can also produce clean energy (Li et al., 2013a; Mikkelsen et al., 2010; Wang et al., 2011). CO₂ can be first liquefied under high pressure, and then rapidly gasified to generate a high-pressure shockwave. The blasting energy associated with of this phase transition can be used to fracture rock or coal bodies. In low permeability coal seams, blasting by high-pressure gas is advantageous for creating fractures and improving gas drainage efficiency (Cao et al., 2017; Chen et al., 2017; Lu et al., 2015). In this study, the liquid CO₂ phase transition fracturing (LCO₂-PTF) technology is proposed. LCO₂-PTF is widely used in boiler clearing, building demolition,
and blasting operations in special areas. This technology has obtained safety certifications in many countries and presents numerous advantages such as in terms of safety, efficiency, environmental friendliness, and controllability. However, the mechanisms of LCO\textsubscript{2}-PTF have rarely been studied, and reasonable technical parameter designs have not been investigated systematically.

To improve the applicability of LCO\textsubscript{2}-PTF, the underlying theory and equipment structure are discussed in detail in the study. The key parameters are determined through preparative tests. Then, fracturing tests is conducted in a coal mine and the fracturing effect on the permeability and gas drainage of the coal seam is evaluated. This study lays the foundation for an improved understanding of LCO\textsubscript{2}-PTF and, in particular, provides new insights into the influence mechanisms of this technique on gas drainage in coal mines.

**Lco\textsubscript{2}-PTF system and technology**

**Phase transition equipment**

The design of the phase transition equipment (PTE) used in this study is shown in Figure 1. The liquid CO\textsubscript{2} is injected into the container space inside the PTE at a certain pressure \(P_1\), which is much higher than the critical pressure \(P_c\) of CO\textsubscript{2}. The switch of the initiator device is rotated and connected to the PTE by a wire. Then, the high-voltage current triggers the heat tube and generates high levels of heat \(\Delta h\) (equation (1)) (Tong and Liang, 1999). Under the stimulation of heat, the liquid CO\textsubscript{2} is transformed to high-pressure gas \(P\) (equation (2)) (Li et al., 2010) in a short time. The plate is broken when the gas pressure reaches the threshold pressure \(P_0\), and then the high-pressure gas is injected into the rock through the reserved hole.

\[
\Delta h = \frac{RT_c[5.37(1 + \omega)] \left(1 - \frac{P}{P_c^{(T_c/19.9605)}}\right)^{1/2}}{1 - 1.67(T_r - 0.76)^2}\tag{1}
\]

\[
P = \frac{RT}{v - b} \cdot \frac{a(T_r) \alpha(T_r, \omega)}{v(v + b) + b(v - b)}\tag{2}
\]

\[
T_r = \frac{T}{T_c}, \quad P_r = \frac{P}{P_c}\tag{3}
\]

\[
a(T_c) = 0.457 \frac{R^2 T_c^2}{P_c}\tag{4}
\]

**Figure 1.** Schematics of the PTE.
\[ a(T_r, \omega) = \left[ 1 + (0.37 + 1.54\omega - 0.27\omega^2)(1 - T_r^{1/2}) \right]^{1/2} \]  

(5)

where \( P \) is the pressure of the space, Pa; \( P_c \) is the critical pressure of the space, Pa; \( T \) is the temperature of the space, K; \( T_c \) is the critical temperature of the space, K; \( R \) is the gas constant, \( 8.314 \text{J} \cdot \text{(K} \cdot \text{mol})^{-1} \); \( \nu \) is the specific volume, \( \text{m}^3 \cdot \text{(K} \cdot \text{mol})^{-1} \); \( a, b \) is the constant; \( \omega \) is the acentric factor; \( \alpha \) is the temperature function; and \( \Delta h \) is the vaporization heat, \( \text{kJ} \cdot \text{mol}^{-1} \).

**Ground blasting test**

**Test method.** Experiments were conducted in an airtight container (Figure 2) composed of a steel tube that ensures sufficient strength and airtightness; the PTE was positioned inside. The container was 300 mm in diameter and 1200 mm in length. Sensors were installed to monitor the pressure, CO2, and temperature. In addition, a gas distribution system was used to mix methane and air to a certain concentration.

Two releasing holes existed in the PTE, and two pressure sensors were installed directly above the releasing hole in a straight line, perpendicular to the PTE (Figure 3(a)).

The pressure sensors are piezoelectric (Figure 3(b)), and the voltage signal (\( U \)) is received by the oscilloscope (Figure 3(c)). The pressure sensor can convert the pressure variable into the standardized output signal. Moreover, there is the linear function relationship between the output signal and the pressure variable (Liu, 2015). The function parameters are recommended by the manufacturer based on a large number of tests and calibrations, and the releasing pressure \( P(x) \) is calculated by equation (7),

\[ P = 75U - 37.5 \]  

(7)

In addition, the distance \( x \) between the releasing hole and sensor was changed to determine the relationship between the releasing pressure and distance (Figure 3(a)).

