

## Research Article

## Gas Displacement Engineering Test by Combination of Low and Medium Pressure Injection with Liquid CO<sub>2</sub> in High Gas and Low Permeability Coal Seam

Hu Wen (b,<sup>1,2</sup> Mingyang Liu (b,<sup>1,2</sup> Gaoming Wei (b,<sup>1,2</sup> Xiaowei Zhai (b,<sup>1,2</sup> Shixing Fan (b,<sup>1,2</sup> Xiaojiao Cheng (b,<sup>1,2</sup> Hu Wang (b,<sup>1,2</sup> and Jianchi Hao (b)<sup>1,2</sup>

<sup>1</sup>College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China <sup>2</sup>Shaanxi Key Laboratory of Prevention and Control of Coal Fire, Xi'an 710054, China

Correspondence should be addressed to Mingyang Liu; 17120089012@stu.xust.edu.cn and Shixing Fan; fanxing@xust.edu.cn

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Mining high-gas coal seams in China has the characteristics mining of deep, high storage and low permeability, and low drainage efficiency, which seriously restrict the efficient prevention and control of mine gas disasters. Based on the characteristics of low viscosity and permeability, phase change pressurization, and strong adsorption potential energy of liquid  $CO_2$ , the technology system of liquid  $CO_2$  displacement for high-gas and low-permeability coal seam was developed, and field industrial of low-pressure (0.5~2.5 MPa) and medium-pressure (2.5~15.0 MPa) combined injection test was carried out. In this test, the mode of injection followed by drainage was adopted, and the gas drainage effect was investigated for 30 days. The test results show that the effective influence radius of  $CO_2$  in this test is 20 m, and the liquid seepage radius is 5 to 7 m. After the injection of liquid  $CO_2$  into coal seam, the average gas drainage concentration and drainage purity of all drainage holes were increased by 3.2 and 3.4 times, respectively, and the gas promotion effect was significant. Taking the liquid  $CO_2$  low-medium-pressure displacement gas test area as the calculation unit, from the comprehensive benefit analysis, compared with the original drainage mode, the liquid  $CO_2$ -combined pressure injection process can save 34.7% of the engineering cost and shorten the gas drainage standard time by 45.9%. Therefore, the application of this technology has important technical support and reference significance for the efficient management of gas in the same type of mine.

## 1. Introduction

"High storage and low permeability" is a common attribute of most of the coal seams in deep mines in China. That is, as the depth of coal seam mining increases, the gas content of the coal seam increases, and the permeability is low, which restrict the efficient extraction of coal seam gas and the effective prevention of mine gas [1]. Gas disaster can be said to be not only the most destructive disaster affecting mine safety production but also a serious threat to the safety of production workers one of the major disasters [2]. Excessive emissions of  $CH_4$  cause incalculable damage to the environment, and the greenhouse effect of  $CH_4$  is 25 times that of  $CO_2$  [3]. From the perspective of energy utilization and environmental protection, gas is a kind of efficient and clean energy; capturing and utilizing this gas are able to decrease greenhouse gas emissions [4]. Coalbed methane (CBM) is abundant in China. With the importance of environmental protection in China, enhanced coalbed methane (ECBM) recovery technology has become the focus of gas prevention and control.

ECBM recovery technology is one of the key technologies that must urgently be addressed in the process of coalbed methane development both within and outside of China. Based on the mechanism of  $CH_4$  generation, storage, and migration, increasing coal seam  $CH_4$  production mainly starts from two aspects: one is to promote the desorption of coalbed methane, so that the  $CH_4$  adsorbed on the inner surface of the coal matrix pores can be changed from the adsorbed state to the free state as much as possible, and the

diffusion of CBM from the matrix and micropores to the cracks is expanded [5]. The second is to expand the gas migration channel, so that CBM seeps to the borehole along more fracture channels [6, 7]. To improve the efficiency of CBM disaster control and reuse in deep well mining, a variety of coal seam permeability enhancement and gas drainage promotion technologies have been developed, mainly including protective layer mining, hydraulic fracturing, hydraulic slotting, highenergy detonation wave blasting fracturing, shock wave fracturing, and liquid  $CO_2$  blasting [8–10]. From the analysis of the engineering application effect, the above-mentioned technical processes can obviously improve the permeability of the coal seam and achieve the purpose of promoting gas drainage. However, due to the limitations of the technology, there are all kinds of technical defects and negative effects in the engineering application process. Therefore, it is very urgent to research and develop a new innovative technology for gas extraction in high-gas permeability and low-permeability coal seams.

