CrossMark

ORIGINAL PAPER

Effect of liquid carbon dioxide phase change fracturing technology on gas drainage

Hai-dong Chen[1,2,3] · Zhao-feng Wang[1,3] · Ling-ling Qi[1] · Feng-hua An[1]

Abstract Coal mine researchers have been studying the subject of improving the effect of gas drainage to control gas accident. This paper focuses on a new permeability-improvement technology, liquid carbon dioxide phase change fracturing technology. This technology can be classified as physical blasting by using the phase energy of liquid carbon dioxide in the drilling underground coal mine. According to the results of field tests, by applying the liquid carbon dioxide phase change fracturing technology, the radius of the damaged area in the coal body around the drilling reached 5 m. Also, compared with the original coal body, the permeability of the damaged area increased approximately six times. In addition, based on the permeability of the damaged area, the influence of the liquid carbon dioxide phase change fracturing technology on the gas drainage radius was analyzed by numerical calculation. It can be observed from the numerical results that the effect of gas drainage was improved greatly by the liquid carbon dioxide phase change fracturing operation. Research results of this paper can contribute to safe and efficient mining of coal mines.

Introduction

China is a country in which serious gas accidents occur. Gas pre-drainage of coal seams is an effective means to prevent gas accidents in coal mines (Wang et al. 2014; Zhou et al. 2014; Cheng et al. 2011). The characteristics of low permeability, high gas pressure, and high in situ stress around coal seams in most mining areas in China have restricted the development of gas drainage work (Chen et al. 2014; Chen et al. 2013).

To solve the problem on gas drainage of coal seams with low permeability, some fracturing technologies improving the permeability of coal seams would be used. For example, hydraulic fracturing is being used extensively (Barati and Liang 2014; Vengosh et al. 2014; King 2012). In the process of hydraulic fracturing, fracturing fluids are pumped into the coal seam at high pressures to induce fractures and carry proppants to hold open the fractures and create a flow path for the gas to the drilling (Rogers et al. 2015). Involved in the hydraulic fracturing, Zhai et al. (2012) proposed the method of directional hydraulic fracturing and proved the feasibility of this method through field testing. Li et al. (2014) introduced the effect of pulse frequency on crack expansion and concluded that high frequency was more successful in generating cracks. Yan et al. (2015) indicated that a complete pressure relief zone, a transitional pressure relief zone, and the original stress zone would be generated around the borehole after hydraulic fracturing. Through

✉ Zhao-feng Wang
wangzhaofenghpu@outlook.com

1 MOE Engineering Center of Mine Disaster Prevention and Rescue, Henan Polytechnic University, Jiaozuo, Henan 454000, People's Republic of China

2 State Key Laboratory Cultivation Base for Gas Geology and Gas Control, Henan Polytechnic University, Jiaozuo, Henan 454000, People's Republic of China

3 Collaborative Innovation Center of Coal Safety Production of Henan Province, Jiaozuo, Henan 454000, People's Republic of China
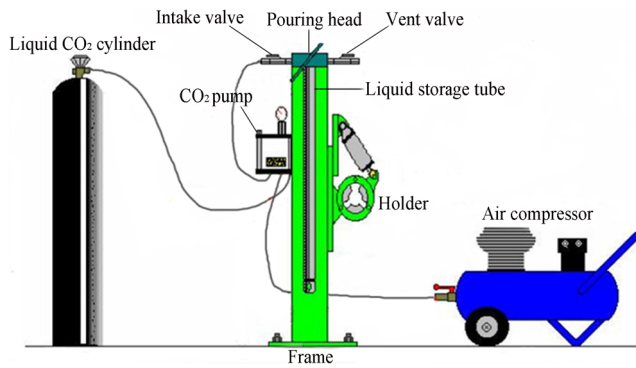
Fig. 1 Aboveground filling system

numerical simulation, Yang et al. (2004) concluded that the mechanical properties of rock cracking had an important influence on the initiation and incrementation of cracking during hydraulic fracturing.

Except for hydraulic fracturing, dynamite blasting is also a common fracturing technology to improve the permeability of coal seams (Guo et al. 2008). This technique makes full use of blasting energy, places explosives in coal seams, and causes fissure development in coal seams. Liu et al. (2014) analyzed fracture and stress evolution characteristics during directional blasting using a test directional blasting system. Zhou et al. (2011) and Cai and Liu (2011) concluded that dynamite blasts in the borehole could improve the effect of gas drainage and eliminate the risk of coal and gas outbursts. Zhu et al. (2013) discovered that dynamite blasts in the coal seam could not only eliminate stress concentration around the borehole but also could increase the permeability coefficient of the damaged area of the coal body around the boreholes.

Hydraulic fracturing and dynamite blasting can improve greatly the permeability of coal seams. However, there are also disadvantages. A wide variety of chemical additives like linear polymer, surfactant, potassium chloride, scale inhibitor, pH adjusting agent, iron control agents, corrosion inhibitors, and biocides are used in the hydraulic fracturing technology (Stringfellow et al. 2017; Stringfellow et al. 2014; Barati and Liang 2014; King 2012; Barati et al. 2009), which could cause both direct and indirect impacts on the environment and human health (Burton et al. 2016; Gregory and Mohan 2015; Long 2014; Vengosh et al. 2014). Also, the process of dynamite blasting in the coal seam often produces a lot of harmful

gases like CO, NO_2, H_2S, and SO_2 and has resulted in the presence of unexploded dynamite, which creates security risks for coal mining.

