

# New Technology of Mechanical Cavitation in a Coal Seam to Promote Gas Extraction

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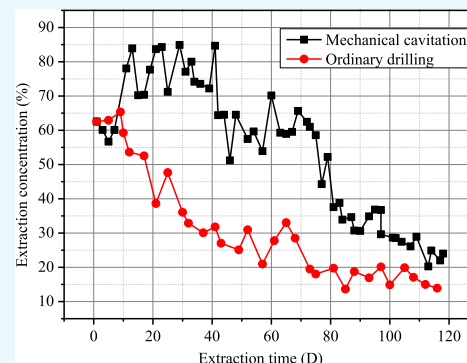
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**ABSTRACT:** Realizing efficient gas drainage in low permeability coal seams has always been a difficult problem for coal miners. Based on this, this paper proposes a new technology of large-diameter mechanical cave-making to promote gas extraction in a coal seam. This technology mainly uses the pressure of a water injection pump to control the automatic opening and closing of a mechanical reaming device to realize mechanical cavitation, and the hole diameter can reach up to 500 mm. The gas drainage effect of mechanical cavitation drilling is analyzed by a numerical simulation, which shows that under the condition of the same drainage time, the larger the cavitation radius is, the larger the effective influence radius of gas drainage is. According to the field test results, the time of single cave-making is about 5 min, and the speed of cave-making is fast. The coal output of a single cave is 0.42 t/m, and the pressure relief effect is obvious. Compared with ordinary drilling, the gas drainage concentration of mechanical cavitation drilling is increased by 2 times and the net amount of drainage is increased by 1.8 times. Large-diameter mechanical cavitation technology can better improve the gas drainage effect of outburst coal seams with low permeability and has a good application prospect.



## 1. INTRODUCTION

The depth of China's coal mines is deepening at a rate of 10–20 m per year. With the continuous increase of coal mining depth, the in situ stress increases, the gas content and gas pressure of coal seams increase, the coal mining conditions deteriorate, and serious casualties and property damage accidents occur frequently.<sup>1–5</sup> According to statistics, more than 70% of these accidents are gas accidents.<sup>6–8</sup> Therefore, improving the coal seam gas extraction rate and reducing coal seam gas energy storage is crucial to coal mine safety production.

For coal seams with high permeability, a reasonable gas drainage system, reasonable drainage negative pressure, drilling and sealing methods, etc., can significantly improve the coal seam gas recovery rate.<sup>9,10</sup> However, due to the influence of coal seam sedimentary environment, geological structure, and other factors, the permeability of coal seams in most mining areas in China is generally low, only  $10^{-4}$ – $10^{-3}$  mD, which is not conducive to gas drainage.<sup>11,12</sup> To achieve the purpose of high-efficiency drainage, some artificial strengthening and antireflection measures must be taken to improve the permeability of coal seam. Among these measures, hydraulic punching, hydraulic slotting, hydraulic fracturing, and other hydraulic measures are commonly used.<sup>13–17</sup> These mainly use the impact, disturbance, and jet of high-pressure water to locally relieve the stress of the coal body around the borehole so as to improve the permeability and gas flow conditions of the coal seam.<sup>18–22</sup>