Liquid CO<sub>2</sub> is a fluid with the properties of low viscosity, easy permeability, phase change enhancement, and high adsorption potential. The liquid CO<sub>2</sub> injection into a coal seam improves gas extraction by fracture enhancement and displacement replacement, with incomparable advantages in reservoir construction and CBM income elevation. On the one hand, coal has a higher adsorption capacity for  $CO_2$ . The adsorption of CO<sub>2</sub> by coal is about 2-10 times that of CH<sub>4</sub>, and the injection of CO<sub>2</sub> reduces the partial pressure of CH<sub>4</sub> and promotes the desorption of  $CH_4$  [11]. On the other hand, after the competitive adsorption of CO2 and CH4, CBM is replaced. Furthermore, liquid CO<sub>2</sub> injection into the coal seam will generate phase change pressurization, which will increase the mutual reverse seepage and diffusion rate of CO<sub>2</sub> and CH<sub>4</sub> in the coal seam, and then promote the CH<sub>4</sub> escape from the coal seam [12]. In terms of engineering applications, the United States, Canada, Poland, Japan, etc. have all carried out engineering tests of CO<sub>2</sub> injection, flue gas, air, nitrogen, etc. to ECBM recovery, and significant results have been achieved [13-19]. However, because the output phase of liquid  $CO_2$  is unstable, the aging characteristics are complex and dynamic. Relatively few fundamental studies on ECBM recovery technologies using liquid CO2 have been conducted, and related studies have mainly focused on the promotion of coal seam gas drainage by gaseous and supercritical  $CO_2$  [20, 21].

Based on the special properties of liquid  $CO_2$ , this paper develops a liquid  $CO_2$  cracking coal seam and gas displacement technology system suitable for high-gas and lowpermeability coal seams. The research team carried out engineering tests at the 401102 working face of Mengcun Coal Mine of Binchang Mining Group, Shaanxi Coal Mining Group. The feasibility of the process technology was debugged on site, the key parameters of the field test were investigated, and the comprehensive benefits of the process technology were verified by subsequent gas drainage effects.

## 2. The Principle of Liquid CO<sub>2</sub> Enhance Permeability and Displace CBM

2.1. Effect of Liquid  $CO_2$  on Permeability Enhancement. Coal is a porous medium; a large pore volume is ineffective despite

being interconnected in a porous medium. Microcapillary pores, which do not allow a fluid to pass through, and pores surrounded by microcapillary pores are considered an ineffective pore space for infiltration. Liquid CO<sub>2</sub> is used as a low-temperature fluid (with a low temperature of -19.5°C). The original temperature of the actual coal seam on-site is higher than 30°C. When liquid  $CO_2$  is injected into the coal seam, convective and phase transformation heat transfers take place upon contact with the coal mass, causing an increase in temperature. A temperature gradient is generated inside the coal matrix scaffold, forming thermal stress. During the injection of liquid CO<sub>2</sub>, heat exchange with the coal mass takes place when CO<sub>2</sub> infiltrates the pores and fractures, causing a cryogenic freezing damage effect [22], triggering a shrinkage of the coal matrix scaffold and damaging the structure of the pores and fractures of the coal mass. During the heat exchange between liquid CO<sub>2</sub> and coal, liquid CO<sub>2</sub> undergoes a phase transformation and an increase in both temperature and pressure as the coal matrix swells [23], inducing a compressive or tensile stress in the pore network inside the coal mass, which forces coal pores to restructure and cracks to extend and elongate. As a result, most of the ineffective pore space, which does not allow a fluid flow, becomes interconnected. Consequently, an ineffective pore space in the coal matrix transforms into an effective pore space, improving the effective porosity of the porous medium. The pore surface area of coal is expanded to a certain extent, improving the permeability [24] (as shown in Equation (1)) [25]. The gas migration channel can be broadened, allowing coal seam gas to flow toward the extraction borehole through more cracks, thus achieving an enhanced permeability by liquid  $CO_2$  [26].

$$\mu_i = -\lambda_i \frac{dp}{dx} = -\lambda_i \text{gradp}, \tag{1}$$

where  $\mu$  is the flow rate (m<sup>2</sup>·Pa<sup>-1</sup>·s<sup>-1</sup>),  $\lambda$  is the permeability coefficient, and dp/dx is the total pressure gradient in the direction of pressure reduction (Pa·m<sup>-1</sup>).

2.2. Displacement Effect of Liquid CO2. The process of gas displacement through the injection of liquid CO<sub>2</sub> into highly gassy coal seams is illustrated in Figure 1 [27]. Liquid CO<sub>2</sub> is injected into a borehole and diffused along the cracks of the coal seam around the borehole [28]. Under the effect of cryogenic damage from CO<sub>2</sub> and the thermal stress generated from the heat exchange between the CO<sub>2</sub> and the coal seam, a swelling of the coal matrix occurs [29]. The coal pores are restructured and the cracks elongate, increasing the effective porosity and permeability of the coal [30], causing an infiltration of liquid CO<sub>2</sub> into the coal. When infiltrated into a certain zone, liquid CO<sub>2</sub> absorbs heat from the coal and gradually transforms into a gaseous state. Gaseous CO<sub>2</sub> continues to infiltrate under pressure and a difference in concentration. Numerous studies have shown that 80%-90% of gas is in an adsorbed state under identical conditions [31] and that the adsorption capacity of  $CO_2$  in a coal matrix is higher than that of CH<sub>4</sub>, leading to competitive adsorption between them [32]. Subsequently, the partial pressure of CO<sub>2</sub> entering