Liquid carbon dioxide phase change fracturing technology has been used formerly for the mining of large coal and for underground excavation (Vidanovic et al. 2011; Singh 1998; Anon 1995). In this paper, liquid carbon dioxide phase change fracturing technology classified as physical blasting by using the phase energy of liquid carbon dioxide in the underground coal mine is applied to increase the permeability of coal seams for gas drainage. No spark appeared in the blasting process, and the transport, storage, and use were all convenient. The experimental device is also very simple.

The kernel of liquid carbon dioxide phase change fracturing technology is the blasting system, which consists of a release tube containing release holes, a cutting plate, a liquid storage tube containing a heating pipe, guide tubes, and a detonator, following that order from top to bottom. By starting the detonator, special chemicals in the heating pipe begin to react, and a lot of heat is then released instantly to heat the liquid carbon dioxide in the liquid storage tube. This process brought about the phase change of carbon dioxide and then caused the dramatic expansion of the volume of carbon dioxide. When the pressure of carbon dioxide in the liquid storage tube exceeds the strength of the cutting plate, the cutting plate is damaged, and high-pressure carbon dioxide enters the release tube and acts on the coal body. Once the technology is applied in the drilling underground coal mine, the amount of the liquid carbon dioxide is 1.248~1.4 kg. According to the field data, the amount of carbon dioxide flowing from the drilling to the roadway is very small and below the safety value. Also, liquid carbon dioxide phase change fracturing technology would not affect water and soil quality and is environmentally friendly.

The permeability-improvement mechanism of the liquid carbon dioxide phase change fracturing technology is similar to hydraulic fracturing. However, the pressurization methods of two technologies are different. Compared with hydraulic fracturing, the equipment of the liquid carbon dioxide phase change fracturing technology is simpler, the pressure is larger, and the process is also faster. More importantly, it is an effective way of achieving the optimum fracture network. The main supplies of this technology are

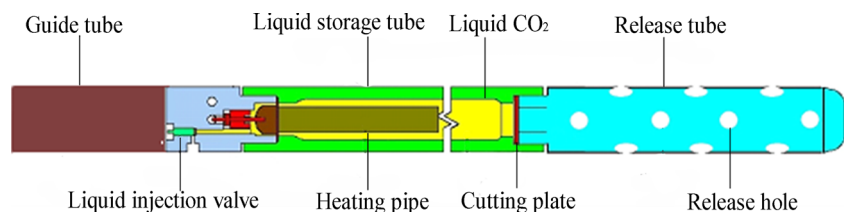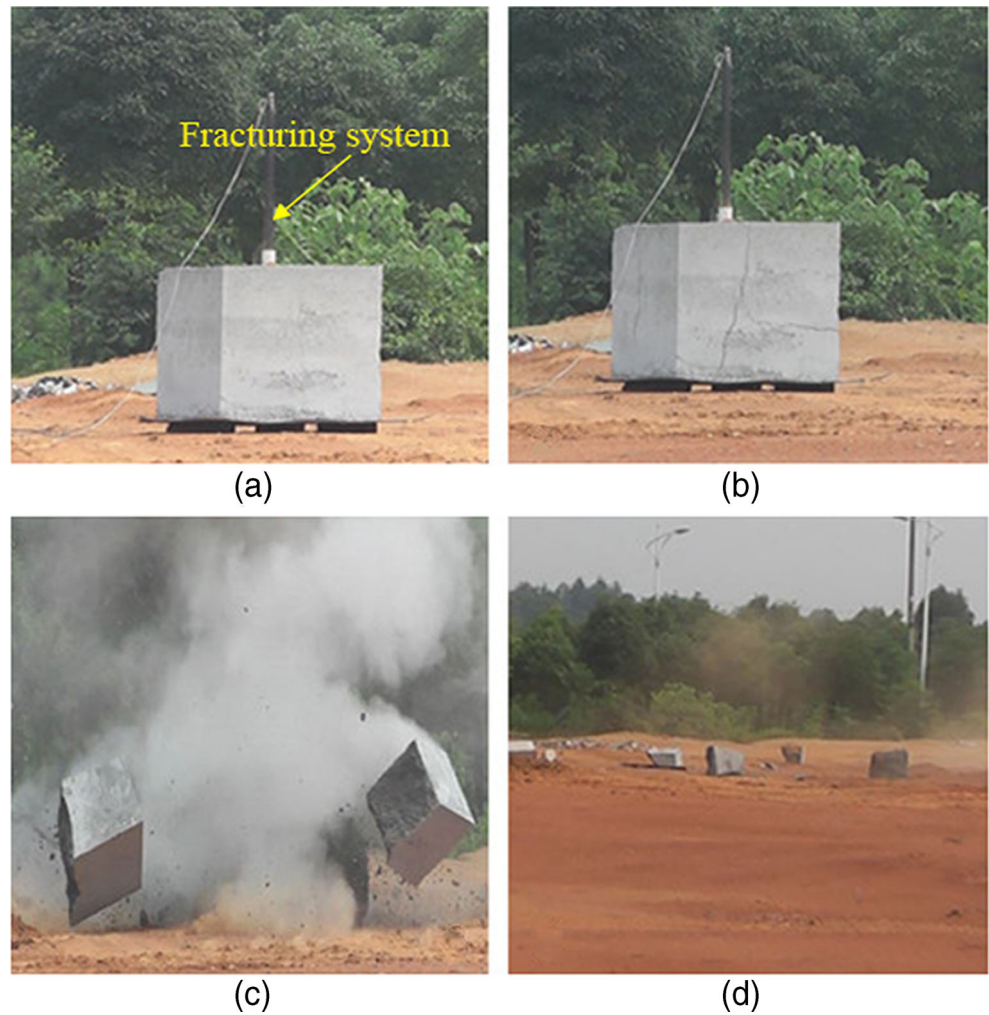Fig. 2 Underground blasting system