Temperature sensors were used to measure the surface temperature of the PTE before and after phase transition and to help determine the law of temperature distribution. CH4 and CO2 sensors were used to measure the dynamic changes of CH4 and CO2 during the experiments.
The CH₄ and air were mixed with a gas distribution system at a concentration of CH₄ of 9%; this concentration produces the most drastic explosive potential. To ensure the PTE detonated the mixed gas, the gas was injected into the airtight container at a pressure of 0.1 MPa.

To realize wider applicability of LCO₂-PTF technology, the fracture pressure of steel plate in PTE is generally designed as 270–300 MPa based on the material tests (Dong et al., 2014; Lu et al., 2015). The kind of outer casing is the steel of P/T91, and its yield strength is 415 MPa. If the blasting pressure is too high, the casing will be cracked or over-aged, and it is not conducive to safety and cyclic utilization. In this study, we set the pressure from 50 to 300 MPa using the same PTE size to investigate the releasing pressure, energy, and safety.

The preparation of the PTE is performed as follows:

1. The PTE was first assembled. Then, 1.14 kg of liquid CO₂ was injected into the PTE under 9.8 MPa to ensure the CO₂ was maintained in its liquid phase for as long as possible.
2. The PTE was fixed inside the airtight container and then connected to the high-voltage-generating initiator device. The container doors were closed to provide an airtight environment.
3. Next, the mixed gas with 9% CH₄ was injected into the airtight container under a pressure of 0.1 MPa. All sensors and monitors were initiated after they are debugged to a steady state.
4. The initiator device was activated to generate a high-voltage current and to trigger the blasting of the PTE. All dates and observed phenomena during the experiment were recorded.
5. These experimental procedures were then repeated 91 times using the remaining PTE.

Energy characteristics. Seven thickness values for the plate were set in this experiment, and the releasing pressure was obtained as follows

\[ P_0 = 3.5 \cdot \frac{S_e \cdot m}{c} \]  

(8)
where $S_c$ is the ultimate tensile strength of the plate, MPa; $m$ is the thickness of the plate, mm; and $c$ is the diameter of broken part of the plate, mm.

Pressure sensors generated voltage signals when they monitored the CO$_2$ releasing from the PTE, and the waveforms captured by the oscilloscope are shown in Figure 4.

Figure 4 shows the seven types of waveforms, where the peak represents the highest releasing pressure. According to equation (7), the experimental value $P_e$ is obtained as shown in Figure 7.

Figure 5 shows that $P_e$ was less than $P_0$, which was due to the non-homogeneity of the plate and measurement deviation. In addition, the range of deviation rate (from 1.63 to

![Figure 4. Waveforms of different releasing pressure shown in oscilloscope. (1) $m=1.5$ mm (2) $m=2.5$ mm. (3) $m=3.5$ mm (4) $m=4.0$ mm. (5) $m=5.0$ mm (6) $m=6.0$ mm. (7) $m=6.5$ mm.](image-url)
7.26% was less than the acceptable value of 10%, which is considered acceptable in engineering practice.

As the experiment revealed, the process of phase transition was so fast (less than 50 ms) that practically no heat exchange occurred between the inside and outside of the PTE. As a result, the process of phase transition can be considered an adiabatic process. The releasing energy $W$ of phase-transition in the PTE can thus be calculated as follows (Li et al., 2010)

$$W = \frac{P_e \cdot V}{K - 1} \left[1 - \left(\frac{P'}{P_e}\right)^{\frac{K-1}{K}}\right]$$

(9)

where $W$ is the actual energy, kJ; $P_e$ is the experimental releasing pressure, Pa; $P'$ is the standard atmospheric pressure, $1.01325 \times 10^5$ Pa; $V$ is the volume of the container, $1 \times 10^{-3}$ m$^3$; $K$ is the adiabatic index of CO$_2$, 1.295.

TNT equivalent, is introduced to evaluate the blasting energy compared to other blasting types, which can be calculated by equation (10)

$$W_{TNT} = \frac{W}{Q_{TNT}}$$

(10)

where $W_{TNT}$ is the TNT equivalent, kg; $Q_{TNT}$ is the explosion energy of 1 kg TNT, 4250 kJ/kg.

Figure 6 shows that the maximum energy of the PTE reached 947.12 kJ, which is equivalent to the blasting energy of 0.22 kg TNT. The energy of LCO$_2$-PTF was clearly sufficient to crack a general rock or coal body. This energy could determine the drilling parameters and the influence radius of engineering applications.

**Pressure characteristics.** Under normal conditions, liquid is so resistant to compressed that the compression factor can be avoided. However, compression is one of the most critical properties for gas. The density will change with gas flow, and this causes the pressure to change based on Avogadro’s hypothesis as follows (Sabdenov and Erzada, 2016; Singh et al., 2011)

$$PM = \rho RT$$

(11)
where \( P \) is the pressure of the gas, Pa; \( M \) is the molar mass of CO\(_2\), 44 g/mol; \( \rho \) is density, kg/m\(^3\); \( R \) is the gas constant, 8.314 J/(K·mol); and \( T \) is the temperature, K.