FIGURE 1: Schematic diagram of coal seam liquid CO2 injection gas flow displacement.

the adsorption site of the coal matrix increases from the transport force, and with the transformation stress of liquid  $CO_2$ , thereby lowering the partial pressure of the  $CH_4$ , the adsorption-desorption equilibrium of the gas components inside the coal matrix is destroyed. The adsorption sites of CH<sub>4</sub> are occupied by CO<sub>2</sub> molecules with a higher adsorption capacity, leading to the desorption and displacement of CH<sub>4</sub> molecules [33, 34]. As the volume of the CO<sub>2</sub> injection increases, the CH<sub>4</sub> molecules are driven out of the coal mass through the competitive adsorption of CO<sub>2</sub>, changing from an adsorbed state to a free state (as shown in Equation (2)). Simultaneously, as the migration channel of the gas is extended, a difference in concentration is formed by the components of the gas mixture at the two ends of the gas migration channel, displacing the CH4 molecules into the corresponding migration channel [35], as shown in Equation (3). Eventually, the dual effects of pressure and a difference in concentration cause a large number of CH<sub>4</sub> molecules to seep and diffuse through the voids of the coal toward the extraction borehole [36].

$$\frac{\partial c_i}{\partial t} + \nabla (-D_i \nabla c_i) = -Q_i, \qquad (2)$$

where *i* is the gas component (CO<sub>2</sub> or CH<sub>4</sub>),  $c_i$  is the concentration of component *i* (kg·m<sup>-3</sup>),  $D_i$  is the diffusion coefficient of component *i* (m<sup>2</sup>·s<sup>-1</sup>), and  $\nabla$  is the Hamiltonian operator.

$$c_{i}(p) = \frac{a_{i}b_{i}p_{i}}{1 + b_{\rm CO_{2}}p_{\rm CO_{2}} + b_{\rm CH_{4}}p_{\rm CH_{4}}}\rho_{i}\rho_{c},$$
(3)

where  $c_i(p)$  is the adsorption capacity of component *i* (kg·m<sup>-3</sup>),  $a_{CO_2}$  and  $a_{CH_4}$  are, respectively, the maximum adsorption capacity of CO<sub>2</sub> and CH<sub>4</sub> when they are adsorbed separately in the coal seam (kg·m<sup>-3</sup>),  $b_{CO_2}$  and  $b_{CH_4}$  are adsorption equilibrium constants of CO<sub>2</sub> and CH<sub>4</sub>, respectively (MP<sup>-1</sup>), and  $p_{CO_2}$  and  $p_{CH_4}$  are the adsorption partial pressure of CO<sub>2</sub> and CH<sub>4</sub>, respectively (MPa).

## 3. Process System for Methane Displacement with Liquid CO<sub>2</sub> in High-Gas and Low-Permeability Coal Seam

This on-site test was selected at the mechatronics chamber of the 401102 working face in the 4# main coal seam of Mengcun Mining Co., Ltd. in the Binchang mining area, Shaanxi (as shown in Figure 2). The 4# coal seam belongs to low metamorphic bituminous coal, and internal fissures developed not well. The average coal thickness is 13.0 m, and the average inclination angle of the coal seam is 3°. Coal industry analysis and coal quality determination results are shown in Table 1.

The predicted value of absolute gas emission in the mine is  $110.5 \text{ m}^3/\text{min}$ , while the predicted value of relative gas emission is  $8.1 \text{ m}^3/\text{t}$ . The 4# coal seam is a typical coal seam with high gas, low permeability, and bursting liability. When gas extraction is carried out by dense drilling, problems such as high cost, long extraction time, and poor extraction effect exist. Mengcun Coal Mine has successively adopted hydraulic fracturing, hydraulic slicing, and other technologies, aiming to reduce the bursting liability of coal seam and improve the efficiency of gas extraction. Through the above technical effect analysis, it can reduce the impact of coal seam and improve the permeability of coal seam. However, due to the water-locking effect of the large-area pore and fracture network in the coal seam [37], the effect of gas extraction is reduced.

Therefore, based on technology comparison and comprehensive benefit analysis, the mine chose to develop liquid  $CO_2$  displacement technology. The purpose is to improve the efficiency of coal seam gas extraction through the implementation of technical processes and reduce the cost of mine gas disaster management.

3.1. Test Process System. The process diagram of the liquid  $CO_2$  pressure injection system is shown in Figure 3. It is mainly composed of a liquid  $CO_2$  tanker, a cryogenic pressure pump, a data acquisition instrument (DAI), a pressure transmitter (PT), a pressure-resistant conveying pipeline, a stop valve, and a pressure relief valves and other components. The cryogenic pressure pump is mainly used for boosting



FIGURE 2: The location of the on-site test.