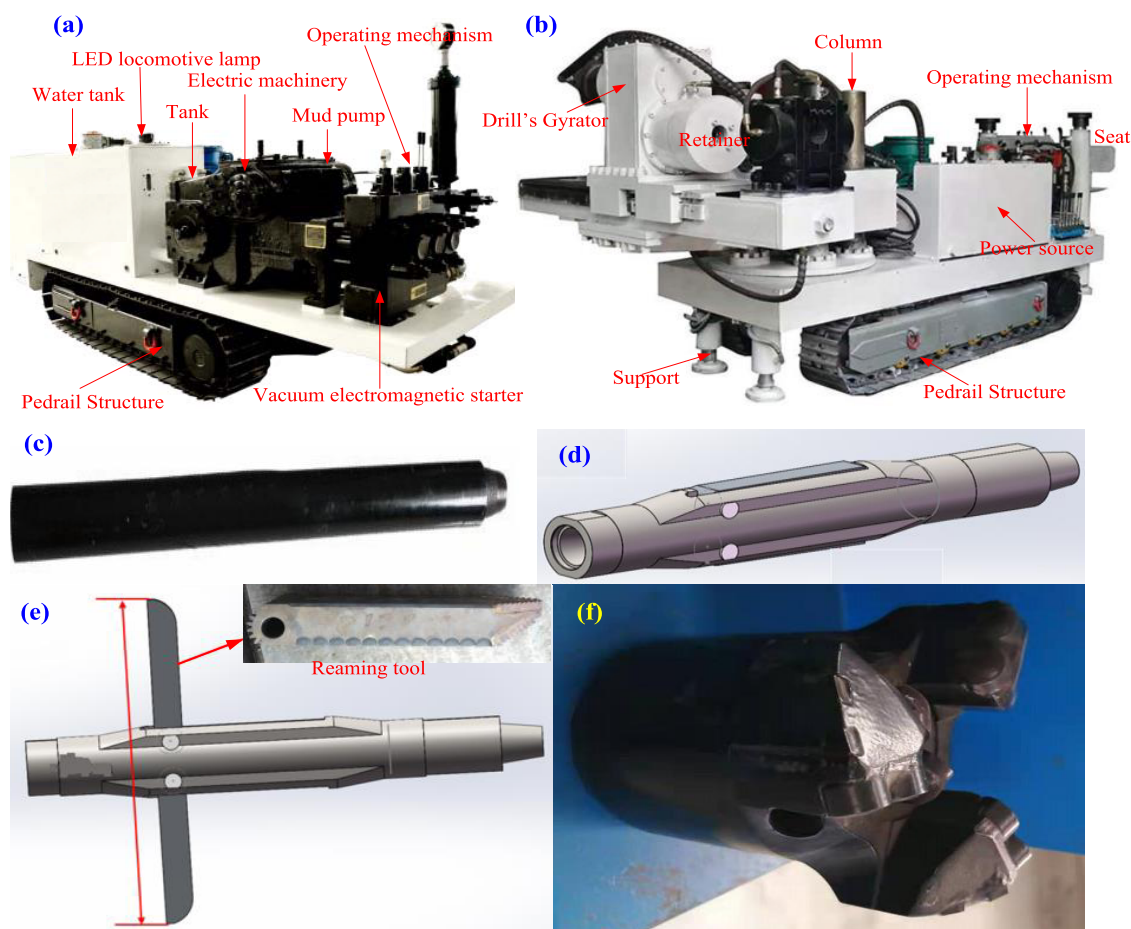
In addition to hydraulic measures, scholars have also put forward many other advanced coal seam gas drainage technologies. Chen et al.,<sup>23</sup> Liu et al.,<sup>24</sup> and Wang et al.<sup>25</sup> use the expansion of high-pressure gas after the phase change of liquid CO<sub>2</sub> to crack the coal body so as to increase the drainage amount of gas in the coal seam. In the laboratory, Tang et al.<sup>26</sup> analyzed the feasibility of injecting CaO demolition materials into the borehole to enhance the permeability of coal seams. Teng et al.,<sup>27</sup> Huang et al.,<sup>28</sup> and Jiang et al.<sup>29</sup> used heat injection, microwave heating, and thermal shock technology to improve the desorption efficiency of gas in the coal seam so as to achieve the purpose of increasing production by heat injection. Based on the displacement effect of CO<sub>2</sub> and N<sub>2</sub>, Zhang et al.,<sup>30</sup> Li et al.,<sup>31</sup> and Lin et al.<sup>32</sup> studied the influence of injecting CO<sub>2</sub>, liquid CO<sub>2</sub>, and N<sub>2</sub> into the coal seam on the gas drainage effect. At the same time, chemical stimulation, freeze-fracturing, destruction blasting, and other technologies had also been applied to improve the permeability of coal seams.<sup>33–37</sup>

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**Figure 1.** Main components of drilling and cavitation integrated equipment: (a) BLY800/2 mining crawler mud pump truck; (b) ZDY10000LPS mining crawler full hydraulic tunnel drill; (c) high-pressure sealed drill pipe; (d, e) variable diameter mechanical cavitation device; and (f) drill bit.<sup>38</sup>

To sum up, although the current permeability improvement technology is effective, most technologies require high precision of equipment, complex processing procedures, large investment, and many constraints in the application process. In this paper, a new permeability improvement technology is proposed, which mainly uses a mechanical reaming device installed on the drill pipe to discharge the coal body around the borehole. The technology has the characteristics of simple equipment, convenient operation, and strong applicability and has a good application prospect.