Fig. 3 Fracturing process in cement block. **a** Ready state. **b** Macroscopic cracks generation. **c** Cement block exploded in a flash. **d** Blasting end

(a)

(b)

(c)

(d)

heating pipes, and its price is approximately 12 dollars, being economically favorable for industry. Therefore, in terms of environment, human health, technical advantages, and economy, liquid carbon dioxide phase change fracturing technology has a greater advantage than that of hydraulic fracturing and dynamite blasting. This paper studied mainly the effect of liquid carbon dioxide phase change fracturing technology on the gas drainage.

Liquid carbon dioxide phase change fracturing system

The liquid carbon dioxide phase change fracturing system contains a ground filling system and an underground blasting system. As shown in Fig. 1, the aboveground filling system consists of an air compressor, CO_2 pump, and CO_2 cylinder. The underground blasting system (shown in Fig. 2) consists of a release tube, liquid storage tube, heating pipe, guide tube, and cutting

plate. The volume of the liquid storage tube is 1.26 L, and the weight of the liquid carbon dioxide in the liquid storage tube is 1.248~1.4 kg. The kernel of this
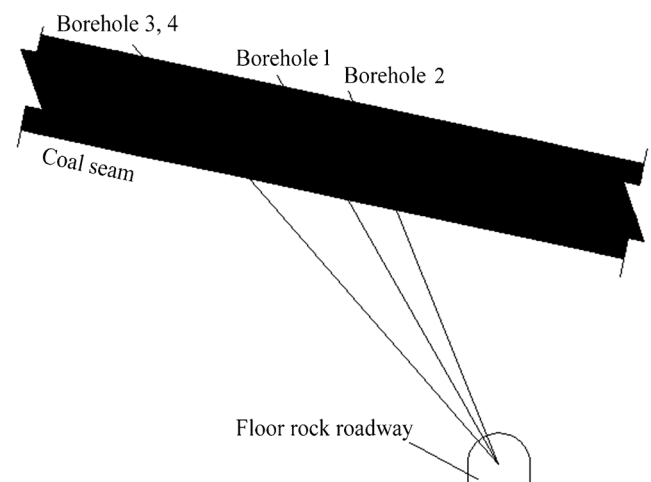

Fig. 4 Sectional view of the drilling arrangement

Table 1   Drilling parameters

Borehole number	Borehole length (m)	Borehole diameter (mm)	Drilling angle (°)	Distance from borehole 1 (m)
1	22.5	94	120	0
2	31.5	94	134	3.5
3	29	94	130	5
4	29	94	130	7

technology is the blasting system, which consists of a release tube containing release holes, a cutting plate, a liquid storage tube containing a heating pipe, guide tubes, and a detonator, following that order from top to bottom. By starting the detonator, special chemicals in the heating pipe begin to react and a lot of heat is then released instantly to heat the liquid carbon dioxide in the liquid storage tube. This process brought about the phase change of carbon dioxide and then caused the dramatic expansion of the volume of carbon dioxide. When the pressure of carbon dioxide in the liquid storage tube exceeds the strength of the cutting plate, the cutting plate is damaged, and high-pressure carbon dioxide enters the release tube and acts on the coal body. According to the laboratory test results, the damage pressure of the cutting plate reaches 270 MPa. Therefore, the pressure of carbon dioxide acting on the coal body is also approximately 270 MPa. The release tube, the liquid storage tube, and the guide rod are connected by screws, and the guide rod has a built-in conducting wire that can conduct electricity after connecting. In the testing process, the release tube and liquid storage tube could be sent to pre-determined positions.
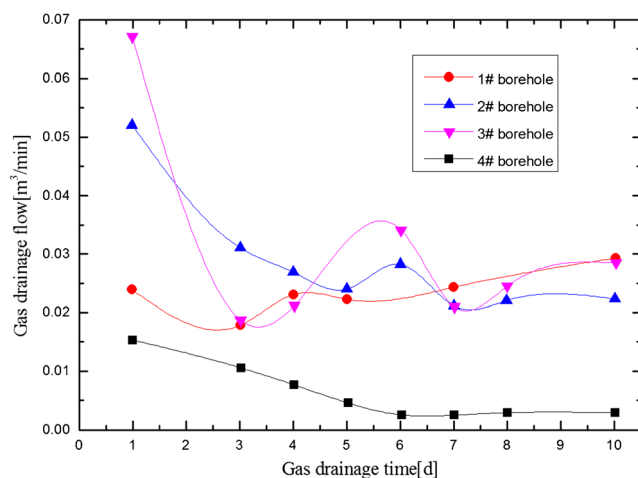
Fig. 5 Borehole gas flows after the liquid carbon dioxide phase change fracturing operation

Due to complex production conditions in an underground coal mine, the fracturing process of this technology is difficult to be captured. In order to understand easily the explosive characterization of liquid carbon dioxide phase change fracturing technology, ground tests using this technology in cement block were done, and the fracturing process is shown in Fig. 3.