According to Avogadro’s hypothesis, the releasing CO\(_2\) can be simplified as a structural model with three areas as shown in Figure 7. Here \( x_1 \) is the core area, and the pressure remains unchanged; \( x_2 \) is the transition area, and the section begins to diverge; and \( x_3 \) is the area of complete divergence. Technically, all areas can be measured in the experiment, but the transition area is not easy to locate because of its proximity to the core. Therefore, in this experiment, the core and transition areas were considered one area and were defined as the initial area \( x_0 \). The pressure was considered unchanged, which was confirmed in the experiment.

Experiments showed that different initial distances \( x_0 \) existed for different PTE, and the higher the thickness of the plate in PTE, the longer was the initial distance \( x_0 \), as shown in Figure 8.

Meanwhile, when \( x \) was less than \( x_0 \), the releasing pressure \( P(x) \) remains unchanged, approximately equaling the designed pressure \( P_c \), for all the kinds of PTE as shown in Figure 9.

However, when \( x \) was less than \( x_0 \), the releasing pressure \( P(x) \) decreased with the distance, which was nearly in line with the exponential function relationship; this is shown
in Figure 10. The results show that when the energy was used for research purpose there were different reasonable diameters of boreholes relative to the different types of PTE.

**Safety properties.** High temperature and heat are common products for most blasting equipment, but this method produces only low-temperature gaseous CO₂. In addition, the surface of the PTE maintains a low temperature at all times, as shown in Figure 11.

The gas in the coal seam is mainly composed of CH₄, and the explosion concentration of mixed gas with CH₄ ranges from 5 to 16% (Li et al., 2013b). To investigate the explosion probability of CH₄, we applied the PTE with mixed gas of 9% CH₄ to conduct an explosion test. The blasting tests of the mixed gas with CO₂ and CH₄ are conducted in the laboratory to simulate an explosion underground instead in the methane-bearing coal seam and to determine whether the CO₂ explosion could cause a CH₄ explosion. More than 91 experiments showed that the temperature ranged from 269.32 to 277.96 K with an average of 269.23 K, which was far from the temperature necessary to produce a gas explosion. Moreover, the methane inside the airtight container with a concentration of 9% was never detonated or ignited.

The coal seams were mostly methane-rich, and the mixed gas had an explosive tendency. The laboratory test simulated this type of underground environment with the PTE; the latter was not used in an actual coal seam. Experimental work on the safety of the heater has
previously been conducted by the Health and Safety Executive Research and Laboratory Services Division, UK (Pickering, 1989). No detonations were detected when the heater was presented with pressurised nitrogen in a 20-bar environment under 9% methane/air mixture conditions, which is the most explosive concentration of methane (Pickering, 1989). Results indicated that the chemical heater would not become initiated in air, under any pressurised conditions, or in a rich methane underground environment such as a coal mine. Therefore, the ground test showed that the application of LCO₂-PTF technology is safe in coal mines.

The adsorption ability of coal to CO₂ is stronger than CH₄. After blasting, CO₂ diffused into the coal seam and could displace CH₄. At the same time, CO₂ might also cause outburst. In order to ensure safety, the risk of outburst induced CO₂ was evaluated before construction.

1. The amount of liquid CO₂ in a single cracker was 1kg, and the gas volume after initiation was about 0.4 m³. Field test found that 90% of CO₂ gas released by PTE moved to the tunnel through the boreholes. Even if the remaining 10% of CO₂ gas was completely absorbed by coal, the residual CO₂ pressure generated was extremely low (0.0017–0.0034 MPa), which was much lower than the critical pressure (0.74 MPa) of gas outburst.

2. LCO₂-PTF is the physical blasting technology, which is different from the explosive blasting. During the explosive blasting, the coal body is destroyed mainly by the blasting

**Figure 10.** Attenuation law of the releasing pressure based on different designed pressures.

**Figure 11.** Distribution of temperature on the surface of the PTE.
wave. Whereas LCO2-PTF fracture coal body by gas expansion energy instead of blasting wave. Compared with explosive, the pressure and detonation velocity of CO2 gas were lower than those of explosives, and the power of stress wave was also lower. Furthermore, there was no superimposed effect of a series of stress waves, which leading to the lower possibility of outburst.

3. Although CO2 gas volume and pressure increased in a certain space after entering the coal seam, the process was transient. After blasting, the high-concentration CO2 gas rapidly moved to the high-density drainage boreholes through the cracks in coal seam. Therefore, CO2 gas could not accumulate and maintain higher pressure for a long time, and the outburst risk was very low.

Field application

Test site and drilling layout

The engineering application was conducted in the M6 coal seam of the Beile coal mine, located in Guizhou, China. The dip angle of the coal seam was 25–39°, and the thickness was 1.75–2.9 m. The lithology of the roof and floor were mainly fine sandstone and siltstone, respectively. The coal seam had a failure type of III–IV, the original gas content was 9.34 m³/t, and the gas pressure was 0.85 MPa, which all met the characteristics of coal and gas outbursts. In addition, the coal seam had a simple structure, including obvious bedding, and developed fissures. Moreover, no fault appeared during excavation. The detailed physical parameters of coal were also obtained through mechanics experiments (Table 1). Because of the low permeability, the ordinary drainage technology used to prevent methane-based hazards was not effective in this experiment. CO2 phase transition technology was applied to this practical problem in an attempt to increase the permeability.