Coal sample	Industrial analysis (%)				£	Coal composition (%)			$\mathbf{D}^{(1)}$
	$M_{\rm ad}$	$V_{\rm ad}$	A <sub>ad</sub>	FC <sub>ad</sub>	$\int_{x}$	$V_0$	$I_0$	$E_0$	$K_{\rm max}(\%)$
Nonstick coal	3.73	35.53	6.92	51.21	2.46	54.36	43.55	20.8	0.63

 $M_{ad}$  is the moisture content of the coal;  $V_{ad}$  is the volatile matter of the coal;  $A_{ad}$  is the ash content of the coal;  $FC_{ad}$  is the fixed carbon of the coal;  $f_x$  is the hardness coefficient of the coal;  $V_0$  is the vitrinite of the coal;  $I_0$  is the inertia of the coal group;  $E_0$  is the coal body's external group;  $R_{max}^0$  is the coal body's maximum vitrinite reflectance.



FIGURE 3: Process diagram of liquid CO<sub>2</sub> injection system.

liquid CO<sub>2</sub>, with rated power of 22 KW, flow rate of 2000 L/h, and maximum working pressure of 15 MPa, which can supercharge and convey liquid CO<sub>2</sub>. The data acquisition instrument can realize multiple sets of data acquisition and monitoring, mainly collecting pump outlet pressure, orifice pressure, etc. The monitoring medium of the tank vehicle differential pressure meter (vortex flowmeter) is liquid, which is mainly used to monitor the flow rate in the pressure injection process and count the accumulative pressure injection amount. The pressure transmitter has a range of 0-30 MPa and mainly monitors the variation of orifice pressure in the process of injection. The conveying pipeline is a highpressure rubber hose with pressure resistance of 0-40 MPa, which has the characteristics of high-pressure and lowtemperature resistance. Globe valve and relief valve are mainly used for backflow, relief, and blowout of pipeline at the end of pressure injection [8].

3.2. Drilling Layout of Working Face. The field test was carried out in the newly excavated 401102 electromechanical chamber. The coal seam in the test area is well distributed, and no gas drainage is carried out. A total of 15 in seam boreholes were constructed, 2 of which were boreholes for the injection of liquid  $CO_2$  (1# and 2#), and 13 were observation boreholes (1#–13#). The drilling layout of the working face is shown in Figure 4, and the detailed parameters of the drilling design are shown in Table 2.

### 4. Industrial Test Results and Discussion

4.1. Dynamic Parameter Analysis of  $CH_4$  Displacement by Liquid  $CO_2$  in High-Gas and Low-Permeability Coal Seam. The liquid  $CO_2$  low-pressure injection system adopts the direct injection of liquid  $CO_2$  tanker, and the maximum pressure of liquid  $CO_2$  tanker is 2.5 MPa. Low-temperature pressure pump is used to supercharge liquid  $CO_2$  with a flow rate of 2000 L/h and a maximum working pressure of 15 MPa. The pressure transmitter and data acquisition instrument were used to monitor the pressure change of the orifice and check the stability of the system. Meanwhile, the  $CO_2$  verification tube (20% range) was used to detect the influence radius of  $CO_2$  seepage.

Low-pressure injection was mainly used to debug the reliability and stability of the injection system. The liquid  $CO_2$  transformed into gaseous  $CO_2$  to disturb the concentration gradient of gas in the steady state of the coal. The medium pressure injection was mainly based on the low-temperature freezing damage and instantaneous phase change of liquid  $CO_2$ , which in order to expand the  $CO_2$  migration radius and increase the influence range of  $CO_2$  displacement gas in the coal seam. When the liquid  $CO_2$  was injected, the pressure gradient and the concentration gradient together drove the migration of  $CO_2$  molecules and competed with the gas in the coal for adsorption and desorption, so as to achieve efficient gas extraction.

# 4.1.1. Pressure Change during Injection of Liquid $CO_2$ into Bedding Borehole

(1) Pressure Change of Liquid CO2 Injection at Low Pressure of Coal Seam. The liquid CO<sub>2</sub> tank was used to conduct two

low-pressure injection on the 1# injection hole  $(1\#-1_L, 1\#-2_L)$ and 2# injection hole  $(2\#-1_L, 2\#-2_L)$ , respectively. The injection parameters are shown in Table 3. The variation of orifice pressure during injection was observed, as shown in Figures 5(a) and 5(b). Using liquid CO<sub>2</sub> increases the permeability and displacement function, pushing the gas migration and desorption, and through the aperture of the gas extraction effect for 30 days observation. At the same time, in the original area, select raw gas drainage borehole as a comparison and mainly observed the gas concentration of extraction, extraction of pure gas amount, and comprehensive inspection of liquid CO<sub>2</sub> displacement test effect of CBM.

It can be seen from the pressure curves of injection processes in 1# and 2# injection holes. The maximum pressure of each hole during the second injection is greater than the maximum pressure of the first one, and the rate of pressure rise is higher than the first one. In the initial stage of pressure injection, liquid  $CO_2$  had good permeability and fast permeability in the coal. During the second injection, the coal matrix expanded, and the pore pressure in the coal body increased [38, 39]. At this time, the permeability was relatively slow, and the pressure gradually increased and kept balance.