Field tests of radius of damaged area in the coal body by using the liquid carbon dioxide phase change fracturing technology

Radius of damaged area in the coal body about the fracturing technology

The influence radius in the coal body of the liquid carbon dioxide phase change fracturing technology was determined in the 16,051 workface of the Jiulishan coal mine at the Jiaozuo coal mining area in China. Average thickness of coal seam is 5.44 m. The depth of the 16,051 workface is 390 m, and the temperature underground is 26 °C. The 16,051 workface had a risk of coal and gas outbursts. The maximum gas content and pressure were 24.36 m^3/t and 2.08 MPa, respectively, and the adsorption constants were 38.597 m^3/t and 0.782 MPa^{-1}. The moisture, ash, and volatile contents of the coal body were 0.81, 15.83, and 7.11%, respectively. The porosity of the coal body is 7.69%.

To determine the influence radius in the coal body of the liquid carbon dioxide phase change fracturing technology, four boreholes were arranged. Borehole 1 was classified as the experimental borehole for the liquid carbon dioxide phase change fracturing operation. Boreholes 2, 3, and 4 were classified as observation boreholes. If the gas flow of an observation borehole increased, it could be ascertained that the observation borehole was influenced by the experimental borehole. Conversely, the observation boreholes were not influenced by the experimental borehole. All of the boreholes were constructed from the bottom roadway of the 16,051 workface. The drilling arrangement and parameters are shown in Fig. 4 and Table 1.

The longest distances among different boreholes are only 7 m, and borehole construction times from boreholes 1 to 4 are very short (approximately 24 h). Due to small borehole spaces, gas flows in the boreholes before CO_2 treatment would be approximately the same according to the field practice experience. Also, we mainly want to gain a radius of damaged area in the coal body about the fracturing technology according to gas flows in the boreholes after CO_2 treatment. Therefore, gas flows in the boreholes before CO_2 treatment were not measured.

Fig. 6 Calculation process for coal body permeability

$$q = \frac{Q}{2 \cdot \pi \cdot r_1 \cdot L}$$

$$A = \frac{q \cdot r_1}{p_0^2 - p_1^2}, B = \frac{4t \cdot p_0^{1.5}}{\alpha r_1^2}$$

Randomly Select a formula from the second column in Table 2 to calculate λ

$$F_0 = B\lambda$$

F_0 is in the range (first column in Table 2) corresponding to the selected λ in step 3 — No → Re-select formula λ
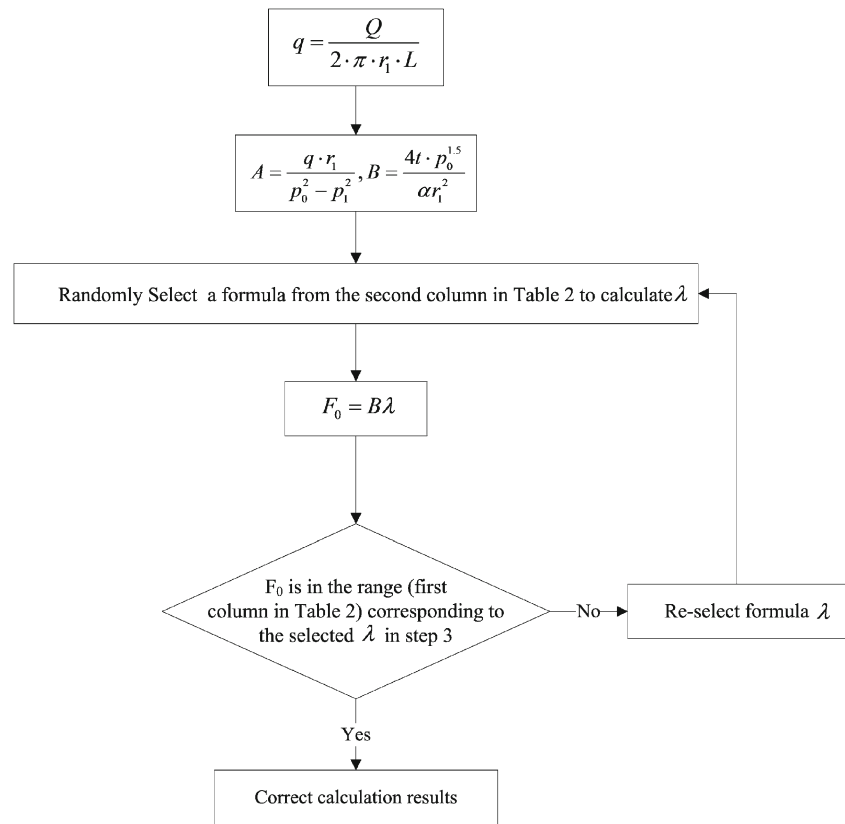
Yes

Correct calculation results

Figure 5 shows the test results of gas drainage flows for 10 days after the liquid carbon dioxide phase change fracturing operation. As can be observed in Fig. 5, after the liquid carbon dioxide phase change fracturing operation, the gas drainage flows from the third day around boreholes 1, 2, and 3 were the same within experimental error and had significant differences with that of borehole 4. The gas flow of borehole 4, the most distant from experimental borehole 1, was the smallest. Therefore, it can also be observed that boreholes 2 and 3 were closer to experimental borehole 1 and that boreholes 2 and 3 were influenced by the liquid carbon dioxide phase change fracturing operation. Conversely, borehole 4 was not influenced by the liquid carbon dioxide phase change fracturing operation. The distances from boreholes 2 and 3 to borehole 1 were 3.5 and 5 m, respectively (shown in Table 1). It can be concluded that the radius of damaged area in the coal body of the liquid carbon dioxide phase change fracturing technology for the 16,051 workface of the Jiulishan coal mine was 5 m.