There are soft and hard layer in M6 coal seam. In order to realized the successful application of this technology in M6 coal seam, the blasting borehole were arranged in the adjacent hard coal layer or rock layer instead of the soft coal layer. The innovative construction plan was conducive to keep borehole steady and deliver PTEs, and the gas drainage effect in both hard and soft layer could simultaneously improved. On the one hand, the original cracks could be expanded and the new cracks could be generated easily by the propagation of CO2 shock wave in hard coal layer, which was conducive to gas migration and drainage in the hard coal layer. On the other hand, the stress of soft layer would decrease after the hard layer was fractured. Then, the gas began to desorb and moved to the drainage system through the cracks in the hard layer, which promoted the gas drainage effect in the soft coal layer. In this work, the innovative deliver, connection and recycle technology of PTE were also applied to realize the fracturing effect in the deep borehole of 60–100 m.

| Physical parameters | Elasticity modulus (MPa) | Poisson ratio | Internal friction angle (°) | Compressive strength (MPa) | Tensile strength (MPa) | Cohesion (MPa) |
|---------------------|--------------------------|---------------|-----------------------------|---------------------------|-----------------------|--------------|
| Value               | 2 \times 10^9            | 0.35          | 33                          | 0.7                       | 0.06                  | 3.5          |
The operational procedure of LCO$_2$-PTF in coal mines is described in detail as follows:

1. Liquid CO$_2$ was poured into the storage tube.
2. A borehole of 80 m with a diameter of 75 mm was drilled in the coal seam.
3. Interconnected tubes were inserted into the borehole and connected it to a blasting igniter.
4. The conduction status of the system was tested using an electronic method and the heater in the tube was ignited using a fire igniter to fracture the coal seam.
5. The concentrations of CH$_4$ and CO$_2$ were measured until the gas concentrations were reduced to safe levels.
6. The tubes were removed from the borehole, and the borehole was sealed using a drainage pipe connected to the drainage system.
7. The CH$_4$ drainage effect was evaluated based on the gas drainage amount, gas emission characteristics, gas permeability coefficient, and the influence radius of the borehole.

The number of PTEs used in the borehole mainly depended on the fracturing radius of the single PTF and the penetration length of borehole in coal seam. The fracturing radius of a single PTF in M6 coal seam was above 5 m. In order to improve the fracturing effect and avoid the fracturing blind zone, the interval of PTEs in the borehole is 5 m. The borehole length was 25–35 m, and the penetrating length in coal seam was 2–10 m. Therefore, only 1–2 PTEs were used in drilling borehole, and the boreholes were arranged in the hard coal layer instead of soft layer to improve the fracturing effect.

To ensure the fracturing effect, 22 boreholes in four groups were constructed in the face of the crosscut (Figures 12 and 13), and the layout of boreholes followed basic principles. The distance between the bottom of the boreholes was 5 m, according to the drainage radius measured in the coal seam using CO$_2$ phase transition technology. A set of PTE was used inside the boreholes (Figure 14) and then all the pieces of the PTE were blasted simultaneously. The blasting energy created fissures around the boreholes. Finally, all boreholes fractured by the PTE were blocked off to drain the methane. After fracturing, the improved permeability was evaluated by investigating the gas drainage, gas emission, permeability coefficient and influence radius.

**Results and discussion**

**Gas drainage amount.** After being cracked by LCO$_2$-PTF, four groups of 22 boreholes were created in the face of the crosscut. After 18 days, the residual gas content in the coal seam
was reduced from 9.34 to 5.67 m³/t and the pressure was reduced from 0.85 to 0.32 MPa. This ensured the safety of the coal seam.

As compared with the usual technology, LCO₂-PTF clearly enhanced the amount and concentration of methane drainage. The greatest capacity of pure gas drainage for a single bore was improved from 9.31 to 31.42 L/min (Fig. 15(a)), which is 3.38 times that of the standard technology. The highest concentration increased from 55 to 89% (Fig. 15(b)). In addition, although the amount and concentration of gas drainage decreased with time, the cracked boreholes decayed more slowly and had a longer effective drainage time than that of the ordinary type.

In theory, the cracks near the borehole in the coal seam were initiated and improved by the shaping charge effect, and the extension of cracks was controlled mainly by the gas pressure inside the crack generated by the thermal expansion of the liquid CO₂ (Lu et al., 2015). Large amounts of CO₂ gas began to diffuse into the artificial and natural cracks of the coal seam. They were then broken by the tension and diffused further in the coal. Thus, a complex fracture network is formed around the borehole. The two stages occur over an

**Figure 13.** Plane figure of drilling layout in crosscut under the coal mine.

**Figure 14.** Layout of PTE in borehole in crosscut.
extremely short period, and the dynamic fracture and expansion can be assumed to stimulate the coal seam simultaneously. This eventually leads to an increase in coal seam gas drainage (Wang et al., 2016).