Figure 5(b) is an enlarged diagram of the downward trend of each pressure curve. According to the analysis, the pressure decline rate of the second injection is slower than that of the first injection. The pressure curve of 2#-1 declines faster and finally reaches 0 due to leakage of #9 observation hole around 2# injection hole. When liquid CO<sub>2</sub> is injected into coal seam, it changes from liquid to gaseous state. Gas molecules will adsorb on the surface of coal, resulting in the decrease of surface tension of coal and the expansion of coal matrix. At the same time, under the action of overburden stress, the increase of CO<sub>2</sub> adsorption pressure and effective stress both increase the internal expansion coefficient of coal [40]. In this case,  $CO_2$  slowly permeates and diffuses under the action of internal pressure difference and concentration difference of coal seam, and competitive adsorption with  $CH_4$  occurs in the coal matrix [41].

(2) Pressure Change of Liquid CO2 Injection at Medium Pressure of Coal Seam. The stability of the system was verified by the test of the liquid  $CO_2$  low-pressure injection system. The injection hole and observation hole were checked, and the leakage area was sealed. On the basis of the low-pressure injection system, the liquid CO<sub>2</sub> medium-pressure injection system adopts the low-temperature pressure pump to pressurize. The 1# injection hole (1#-1<sub>M</sub>, 1#-2<sub>M</sub>) and 2# injection hole  $(2\#-1_M, 2\#-2_M)$  are, respectively, pressurized. The maximum working pressure of the low-temperature pressure pump is 15 MPa, and the flow is 2000 L/h. The pressure transmitter and data acquisition instrument were used to monitor the pressure change of the orifice and check the stability of the system. Meanwhile, the CO<sub>2</sub> verification tube (20% range) was used to detect the influence radius of CO<sub>2</sub> seepage [42]. The injection parameters are shown in Table 4. The variation of orifice pressure during injection was observed (as shown in Figures 6(a) and 6(b)).



FIGURE 4: Schematic diagram of drilling layout of liquid CO<sub>2</sub> injection system.

TABLE 2: Drilling parameter design table.

Drilling name	Hole depth (m)	Azimuth (°)	Inclination (°)	Aperture (mm)	Sealing length (m)
Injection hole	140	90	$0.5^{\circ}-1^{\circ}$	113	40
Observation hole	140	90	$0.5^{\circ}-1^{\circ}$	113	12
Original drainage hole	140	90	$0^{\circ}-1^{\circ}$	113	12

TABLE 3: Table of low-pressure injection parameters.

Drilling name	Volume of injection (m <sup>3</sup> )	Rate of flow (m <sup>3</sup> /min)	Pressure rise rate (MPa/min)	Maximum pressure (MPa)	Dwell time (min)	Depressurization rate (MPa/min)	Minimum pressure (MPa)
1#-1 <sub>L</sub>	2.0	0.028	0.020	0.70	105	0.010	0.17
$1\#-2_{L}$	1.8	0.038	0.069	1.50	38	0.008	0.42
$2\#-1_{L}$	1.8	0.040	0.048	0.95	58	0.040	0
$2\#-2_{L}$	2.0	0.030	0.041	1.30	12	0.022	0.11

According to Figure 6(a), it can be seen that there are basically two stages in the pressure change curve during medium pressure injection. After the initial pressure rises to a certain value, the pressure will remain stable for a period of time and keep rising with the increase of pressure and flow. The reason why the pressure of 1#-1 drops to 0.48 MPa is that leakage phenomenon is observed around 1# inspection hole.

The variation trend of boost rate of medium pressure injection is similar to that of low-pressure injection. The maximum pressure at the second injection of each hole was greater than that at the first injection; meanwhile, pressure rise rate is higher than that of the first injection. Figure 6(b) is an enlarged diagram of the downward trend of each pressure curve. The second injection drop rate of medium pressure injection is slower than that of the first injection.

The pore pressure rises and slippage effect gradually decreases with the increase of injection pressure during medium pressure injection. The gas molecules adsorbed on the surface of the coal matrix increase, and the coal matrix expands further. In this case,  $CO_2$  in coal seam under the action of internal pressure and the concentration difference

of slow diffusion compete with  $CH_4$  in coal matrix inside. Low-pressure and medium-pressure injection tests have proved the stability of the system. At the same time, the sealing quality of the borehole is a key factor in the test. In order to maintain the pressure, sufficient liquid  $CO_2$  raw materials should be ensured.

4.1.2. Effective Influence Radius of Liquid CO<sub>2</sub> Displacement. According to 2# injection hole pressure and the temperature curve of 5 m and 7 m (as shown in Figure 7), the pressure and temperatures at 210 min were taken as a reference. The pressure and temperature values corresponding to distances of 5 m and 7 m are (4.06 MPa, -20.70°C) and (4.06 MPa, 13.90°C) respectively. CO<sub>2</sub> is liquid at 5 m away from the injection hole, while CO<sub>2</sub> is gaseous at 7 m away from the injection hole, so it can be judged that the seepage radius of liquid CO<sub>2</sub> is from 5 m to 7 m.