According to the explosive characterization of liquid carbon dioxide phase change fracturing technology (shown in Fig. 3), the explosion power of this technology is huge, and the permeability-improvement effect would be obvious. It should be noted that though gas flows in the boreholes before CO_2 treatment were not measured, we can infer that gas flow rates from boreholes 1–3 would not be higher than that before CO_2 treatment.

Average permeability of the damaged area

After the liquid carbon dioxide phase change fracturing operation, a damaged area and the original coal body area surrounding the experimental borehole form. Compared with that of the original coal body area, the permeability of the damaged area greatly increased. The permeability of the damaged area had a very important influence on the radius of gas drainage. Therefore, an indirect method was used to calculate the permeability of the damaged area.

Table 2   Formulas for calculating permeability in the coal body

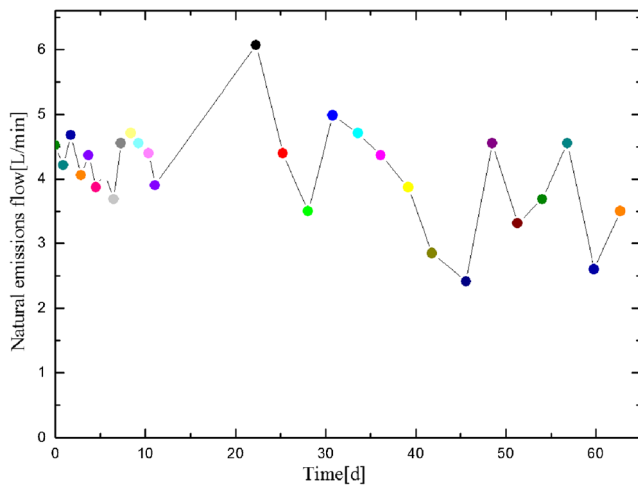| $F_0 = B\lambda$	λ	A	B
$10^{-2}\sim 1$	$\lambda = A^{1.61}B^{0.61}$		
$1\sim 10$	$\lambda = A^{1.39}B^{0.391}$	$A = \frac{q \cdot r_1}{p_0^2 - p_1^2}$	$B = \frac{4t \cdot p_0^{1.5}}{\alpha r_1^2}$
$10\sim 10^2$	$\lambda = 1.1A^{1.25}B^{0.25}$		
$10^2\sim 10^3$	$\lambda = 1.83A^{1.14}B^{0.137}$		
$10^3\sim 10^5$	$\lambda = 2.1A^{1.11}B^{0.111}$		
$10^5\sim 10^7$	$\lambda = 3.14A^{1.07}B^{0.07}$		

Fig. 7 Gas flow attenuation characteristic curve under natural emission conditions

An indirect method of calculating the permeability (Zhou and Kong 1965) for underground coal seams has been widely used in China. The calculation basis for the indirect method of calculating the permeability was the unstable flow of gas in the coal seam along the radial direction. By determining the gas pressure, gas flow, gas emission, thickness, and borehole diameters of coal seams of underground coal mines, as well as by performing an industrial analysis, the permeability of the coal seams was calculated. The formulas and calculation processes are shown in Fig. 6 and Table 2.

In Fig. 6, λ is the permeability of the coal seam in $m^2/(MPa^2\ day)$, Q is the total gas flow at time t in m^3/day, r_1 is the drilling radius in m, L is the length of the coal bearing section for drilling in m, and $q = Q/2\pi r_1 L$ is the gas flow per unit area of drilling at time t in $m^3/(m^2\ day)$. p_0 is the absolute gas pressure of the original coal seam in MPa; p_1 is the atmospheric pressure, typically 0.1 MPa; $\alpha = X/\sqrt{p}$ is the factor of gas content around the coal seam; X is the gas content of the coal seam in m^3/m^3; and P is the gas pressure of the coal seam in MPa.

Based on the average gas flows of boreholes 1, 2, 3, and 4 and the basic parameters of the gas and coal seam shown in Table 2 and Fig. 6, the permeability was calculated. The permeability of the coal body surrounding boreholes 1, 2, 3, and 4 were approximately 2.1×10^{-17}, 2.7×10^{-17}, 3.0×10^{-17}, and 5.0×10^{-18} m^2, respectively. The average permeability of the damaged area (boreholes 2 and 3) after the liquid carbon dioxide phase change fracturing operation was 2.9×10^{-17} m^2. Therefore, after the liquid carbon dioxide phase change fracturing operation, the average permeability of the damaged area increased approximately to six times that of the original coal body area (borehole 4).

Influence of the liquid carbon dioxide phase change fracturing operation on gas drainage

The influence of the liquid carbon dioxide phase change fracturing operation in the coal body on the gas drainage was the basis for carrying out industrial experiments in an underground coal mine. In combination with gas drainage research at the Pingdingshan Tianan Coal Mining Corporation No. 13 coal mine in Henan Province, China, Comsol Multiphysic numerical simulation software was used to analyze the influence of the liquid carbon dioxide phase change fracturing operation on the gas drainage in the coal body.

The No. 13 coal mine of the Pingdingshan Tianan Coal Mining Corporation had coal and gas outbursts. The maximum gas pressure and content are 2.7 MPa and 20 m^3/t, respectively. The permeability of the coal seam is very low, 10^{-15} m^2, and the gas flow attenuates slowly under the natural emission conditions (shown in Fig. 7). The gas drainage work for the coal seam is difficult.