Gas emission characteristic. Two parameters that affect the gas emission characteristics of the borehole are the initial gas emissions $q_0$ and attenuation coefficient $\alpha$. The attenuation coefficient is a major indicator used to evaluate the difficulty of the pre-drainage of coal seam gas. Gas emission behaviour can be described by the following equation (Fan and Wang, 2012):

$$q_t = q_0 e^{-\alpha t}$$  \hspace{1cm} (12)

where $q_t$ is the gas emission amount (m$^3$/min), $q_0$ is the initial gas emission amount (m$^3$/min), $\alpha$ is the attenuation coefficient (d$^{-1}$), and $t$ is the time (d).

Gas emission test results are shown in Figure 16 and Table 2. A negative exponential relationship was found to exist between gas emission and time. However, the attenuation

\[\text{Figure 15.} \quad \text{Contrasting concentrations and amounts between cracked and un-cracked boreholes. (a) The amount of drainage gas. (b) The concentration of drainage gas.}\]

\[\text{Figure 16.} \quad \text{The attenuation curve of gas emissions.}\]
The gas emission decreased rapidly before fracturing, and the attenuation coefficient was 0.5443. However, the attenuation rate became slower after fracturing, and the attenuation coefficient was only 0.0336, which is a reduction of 94%. The great change in the attenuation coefficient indicates that the gas supply was more abundant because the crack connectivity was improved after LCO2-PTF was employed. As a result, the drainage time increased.

The LCO2-PTF in a coal seam is a dry fracturing technology by which dry CO2 gas can promote CH4 desorption and diffusion from the coal matrix. In enhanced coalbed methane production schemes, CO2 is injected into the coal seams and displaces the CH4 adsorbed on the internal surface of the coal matrix. At least two molecules of CO2 can be sequestered for every CH4 molecule released (Gunter et al., 1997; Hamelinck et al., 2002). This replacement effect occurs either by a reduction in the partial pressure of CH4 or by a higher selective sorption of CO2 over CH4. As the concentration gradient of CH4 in the matrix is compared to the cleat system, CH4 can diffuse from the coal matrix into the latter (Busch and Gensterblum, 2011).

**Gas permeability coefficient.** Gas permeability characterises the resistance of coal seams to gas flow, thus reflecting the ease or complexity of gas flow in a coal seam. To evaluate the fracturing effect on gas flow, gas permeability was investigated in this study. The permeability coefficient was calculated by the radial flow method, as shown in Table 3 (Guo and Zhou, 1984; Wang and Yang, 2011).

Based on the gas radial unstable flow theory and similarity criterion method, the initial permeability coefficient was 0.58 m²/(MPa²·d) and increased to 13.35 m²/(MPa²·d) after fracturing. Because of the application of LCO2-PTF, the gas permeability coefficient of the coal body was increased by more than 23 times. Many cracks were generated by the high-pressure shock wave after fracturing. In general, when the ultimate strength of the coal body

### Table 2. Fitting equation of gas emission.

| Test condition | Fitting equation | R2   | Attenuation coefficient (d⁻¹) |
|---------------|-----------------|------|-----------------------------|
| Before fracturing | \( q_t = 14.50e^{-0.5443t} \) | 0.9948 | 0.5443 |
| After fracturing | \( q_t = 16.60e^{-0.0336t} \) | 0.9768 | 0.0336 |

### Table 3. Fitting equation of gas emission.

| Time dimensionless number \( F_0 = B\lambda \) | Permeability coefficient \( \lambda \) | Constant \( A \) | Constant \( B \) |
|---------------------------------------------|---------------------------------|----------------|----------------|
| \( 10^{-2} - 1 \) | \( \lambda = A^{1.61}B^{0.61} \) | \( A = \frac{q\cdot r_1}{P_2 - P_1} \) | \( B = \frac{4\cdot P_1^{1.5}}{\mu r_1^2} \) |
| \( 1 - 10 \) | \( \lambda = A^{1.39}B^{0.391} \) | \( \lambda = 1.1A^{1.25}B^{0.25} \) | \( \lambda = 1.83A^{1.14}B^{0.137} \) |
| \( 10^{-2} - 10^{3} \) | \( \lambda = 2.1A^{1.11}B^{0.111} \) | \( \lambda = 1.61A^{1.07}B^{0.07} \) | \( \lambda = 2.1A^{0.7}B^{0.39} \) |
| \( 10^{-3} - 10^{5} \) | \( \lambda = 3.14A^{1.07}B^{0.07} \) | \( \lambda = 2.1A^{0.7}B^{0.39} \) | \( \lambda = 3.14A^{1.07}B^{0.07} \) |

\( \lambda \) is the permeability coefficient, \( m^2/(MPa^2·d) \), \( q \) is the gas emission, \( m^3/(m^2·d) \), \( r_1 \) is the borehole radius (mm), \( P_0 \) is the atmospheric pressure underground (MPa), \( P_1 \) is the initial gas pressure (MPa), \( L \) is the borehole length (m); \( \beta \) is the gas content coefficient, \( m^3/(m^3·MPa^{0.5}) \).
body is less than the blasting stress, cracks will develop and extend under the tensile shear stress close to the fracturing borehole.