## 2. MECHANICAL CAVITATION EQUIPMENT AND CONSTRUCTION TECHNOLOGY

**2.1. Mechanical Cavitation Equipment.** Large-diameter mechanical cave-making equipment is mainly composed of a BLY800/2 mining crawler mud pump truck (Figure 1a), ZDY10000LPS mining crawler full hydraulic tunnel drill (Figure 1b), KFS-50/11 mining vibrating screen solid–liquid separator, high-pressure sealed drill pipe (Figure 1c), high-pressure rotary joint, drill bit (Figure 1f), variable diameter mechanical cavitation device (Figure 1d,e), and so on.

The existing cave-making technology is mainly hydraulic punching technology. In the process of use, it is necessary to often return the drill, replace the drill bit, and resend the drill bit to the punching position. In soft coal, it is easy to collapse and block the hole. It is also difficult to redrill after withdrawing the drill, which seriously affects the construction

efficiency. The high-torque reaming rig adopts an integrated drilling tool and integrated design for the variable diameter coal cutting and cave-making device. When in use, the drill bit is installed on the end of the drill pipe, and the reaming device is in a retracted state. When the coal cutting position is reached, high-pressure water is delivered to the drill body. At this time, the one-way mechanism acts as a throttling function, and the high-pressure water controls the limit mechanism. Under the action of the spring, the hole reaming device is in a continuous expansion state, and then, the integrated drill bit is rotated and reciprocated to realize coal cutting.

**2.2. Construction Technology.** The underground construction process of mechanical cavitation equipment is as follows: drilling construction, reaming, unloading drill pipe, installing the sealing pipe, drilling hole sealing, connection, and pumping.

- (1) During normal drilling, the pressure of the pump station is within 3 MPa. When preparing for reaming, the pressure of the water injection pump station is increased to 4 MPa. The reaming robotic arm (the length that the robotic arm is fully opened is 0.5 m) starts to open and rotate slowly. The change of the rotary pressure gauge of the drilling rig is observed to see if the pointer swings greatly. When the rotation pressure of the drilling rig remains unchanged, the pressure of the pump station is gradually increased, and in this way, the robotic arm is

slowly opened, and it is fully opened when the pressure of the pump station reaches 12 MPa.

- (2) When the pressure of the water injection pump station reaches 12 MPa, the fully opened drill bit opens fully and advances slowly from the reaming position. During the reaming process, we should observe the rotation pressure indication of the drilling rig. During normal reaming, the rotation pressure of the drilling rig is generally 4–8 MPa. When the indication exceeds 10 MPa, we should stop the drilling rig from advancing immediately and make the rig rotate in place by reducing the speed. When the rotating pressure drops below 10 MPa, the hole expands slowly.
- (3) After reaming, the pressure of the water injection pump station is completely unloaded, and the cutter arm is automatically recovered, normally drilled to the next reaming position, and then reamed for the second time so as to realize circular reaming.

### 3. NUMERICAL SIMULATION OF THE GAS DRAINAGE EFFECT OF MECHANICAL CAVITATION DRILLING

A numerical simulation is based on the mining of no. 15 coal seam in the Sijiazhuang coal mine in China. By establishing the mechanical model and using COMSOL Multiphysics software, the gas drainage effect of mechanical cavitation drilling can be analyzed.

**3.1. Governing Equation.** **3.1.1. Coal Deformation Equation.** According to the relationship between displacement and strain of elastic medium after stress, the geometric equation of an isotropic continuous medium is

$$\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i}) \quad (1)$$

where  $u$  is the element displacement,  $m$ .

The study on the mechanical effect of gas on coal and rock shows that free gas will affect the effective stress of coal, and adsorbed gas will affect the deformation and mechanical properties of coal and then affect the stress field. Considering the influence of pore pressure of free gas in coal, the stress balance equation of a dual porous medium can be expressed as

$$\sigma'_{ij} - \gamma_f p_{f,i} - \gamma_p p_{m,i} + f_i = 0 \quad (2)$$

For the adsorbed phase gas, due to the reduction of surface potential energy and coal surface tension after adsorbing gas, the coal body expands and deforms. Considering the deformation caused by adsorption, the relationship between effective stress and strain of coal can be expressed as

$$\sigma'_{ij} = \lambda \varepsilon_v \delta_{ij} + 2G \varepsilon_{ij} - K \varepsilon_v^s \delta_{ij} \quad (3)$$

where  $\lambda$  is the lame constant,  $\lambda = E\nu/((1+\nu)(1-2\nu))$ ;  $G$  is the shear modulus,  $G = E/(2(1+\nu))$ ;  $K$  is the bulk modulus,  $K = E/3(1-2\nu)$ ; and  $\varepsilon_v^s$  is the deformation caused by gas adsorption.