To compare the influence of the liquid carbon dioxide phase change fracturing operation on the gas drainage radius in the coal body, gas drainage models that did and did not consider the liquid carbon dioxide phase change fracturing operation were established. Due to similar mining conditions and depths of the coal seams in the Jiulishan and No. 13 coal mines, the influence radius of the liquid carbon dioxide phase change fracturing operation in the coal body at the No. 13 coal mine could be set as approximately 5 m.

The permeability-improvement effect of liquid carbon dioxide phase change fracturing technology could be different in different coal mine, which needs to be measured in engineering practice. The permeability of the damaged area caused by the fracturing technology at the No. 13 coal mine is not measured. In this study, we mainly want to gain the influence of the liquid carbon dioxide phase change fracturing operation
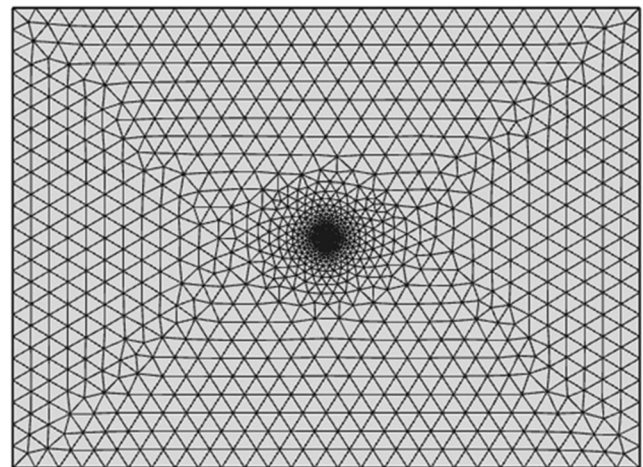

Fig. 8 Model mesh

on the gas drainage in the coal body. For a coal seam with low permeability, the specific value of permeability of the damaged area caused by the fracturing technology mainly affects the decline range of the gas pressure inside the coal seam for different drainage times; however, the permeability-improvement effect of the fracturing technology is mainly related to the influence range of this technology in the coal seam (shown in Figs. 9 and 10). Therefore, considering similar mining conditions and depths of the coal seams in the Jiulishan and No. 13 coal mines, the permeability of the damaged area of coal seam in the No. 13 coal mines is also set to six times larger than that of the original coal body area. This permeability value is only used to analyze the influence of the liquid carbon dioxide phase change fracturing operation on the gas drainage in the coal body and has no true physical meaning.

Governing equation

The gas migration in the coal body can be indicated by Eq. 1.

$$\frac{\partial m}{\partial t} + \nabla\left(\rho_g q_g\right) = Q. \tag{1}$$

where m is the gas content of the coal seam in kg/m^3, t is the time variable in s, ρ_q is the gas density in kg/m^3, q_g is the gas seepage speed in m/s, and Q is the gas source in kg/(m^3 s).

When the gas is the ideal gas, its density and gas pressure satisfy Eq. 2.

$$\rho_g = \beta p. \tag{2}$$

where p is the gas pressure of the coal seam in Pa and β is the gas compression factor, in kg/(m^3 Pa).

β can be indicated by Eq. 3.

$$\beta = M_g \big/ (\text{RT}. \tag{3}$$

where M_g is the molecular weight of the gas in kg/kmol, R is the ideal gas constant in kJ/(kmol K), and T is the absolute temperature in K.

The gas content of the coal seam could be expressed by Eq. 4 (Rutqvist and Tsang 2002).

$$m = \beta\left(\frac{\phi}{p_a} + \frac{a_1 a_2 \rho_s}{1 + a_2 p_1}\right)p_1{}^2. \tag{4}$$

where ϕ is the porosity, p_1 is the atmospheric pressure in Pa, ρ_s is the density of coal in kg/m^3, and a_1 and a_2 are the adsorption constants, with units of m^3/kg and Pa^{-1}, respectively.

Moreover, the flow of gas in the coal body obeys Darcy's law, which is shown in Eq. 5.

$$q_g = \frac{k_g}{\mu_g}\nabla p. \tag{5}$$

where q_g is the gas seepage speed in m/s, μ_g is the dynamic viscosity of the gas in Pa s, and ∇p is the pressure gradient of the gas.

Model and boundary conditions

The length and width of the models that did not consider the liquid carbon dioxide phase change fracturing operation were 150 and 150 m, respectively. The length and width of the models that considered the liquid carbon dioxide phase change fracturing operation were 150 and 200 m, respectively. The mesh of the models is shown in Fig. 8. The diameter of the drill was 94 mm, and the negative pressure for gas drainage was 32 kPa. No-flow boundaries were used around the models. The gas pressure of the coal seam was 2.7 MPa, which is consistent with the maximum gas pressure measured at the No. 13 coal mine. The other parameters used in the simulations are shown in Table 3.

Results of numerical simulation analysis

The gas pressure changes for different drainage times of 1, 3, 6, and 9 months were simulated. To clearly observe the results of the numerical simulation, sectioning was performed at the central site along the longitudinal direction. The results of the numerical simulation that did not consider the liquid carbon dioxide phase change fracturing operation and those of the simulation that considered the liquid carbon dioxide phase change fracturing operation are shown in Figs. 9 and 10, respectively.