The permeability and porosity of the coalbed methane reservoir are generally derived from the cleats, and the permeability in the direction of the face cleat can be 3–10 times greater than in other directions (Laubach et al., 1998). The cleat system weakens the mechanical strength of coal and increases its brittleness, promoting the engineering application effect of LCO₂-PTF. Although the cleat system in the coal seam is developed, the permeability of the fracture will be reduced significantly because of the presence of minerals such as clay and calcite in the coal. High pressure CO₂ gas can scour the minerals, thereby greatly increasing the permeability of the cleat (Cao et al., 2017). In addition, this permeability of cleat system is related to crustal stress and decreases exponentially with an increase in net confining pressure (Durucan and Edwards, 1986). It has been shown that the stress of a coal seam can be reduced by destress blasting. The destress effect of LCO₂-PTF technology will also reduce the stress of the coal and rock seam, and reduce the strength and deformation characteristics of the coal seam around the borehole. Therefore, the stress concentration area will move to the deeper coal and rock body, and the permeability of the coal seam near the borehole will increase (Lu et al., 2015).

**Influence radius.** The influence radius of drainage bores refers to the distance from the test point where the original gas pressure begins to decrease to the centre of the drainage hole within a specified time. The effective influence radius is indispensable basic data used in gas drainage design and preparation of coal and gas hazard prevention measures in coal mines. To arrange drainage holes reasonably, the radius of influence of the blasting hole was investigated in this study. A tracer gas was used to determine the influence radius; the farthest drainage distance that the tracer gas can reach in a certain period is the effective influence radius of the drainage period. The influence radius of the original and the pre-cracking coal seam are shown in Tables 4 and 5, respectively.

The influence radius of the original coal seam and the blasting bore both increased with time. The influence radius was 4.4 times that of the original coal seam after blasting, indicating that the pre-crack effect was obvious and could effectively expand the crack range around the borehole. The maximum influence radius of the original coal seam was 1.2 m, and the influence radius of the pre-cracking coal seam was 8.1 m, which was 6.75 times that of the original coal seam. This means that the fracture field considerably expanded with drainage time. After pre-cracking, the influence radius and drainage time showed an exponential relationship, as depicted in Figure 17. The increased influence radius could

| Number | Drainage time (d) | Drainage radius (m) |
|--------|-------------------|---------------------|
| 1      | 0                 | 0.5                 |
| 2      | 3                 | 0.5                 |
| 3      | 9                 | 1.2                 |
| 4      | 12                | 1.2                 |
| 5      | 14                | 1.2                 |
| 6      | 15                | 1.2                 |

**Table 4.** The influence radius in the original coal seam.
reduce the construction workload, improve construction efficiency, and reduce costs. In addition, the drainage capacity of the single bore and drainage efficiency are enhanced using LCO₂-PTF.

The numerical simulation revealed that after the application of fracturing technology, the closer the coal body was to the blasting position, the more severely it was damaged and greater the increase in permeability was (Chen et al., 2017). Field investigation of the permeability-improvement effect of liquid CO₂ phase change fracturing also supported this conclusion.

This pressure, which is generated by thermal expansion of gases, has been widely used in rock/coal fracturing. One example is high-energy gas fracturing in which the action of gas forcing its way through the cracks surrounding an explosion cavity plays a dominant role in the rock blasting process (Saharan and Mitri, 2011). As CO₂ gas expands, the initial crack spreads from the fracture hole to a certain removed distance, the latter defines the fracturing radius (Lu et al., 2015). LCO₂-PTF can induce a much longer fracturing radius compared to the traditional explosion method. LCO₂-PTF is also more economical and efficient compared to the mining protective seam, dense borehole drainage method, and thermal stimulation for low permeability coal seams (Cao et al., 2017).

### Table 5. The influence radius of the blasting bore.

| Number | Drainage time (d) | Drainage radius (m) |
|--------|-------------------|---------------------|
| 1      | 0                 | 2.2                 |
| 2      | 6                 | 3.8                 |
| 3      | 8                 | 4.5                 |
| 4      | 10                | 6.1                 |
| 5      | 13                | 8.1                 |
| 6      | 15                | 8.1                 |
| 7      | 18                | 8.1                 |
| 8      | 22                | 8.1                 |
| 9      | 25                | 8.1                 |
| 10     | 27                | 8.1                 |
| 11     | 30                | 8.1                 |

### Figure 17. The change curve of the influence radius.
**Permeability-improvement mechanism of LCO\textsubscript{2}-PTF technology**

LCO\textsubscript{2}-PTF the permeability of the coal seam and the gas extraction effect were enhanced by LCO\textsubscript{2}-PTF based on the comprehensive influence of the mechanical effect of high-pressure gas, stress waves, gas pressure and displacement effect in the coal seam.