In the process of injecting liquid  $CO_2$  into coal seam, the migration force generated in the process of phase transition to gaseous  $CO_2$ . The seepage of liquid  $CO_2$  along the large-scale through fracture and the diffusion of gaseous  $CO_2$  in



FIGURE 5: Variation of orifice pressure during low pressure injection.

TABLE A. Table of medium	proceure injection	narameters
TABLE 4. Table of meanum	pressure injection	parameters.

Drilling name	Volume of injection (m <sup>3</sup> )	Rate of flow (m <sup>3</sup> /min)	Pressure rise rate (MPa/min)	Maximum pressure (MPa)	Dwell (time/min)	Depressurization rate (MPa/min)	Minimum pressure (MPa)
1#-1 <sub>M</sub>	2.0	0.018-0.025	0.048	3.16	25	0.038	0.48
1#-2 <sub>M</sub>	2.0	0.020-0.025	0.090	3.28	15	0.005	2.73
2#-1 <sub>M</sub>	2.0	0.015-0.020	0.040	5.30	30	0.027	1.34
2#-2 <sub>M</sub>	2.0	0.015-0.025	0.067	5.90	25	0.010	3.50



FIGURE 6: Variation of orifice pressure during medium pressure injection.



FIGURE 7: Temperature-pressure curve.

the open pore were promoted. This is a solid-liquid-gas coupling process, temperature, stress, concentration, and other multifield coupling results. Therefore, in order to determine the effective influence range of liquid CO<sub>2</sub> displacement in coal seam, the effective influence range of CO<sub>2</sub> in coal seam was determined by the concentration of CO<sub>2</sub> in coal seam. After a period of holding pressure, the CO<sub>2</sub> concentration of each observation hole on both sides of the injection hole was monitored by using industrial CO<sub>2</sub> calibration tube (with a maximum measurement range of 20.0%, where a measurement of 20% indicates that the  $\mathrm{CO}_2$  concentration exceeded the measurement range). The variation of CO<sub>2</sub> concentration in observation holes at different distances is shown in Figures 8. The CO<sub>2</sub> concentration at different distances after first medium pressure injection in 1# and 2# holes is shown in Figure 8(a), and after second injection in 1# and 2# holes is shown in Figure 8(b).

According to the data analysis of gas drainage, the maximum original CO<sub>2</sub> concentration in coal seam is 2.78%. As shown in Figure 8(a), when the low pressure is injected, the accumulated injection quantity of liquid CO<sub>2</sub> is 3.8m<sup>3</sup> in the 1# injection hole, and the concentration of CO<sub>2</sub> was 2.4% at 25 m from 1#, slightly lower than the maximum original  $CO_2$  content of coal seam by 2.78%. The concentration of  $\mathrm{CO}_2$  was 1.64% at 25 m from no. 2 less than 2.78% of the maximum original CO<sub>2</sub> concentration in coal seam, when liquid CO<sub>2</sub> was injected 3.8 m<sup>3</sup> cumulatively. It showed that the gas-phase migration range of liquid CO<sub>2</sub> might be 20-25 m, and the minimum is not less than 20 m. From Figure 8(b), it showed that the  $CO_2$  concentration at the distance of 25 m from 1# injection hole is 1.6%, which is lower than 2.78% of the maximum original  $CO_2$  concentration of coal seam. While the accumulated injection quantity of liquid  $CO_2$  is 4.0 m<sup>3</sup> in no. 2 injection hole, the  $CO_2$  concentration is 1.2% at 25 m from 2# injection hole, which is lower than 2.78% of the maximum original CO<sub>2</sub> concentration in coal seam. It can be concluded that the gas-phase migration of liquid  $CO_2$  might be in the range of 20–25 m, and the minimum is not less than 20 m.

Therefore, the effective influence radius of liquid  $CO_2$ displacement is basically the same between low-pressure injection and medium-pressure injection, the gas migration range is 20–25 m, and the minimum is not less than 20 m. The  $CO_2$  diffusion is faster in the middle-pressure injection, but with the increase of the injection volume and pressure, it could spread further. Based on the observation of the distribution of  $CO_2$  concentration after the injection holes of 1# and 2#, it is determined that the effective influence radius of gas displacement by liquid  $CO_2$  is 20 m in bedding boring of 4# seam in Mengcun coal mine; this result is basically similar to the method and results used in previous field tests [43].

4.2. Analysis on Gas Displacement Effect of Coal Seam by Liquid  $CO_2$ . After field test of gas displacement by liquid  $CO_2$  injection in coal seam of 401102 mechatronics chamber, the effect of gas drainage was investigated for 30 days, and the gas drainage concentration and flow rate were observed. The gas drainage purity was calculated, while the 5#–9# observation hole was selected; the Y01–Y05 was selected as the contrast hole. The contrast hole are 30 m away from the test area in the same roadway; the effect of gas displacement by liquid  $CO_2$  was investigated by comparing the average gas drainage concentration and the average gas drainage purity between the test area and the original gas drainage area. The relationship between the average gas drainage concentration and the average gas drainage purity is shown in Figures 9(a) and 9(b).