As shown in Figs. 9 and 10, as the gas drainage time increases, the gas pressure around the gas drainage drilling decreases, and the influence radius for gas drainage also

Table 3 Other parameters used in the simulations

Molar mass of gas (g/mol)	Ideal gas constant (J/(mol K))	Temperature (K)	Permeability (m^2)	Adsorption constant a (m^3/t)	Adsorption constant b (MPa^{-1})	Porosity (%)
16	8.41351	293	10^{-15}	31.874	0.929	6.5

Fig. 9 Gas pressure changes with varying gas drainage times not considering the liquid carbon dioxide phase change fracturing operation
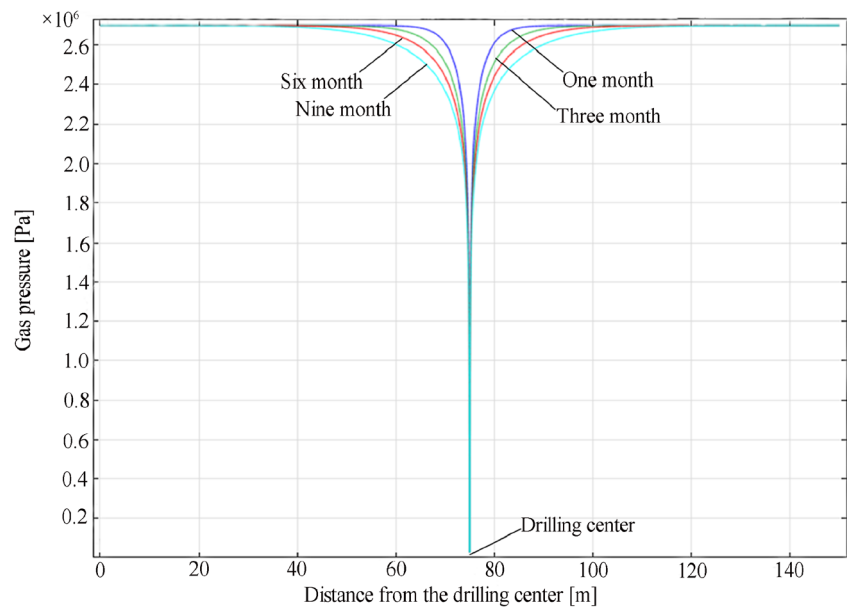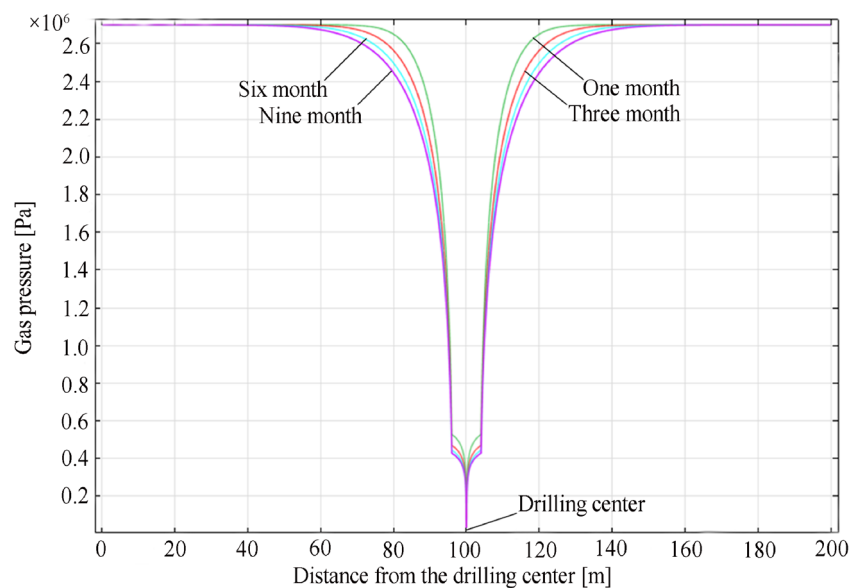

increases. Compared with the model that did not consider the liquid carbon dioxide phase change fracturing operation, the gas pressure had a more significant reduction at the time of gas drainage than the model that considered the fracturing operation. Due to low permeability and high gas pressure, when the fracturing operation was not considered, the gas drainage effect was poor; the gas pressure inside the coal seam for the drainage time of 9 months could not decline to 0.74 MPa, which is the threshold used in China to judge the danger of coal and gas outbursts (National Coal Mine Safety Supervision Bureau 2009). However, when the fracturing operation was considered, the gas pressure inside the coal seam declined to 0.74 MPa for a drainage time of 1 month.

Moreover, the declining areas of gas pressure were consistent with the influence radius of liquid carbon dioxide phase change fracturing technology in the coal body.

Conclusions

This paper mainly focuses on the effect of liquid carbon dioxide phase change fracturing technology on the gas drainage radius of coal seams. After applying the liquid carbon dioxide phase change fracturing technology, the damaged area radius in the coal body reached 5 m. After using the liquid carbon dioxide phase change

Fig. 10 Gas pressure changes with varying gas drainage times considering the liquid carbon dioxide phase change fracturing operation

fracturing technology, the permeability of the damaged area increased approximately six times.

To compare the influence of the liquid carbon dioxide phase change fracturing operation on the gas drainage radius, gas drainage models that did and did not consider the liquid carbon dioxide phase change fracturing operation were established. For the same gas drainage times, the gas pressure showed a more significant reduction at the time of gas drainage when the fracturing technology was used.