The fracture effect of gas on coal related to the development of original cracks and fracturing field under the stress wave. The high-pressure CO\textsubscript{2} gas fractured coal body and created a blasting cavity. Then, the high-pressure gas wedged into the open cracks in the coal and generated the new cracks in the direction of gas injection. The stress concentration was formed under gas pressure at the tip of the crack, which leading to the further development of cracks. During the crack extension, CO\textsubscript{2} gas first entered the wide and large cracks, and then entered the small cracks that communicated with large cracks until the gas pressure faded away. When the pressure decreased to the critical value, the elastic energy in the coal body would release and generated hoop cracks. As a result, the connection between the radial and hoop cracks promoted the optimization of the crack network system.

**Conclusion**

This study introduced a new technology that uses the phase change energy of liquid CO\textsubscript{2} to improve the effect of gas drainage in coal mines. We discussed in detail the mechanisms of LCO\textsubscript{2}-PTF and then developed the testing equipment. Finally, the application effect derived from enhancing gas drainage in a coal mine was investigated. Several conclusions were obtained based on test results.

1. Experimental results showed that LCO\textsubscript{2}-PTF has a technical advantage over other blasting equipment. PTE, which is a type of physical explosion equipment, has been shown to be fully safe because of its use of anti-explosive blasting products that operate without a spark, flame or other hazardous substance. The releasing pressure and energy can be controlled and modified easily according to requirements.
2. Engineering applications of LCO\textsubscript{2}-PTF in coal mine showed that the amount of gas drainage increased by 3.38 times and the concentration increased from 55 to 89% as compared when standard technology is employed. The attenuation coefficient of gas emissions showed a sharp decrease after fracturing, which is conducive to extending the drainage time.
3. The study showed that shock waves from high-pressure gas can produce plentiful fractures and pore spaces. New cracks were shown to develop and expand under blasting stress, leading to a significant increase in the gas permeability of the coal seam. The influence radius of blasting bores increased with time and the drainage effect was enhanced under the application of LCO\textsubscript{2}-PTF.

**Declaration of Conflicting Interests**

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding**

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: The authors are grateful to the National Science Fund for
Distinguished Young Scholars (51825402), and the National Natural Science Foundation of China (51476184).

ORCID iDs
Botao Qin https://orcid.org/0000-0001-8625-0833
Jiahao Wu https://orcid.org/0000-0003-2388-4120

References
Aguado MBD and Nicieza CG (2007) Control and prevention of gas outbursts in coal mines, Riosa–Ollonieigo coalfield, Spain. International Journal of Coal Geology 69(4): 253–266.
Bell CE and Brannon HD (2011) Redesigning fracturing fluids for improving reliability and well performance in horizontal tight gas shale applications. In: SPE Hydraulic Fracturing Technology Conference, 24-26 January 2011, The Woodlands, Texas, USA. Society of Petroleum Engineers.
Bunger AP, Detournay E and Garagash DI (2005) Toughness-dominated hydraulic fracture with leak-off. International Journal of Fracture 134(2): 175–190.
Busch A and Gensterblum Y (2011) CBM and CO2-ECBM related sorption processes in coal: A review. International Journal of Coal Geology 87(2): 49–71.
Cao Y, Zhang J, Zhai H, et al. (2017) CO2 gas fracturing: A novel reservoir stimulation technology in low permeability gassy coal seams. Fuel 203: 197–207.
Chen H, Wang Z, Chen X, et al. (2017) Increasing permeability of coal seams using the phase energy of liquid carbon dioxide. Journal of CO2 Utilization 19: 112–119.
Colmenares LB and Zoback MD (2007) Hydraulic fracturing and wellbore completion of coalbed methane wells in the Powder River Basin, Wyoming: Implications for water and gas production. AAPG Bulletin 91(1): 51–67.
Dong Q, Wang Z, Han Y, et al. (2014) Research on TNT equivalent of liquid CO2 phase-transition fracturing. China Safety Science Journal 24(11): 84–88.
Durucan S and Edwards J (1986) The effects of stress and fracturing on permeability of coal. Mining Science and Technology 3(3): 205–216.
Fan Y and Wang Z (2012) Effect analysis of strengthening permeability in soft and low permeability outburst coal seam by hydraulic flushing. Safety in Coal Mines 6: 137–140.
Gunter W, Gentzis T, Rottenfusser B, et al. (1997) Deep coalbed methane in Alberta, Canada: A fuel resource with the potential of zero greenhouse gas emissions. Energy Conversion and Management 38: S217–222.
Guo Y and Zhou S (1984) Complete solutions of the law of gas flow in coal seams with one dimensional gas flow fields. Journal of China University of Mining & Technology 2: 22–31.
Hamawand I, Yusaf T and Hamawand SG (2013) Coal seam gas and associated water: A review paper. Renewable and Sustainable Energy Reviews 22: 550–560.
Hamelink CN, Faaj APC, Turkenburg WC, et al. (2002) CO2 enhanced coalbed methane production in The Netherlands. Energy 27(7): 647–674.
Jiang J, Cheng Y, Zhang P, et al. (2015) CBM drainage engineering challenges and the technology of mining protective coal seam in the Dalong Mine, Tiefa Basin, China. Journal of Natural Gas Science and Engineering 24: 412–424.
Jin K, Cheng Y, Wang W, et al. (2016) Evaluation of the remote lower protective seam mining for coal mine gas control: A typical case study from the Zhuxianzhuang Coal Mine, Huaibei Coalfield, China. Journal of Natural Gas Science and Engineering 33: 44–55.
Karacan CO, Ruiz FA, Coté M, et al. (2011) Coal mine methane: A review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction. International Journal of Coal Geology 86(2-3): 121–156.
Laubach S, Marrett R, Olson J, et al. (1998) Characteristics and origins of coal cleat: A review. International Journal of Coal Geology 35(1-4): 175–207.
Li L, Zhao N, Wei W, et al. (2013a) A review of research progress on CO₂ capture, storage, and utilization in Chinese Academy of Sciences. *Fuel* 108: 112–130.