As shown in Figure 9(a), the maximum concentration of gas drainage from observation holes in the test area is 39.28%, the minimum is 9.39%, and the average is 17.73%, while the maximum, the minimum, and the average concentration of gas drainage from original holes are 11.64%, 1.46%, and 5.60%, respectively. The concentration of gas drainage in the test area is 3.2 times that of the original gas drainage. According to the concentration curve of gas drainage from



FIGURE 8: Concentration variation of observation hole.



FIGURE 9: Correlation diagram between average gas drainage concentration and average gas drainage purity.

observation hole, it can be seen that in the early period of liquid  $CO_2$  injection, the coal matrix was embrittled deformed by the low-temperature damage of liquid  $CO_2$ , and the pores of coal body developed twice. The fractures continued to expand and extend; the pore ratio of coal and the permeability of coal seam increases; meanwhile, there were more migration pathway. Under the action of concentration difference and pressure difference, the gas can be released advantageously, and the moving power and rate of gas in coal seam can be further improved. With the heat exchange between liquid  $CO_2$  and coal, liquid  $CO_2$  is gradually transformed into gas and diffused in coal; meanwhile, it competed with  $CH_4$  in coal to adsorb and displaces the adsorbed  $CH_4$  in coal. The concentration of gas extraction decreases rapidly and fluctuates about 17% after 5 days.

It can be seen from Figure 9(b) that the change law of gas extraction purity is consistent with the change law of gas extraction concentration from observation hole and original gas extraction hole. The comparison curve of gas extraction purity can be divided into three stages, which correspond to the ①, ②, and ③ stages of the curve, and the 123 stages of the curve, respectively; a large amount of free  $CH_4$  is transported along the original fracture of coal seam and the new fracture formed by pressure injection of liquid  $CO_2$ , and the attenuation coefficient of gas extraction purity is 0.7426 in

the original gas extraction area, and the gas in the experimental area is more favorable for gas drainage. 2 and 3 stages of curves show that after 15 days of gas pumping, CO<sub>2</sub> gas is adsorbed in the coalbed matrix, which forms competitive adsorption with CH<sub>4</sub> and displaces the adsorbed CH<sub>4</sub>, and the pure measuring range changes periodically. Among them, the attenuation coefficient of the pure gas extraction is 0.3229 and 0.2236, and the attenuation coefficient of the pure gas extraction is 0.1685 and 0.0830 in the original gas extraction area, the gas extraction purity is relatively low, and the gas attenuation coefficient is kept at a relatively low level, while the gas extraction purity remains at a relatively high level in the experimental area with the CO<sub>2</sub> percolation and diffusion, CO<sub>2</sub> adsorption in the coal matrix and displacement of CH<sub>4</sub>. In the test area, the maximum value and the average value of gas extraction purity are 0.313 m<sup>3</sup>/min, 0.029 m<sup>3</sup>/min, 0.109 m<sup>-3</sup>/min, 0.70 m<sup>3</sup>/min, 0.011 m<sup>3</sup>/min, and 0.032 m<sup>3</sup>/min, respectively. The purity of gas extraction in the test area is 3.4 times of that of the original gas extraction, and the active period of gas extraction is about 30. The results show that liquid CO<sub>2</sub> injected into coal seam increases the gas drainage flow, especially the displacement effect of gas is the most obvious. Based on the 30-day observation data, the gas drainage effect of CH<sub>4</sub> test in coal seam driven by liquid CO<sub>2</sub> is obviously improved, and the gas drainage efficiency will inevitably decline in the later period and timely observation of pressure injection effect [44, 45].

#### 4.3. Comprehensive Benefit Analysis

4.3.1. Economic Benefit Analysis. By means of measuring the gas pressure and gas concentration of coal seam before and after the injection of liquid CO<sub>2</sub>, it is shown that the gas pressure of coal seam in the field test area reduced by 12% after 30 days promoting of gas drainage. Ton coal with gas content decreased from 3.12 m<sup>3</sup>/t to 1.41 m<sup>3</sup>/t, which decreased the gas pressure and gas drainage time significantly. According to the gas displacement test using liquid CO<sub>2</sub> and the borehole layout for mine gas extraction, the economic costs of the project under two scenarios were compared. An observation area with a length of 70 m was applied as the basis of the calculation. In the original gas drainage area, there were 28 boreholes for methane extraction, distributed at intervals of 2.5 m, each of which was 140 m long. In the observation area used during the test, there were 15 boreholes of 140 m in length and with a liquid  $CO_2$  consumption of 20 m<sup>3</sup>, with 2 of the boreholes used for the pressure injection. The construction cost of the boreholes was RMB 55 per meter. The costs of the liquid carbon dioxide displacement zone included the construction cost of the boreholes, cost of laboratory equipment, and the raw material cost of the liquid CO<sub>2</sub>. A cost comparison is shown in Table 5. It was calculated that a reduction in the project cost of approximately RMB 139,700 can be achieved from the gas displacement test through the use of CO<sub>2</sub> within this calculation unit, cutting the project cost by 34.7%.