References

Anon (1995) Cardox system brings benefits in the mining of large coal. Coal International 243(1):27–28

Barati R, Hutchins RD, Friedel T, Ayoub JA, Dessinges M, England KW (2009) Fracture impact of yield stress and fracture-face damage on production with a three-phase 2d model. SPE Prod Oper 24(2):336–345

Barati R, Liang JL (2014) A review of fracturing fluid systems used for hydraulic fracturing of oil and gas wells. J Appl Polym Sci 131(16)

Burton TG, Rifai HS, Hildenbrand ZL, Carlton DD, Fontenot BE, Schug KA (2016) Elucidating hydraulic fracturing impacts on ground water quality using a regional geospatial statistical modeling approach. Sci Total Environ 545:114–126

Cai F, Liu Z (2011) Intensified extracting gas and rapidly diminishing outburst risk using deep-hole presplitting blast technology before opening coal seam in shaft influenced by fault. Procedia Eng 26: 449–456

Cheng YP, Wang L, Zhang XL (2011) Environmental impact of coal mine methane emissions and responding strategies in China. Int J Greenh Gas Control 5:157–166

Chen HD, Cheng YP, Zhou HX, Li W (2013) Damage and permeability development in coal during unloading. Rock Mech Rock Eng 46: 1377–1390

Chen HD, Cheng YP, Ren T, Zhou HX, Liu QQ (2014) Permeability distribution characteristics of protected coal seams during unloading of the coal body. Int J Rock Mech Mining Sci 71:105–116

Gregory K, Mohan AM (2015) Current perspective on produced water management challenges during hydraulic fracturing for oil and gas recovery. Environ Chem 12(3):261–266

Guo D, Pei H, Song J, Qin F, Liu X (2008) Study on splitting mechanism of coalbed deep-hole cumulative blasting to improve permeability. J China Coal Soc 33:1381–1385

King GE (2012) Hydraulic fracturing 101: what every representative, environmentalist, regulator, reporter, investor, university researcher, neighbor and engineer should know about estimating frac risk and improving Frac performance in unconventional gas and oil wells.

SPE Hydraulic Fracturing Technology Conference. Society of Petroleum Engineers, The Woodlands, Texas. February, In, pp 6–8

Li Q, Lin B, Zhai C (2014) The effect of pulse frequency on the fracture extension during hydraulic fracturing. J Nat Gas Sci Eng 21:296–303

Liu J, Liu Z, Gao K, Ma X, Li Z, Guo L (2014) Experimental study and application of directional focused energy blasting in deep boreholes. Chin J Rock Mech Eng 33:2490–2496

Long SC (2014) Direct and indirect challenges for water quality from the hydraulic fracturing industry. J Am Water Works Assoc 106(11):53–57

National Coal Mine Safety Supervision Bureau (2009) Provisions of the prevention of coal and gas outburst, Beijing

Rogers JD, Burke TL, Osborn SG, Ryan JN (2015) A framework for identifying organic compounds of concern in hydraulic fracturing fluids based on their mobility and persistence in groundwater. Environ Sci Technol Lett 2(6):158–164

Rutqvist J, Tsang CF (2002) A study of caprock hydro-mechanical changes associated with CO_2-injection into a brine formation. Environ Geol 42:296–305

Singh SP (1998) Non-explosive applications of the PCF concept for underground excavation. Tunneling and Underground Space Technology 13:305–311

Stringfellow WT, Domen JK, Camarillo MK, Sandelin WL, Borglin S (2014) Physical, chemical, and biological characteristics of compounds used in hydraulic fracturing. J Hazard Mater 275:37–54

Stringfellow WT, Camarillo MK, Domen JK, Sandelin WL, Varadharajan C, Jordan PD, Reagan MT, Cooley H, Heberger MG, Birkholzer JT (2017) Identifying chemicals of concern in hydraulic fracturing fluids used for oil production. Environ Pollut 220:413–420

Vengosh A, Jackson RB, Warner N, Darrah TH, Kondash A (2014) A critical review of the risks to water resources from unconventional shale gas development and hydraulic fracturing in the United States. Environ Sci Technol 48(15):8334–8348

Vidanovic N, Ognjanovic S, Ilincic N, Ilic N, Tokalic R (2011) Application of unconventional methods of underground premises construction in coal mines. Technics Technol Educ Manag-ttem 6(4):861–865

Wang HF, Cheng YP, Wang W, Xu R (2014) Research on comprehensive CBM extraction technology and its applications in China's coal mines. J Nat Gas Sci Eng 20:200–207

Yan F, Lin B, Zhu C, Shen C, Zou Q, Guo C, Liu T (2015) A novel ECBM extraction technology based on the integration of hydraulic slotting and hydraulic fracturing. J Nat Gas Sci Eng 22:571–579

Yang T, Tham L, Tang C, Liang Z, Tsui Y (2004) Influence of heterogeneity of mechanical properties on hydraulic fracturing in permeable rocks. Rock Mech Rock Eng 37:251–275

Zhai C, Li M, Sun C, Zhang J, Yang W, Li Q (2012) Guiding-controlling technology of coal seam hydraulic fracturing fractures extension. Int J Min Sci Technol 22:831–836

Zhou C, Lin B, Li F, Zhao S, Liu F (2011) The research of quaternity of drilling-blasting-fracturing-extracting technology and application of outburst. Procedia Eng 26:449–456

Zhou HX, Yang QL, Cheng YP, Ge CG, Chen JX (2014) Methane drainage and utilization in coal mines with strong coal and gas outburst dangers: a case study in Luling mine, China. J Nat Gas Sci Eng 20: 357–365

Zhou SN, Kong JZ (1965) Gas flow theory and its applications in coal seam. J China Coal Soc 2:24–37

Zhu W, Wei C, Li S, Wei J, Zhang M (2013) Numerical modeling on destress blasting in coal seam for enhancing gas drainage. Int J Rock Mech Mining Sci 59:179–190