Li W, Di G and Wang R (2010) Analysis of a liquid CO₂ tank explosion on a shin. *Safety and Environmental Engineering* 17: 95–98.

Li Y, Liu Y and Yang X (2013b) Proportion pressure swing adsorption for low concentration coal mine methane enrichment. *Separation Science and Technology* 48(8): 1201–1210.

Liu J (2015) Calculation of pressure transmitter. *Electronic Test* 17: 97–98.

Liu Y, Zhou F, Liu L, et al. (2011) An experimental and numerical investigation on the deformation of overlying coal seams above double-seam extraction for controlling coal mine methane emissions. *International Journal of Coal Geology* 87: 139–149.

Lu S, Cheng Y, Ma J, et al. (2014) Application of in-seam directional drilling technology for gas drainage with benefits to gas outburst control and greenhouse gas reductions in Daning coal mine, China. *Natural Hazards* 73(3): 1419–1437.

Lu T, Wang Z, Yang H, et al. (2015) Improvement of coal seam gas drainage by under-panel cross-strata stimulation using highly pressurized gas. *International Journal of Rock Mechanics and Mining Sciences* 77: 300–312.

Mikkelsen M, Jørgensen M and Krebs FC (2010) The teraton challenge: A review of fixation and transformation of carbon dioxide. *Energy & Environmental Science* 3(1): 43–81.

Moore TA (2012) Coalbed methane: A review. *International Journal of Coal Geology* 101: 36–81.

Noack K (1998) Control of gas emissions in underground coal mines. *International Journal of Coal Geology* 35(1-4): 57–82.

Pickering D (1989) Tests on cardox for the reinstatement of approval for use in coal mines. *Proceedings of Industry Applications Society Annual Meeting* : 251–259.

Sabdenov K and Erzada M (2016) Negative erosion effect and the emergence of unstable combustion. 1. Analysis of the models. *Combustion, Explosion, and Shock Waves* 52(1): 67–73.

Saharan MR and Mitri H (2011) Destress blasting as a mines safety tool: Some fundamental challenges for successful applications. *Procedia Engineering* 26: 37–47.

Singh A, Goerke U and Kolditz O (2011) Numerical simulation of non-isothermal compositional gas flow: Application to carbon dioxide injection into gas reservoirs. *Energy* 36(5): 3446–3458.

Sharma V, Chattopadhyaya S and Hloch S (2011) Multi response optimization of process parameters based on Taguchi—Fuzzy model for coal cutting by water jet technology. *The International Journal of Advanced Manufacturing Technology* 56(9-12): 1019–1025.

Tong J and Liang Y (1999) Calculation of vaporization-heat of pure substances by using thermal pressure. *Natural Gas Chemical Industry* 24: 58–60.

Wang F, Ren T, Tu S, et al. (2012) Implementation of underground longhole directional drilling technology for greenhouse gas mitigation in Chinese coal mines. *International Journal of Greenhouse Gas Control* 11: 290–303.

Wang H, Cheng Y and Yuan L (2013) Gas outburst disasters and the mining technology of key protective seam in coal seam group in the Huainan coalfield. *Natural Hazards* 67(2): 763–782.

Wang W, Wang S, Ma X, et al. (2011) Recent advances in catalytic hydrogenation of carbon dioxide. *Chemical Society Reviews* 40(7): 3703–3727.

Wang Z and Yang R (2011) Optimization study on calculation method on coal seam gas permeability coefficient in locale measurement. *China Safety Science Journal* 21: 23–28.

Wang Z, Zhang H, Ma T, et al. (2016) Characterizations and applications of SC-CO₂ in coal bed gas well fracturing technology. *Coal Mine Mach* 37(1): 184–187.

Zhou D, Zhang G, Zhao P, et al. (2018) Effects of post-instability induced by supercritical CO₂ phase change on fracture dynamic propagation. *Journal of Petroleum Science and Engineering* 162: 358–366.

Zhou H, Zhang R, Cheng Y, et al. (2015) Methane and coal exploitation strategy of highly outburst-prone coal seam configurations. *Journal of Natural Gas Science and Engineering* 23: 63–69.

Zhu W, Gai D, Wei C, et al. (2016) High-pressure air blasting experiments on concrete and implications for enhanced coal gas drainage. *Journal of Natural Gas Science and Engineering* 36: 1253–1263.