4.3.2. *Time Analysis of Gas Extraction Standard*. Because the gas emissions of the mine are mainly from the mining face of

the production layer, a predrainage rate of the gas of  $\eta \ge 35\%$  was set based on the standard for coal mine gas extraction (where  $\eta$  is the volume of gas extracted/volume of gas reserve). Combined with the characteristics of the experiment area used in this study, a calculation unit of 80 m in length with a working face of 180 m in width was selected for comparison with the time required to meet the gas extraction standard.

For the volume of gas extracted,  $\eta$  represents the volume of gas extracted from a unit of coal mass within the target time period (m<sup>3</sup>).

For the volume of the gas reserve, the gas reserve from the coal mass is within the control area of the unit of the predrainage borehole  $(m^3)$ .

For the calculation of the gas reserve, a length of 80 m with a 180 m wide working face, an average coal seam thickness of 13 m, and an average original coal seam gas content of  $3.12 \text{ m}^3$ /t were applied. Therefore,

$$Q_{\text{reserve}} = 80 \times 180 \times 13 \times 1.36 \times 3.12 = 584000 \text{ m}^3.$$
 (4)

According to the observation data of the volume of pure gas extracted from a single borehole, the average gas emission from a single borehole in the original extraction project was  $0.032 \text{ m}^3/\text{min}$ , whereas that from a single borehole in the experimental project of gas displacement using CO<sub>2</sub> was  $0.109 \text{ m}^3/\text{min}$ . As a result, the corresponding predrainage times required to meet the standard are as follows:

$$T_{1} = \frac{Q_{\text{reserve}} \times \eta}{Q_{\text{daily extraction}}} = \frac{58.4 \times 0.35}{(0.032 \times 24 \times 60 \times 24)} = 185 \text{ d}, \quad (5)$$
$$T_{1} = \frac{Q_{\text{reserve}} \times \eta}{Q_{\text{daily extraction}}} = \frac{58.4 \times 0.35}{(0.109 \times 13 \times 60 \times 24)} = 100 \text{ d}.$$
(6)

From the above calculations, it was found within the calculation unit that the predrainage time required to meet the standard for the original extraction project was 185 days, whereas that for the gas displacement through the liquid  $CO_2$  project was 100 days. The time required to meet the standard was decreased by 85 days, thus reducing the extraction time by 45.9%, and significantly improving the extraction efficiency. Within the calculation unit, the gas extraction time required to meet the standard was decreased by 85 days, cutting the drainage duration by 45.9% [42].

## 5. Conclusions

(1) A liquid  $CO_2$  pressure injection system was tested using a low-pressure injection system in high-gas and low-permeability coal seam. The results showed that the injection process system is stable. The dynamic parameters such as pressure and flow rate keep fluctuating characteristics in the process of liquid  $CO_2$  injection. Among them, the pressure of liquid  $CO_2$  injection at low pressure fluctuated between 0.7 MPa and 1.51 MPa, while that of liquid

 TABLE 5: Comparison of economic benefits.

Name of project	Number of boreholes	Depth of borehole (m)	Construction cost (in RMB 10000)	Raw material cost (in RMB 10,000)	Project cost (in RMB 10,000)
Original gas extraction project	56	140	43.12	_	43.12
Project of gas displacement by liquid CO <sub>2</sub>	15	140	11.55	16.6	28.15

 $CO_2$  injection at medium pressure ranged from 5.3 MPa to 5.9 MPa. When the single hole liquid  $CO_2$  injection volume reaches 4-6 m<sup>3</sup>, the liquid seepage radius is 5 to 7 m, and the effective migration radius of  $CO_2$  is 20 m in the process of liquid  $CO_2$  displacement gas in the test area through the distribution law of  $CO_2$  gas concentration in the coal seam

- (2) It was found from the inspection of the gas extraction field during the test process that the concentration of  $CH_4$  extracted increased from 5.60% to 17.73% after the injection of liquid  $CO_2$  into the coal seam, increasing the concentration of gas extracted by 3.2fold. The pure flow of gas extracted increased from  $0.032 \text{ m}^3/\text{min}$  to  $0.109 \text{ m}^3/\text{min}$ , increasing the pure flow of gas extracted by 3.4-fold. The gas extraction efficiency improved significantly
- (3) The test results of gas displacement using liquid  $CO_2$ in calculation unit showed that the project cost can be reduced by 34.7% and the time required to meet the extraction standard within the calculation unit can be shortened by 45.9%. The use of gas displacement technology by applying liquid CO<sub>2</sub> can not only reduce the project cost but also improve the extraction efficiency and shorten the time required to meet the extraction standard, ensuring a continuous mine production. A reduction in the efficiency of the gas extraction was not considered in the selection of the calculation unit. In an actual experiment, a second pressure injection into the original boreholes can be conducted when a reduction in the extraction efficiency occurs, ensuring that the concentration and pure flow of the gas extracted are maintained at highly efficient levels. The new technology and reference for mine gas extraction were put forward

## **Data Availability**

The data are all available and have been explained in this article; readers can access the data supporting the conclusions of the study.

## **Conflicts of Interest**

The authors declare that they have no conflicts of interest.

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