For the deformation caused by gas adsorption on coal, the experiment shows that the deformation is directly proportional to the gas adsorption, and the gas adsorption changes in the form of Langmuir with the increase of gas pressure. Therefore, the adsorption line expansion deformation is expressed as

$$\varepsilon_i^s = \frac{\varepsilon_{Li}^s p}{p + p_L^s} \quad (4)$$

The Drucker–Prager (DP) criterion is adopted as the criterion for yield failure of coal and rock

$$F = \alpha_{DP} I_1 + k_{DP} - \sqrt{J_2} \quad (5)$$

where  $I_1$  is the first invariant of stress tensor,  $J_2$  is the second invariant of stress tensor, and  $\alpha_{DP}$  and  $k_{DP}$  are the matching parameters with the Mohr–Coulomb criterion in the case of plane strain correlation flow rule.

The relationship between them and adhesion and internal friction angle is

$$\alpha_{DP} = \frac{2 \sin \varphi}{\sqrt{3}(3 \pm \sin \varphi)} \quad (6)$$

$$k_{DP} = \frac{6c \cos \varphi}{\sqrt{3}(3 \pm \sin \varphi)} \quad (7)$$

**3.1.2. Gas Migration Control Equation.** As a natural porous medium, the scale and span of voids in coal and rock are large. According to the difference in its influence on mechanical properties and flow mechanism, it is mostly simplified as a dual porous medium containing pore and fracture. Fractures divide the coal body into a large number of coal matrices, and pores exist in the coal matrix. The study on the movement law of gas in the coal matrix shows that it conforms to Fick's diffusion law. The flux formula of mass exchange between the coal matrix and fracture system can be expressed as

$$q = D \vartheta V_m (c_m - c_f) \quad (8)$$

where  $q$  is the diffusion flux, g/s;  $D$  is the diffusion coefficient,  $\text{cm}^2/\text{s}$ ;  $\vartheta$  is the shape factor,  $\text{cm}^{-2}$ ;  $V_m$  is the matrix block volume, mL;  $c_m$  is the gas mass concentration of matrix block, g/mL; and  $c_f$  is the gas mass concentration of fissure, g/mL.

The study of the gas diffusion mechanism in coal shows that the types of gas diffusion in coal mainly include volume diffusion, Knudsen diffusion, and mixed diffusion. It can be considered that the gas mass concentration in the formula is the concentration of free phase gas in pores and fractures, so the gas concentration of free phase in pores in the coal matrix can be expressed as

$$c_m = \frac{M}{RT} p_m \quad (9)$$

where  $p_m$  is the matrix block pore gas pressure, MPa;  $M$  is the molar mass of methane, 16 g/mol;  $R$  is the universal gas constant, 8.314510 J/(mol·K); and  $T$  is the gas temperature, K.

Similarly, the concentration of free phase gas in the fracture can be expressed as

$$c_f = \frac{M}{RT} p_f \quad (10)$$

where  $p_f$  is the gas pressure in fracture, MPa.

The matrix shape factor is directly related to the matrix geometry and scale. For the coal matrix, it is often simplified into three kinds of shape factors: plate, rectangular cylinder, and cube. For the matrix of plate type, its shape factor can be expressed as

$$\vartheta = \frac{\pi^2}{L^2} \quad (11)$$

where  $L$  is the crack spacing.

For coal rock, it is a matrix polymer formed by cutting multiple groups of fractures, and its shape factor can be expressed as

$$\vartheta = \pi^2 \left( \frac{1}{L_x^2 + L_y^2 + L_z^2} \right) \quad (12)$$

where  $L_x$ ,  $L_y$ , and  $L_z$  are the isotropic fracture spacing.

If the coal body is further simplified and regarded as a dual porous medium model with the matrix as a cube, the matrix shape factor can be expressed by eq 13.

$$\vartheta = \frac{3\pi^2}{L^2} \quad (13)$$

Because the measurement of the diffusion coefficient and shape factor is relatively cumbersome, adsorption time is often used to approximate the speed of diffusion in coal-bed methane mining, that is, the time taken for 63.2% of coal gas content to be desorbed. The adsorption time is inversely related to the product of diffusion coefficient and shape factor.

$$\tau = 1/D\vartheta \quad (14)$$

According to the definition of adsorption time, the shorter the adsorption time of coal, the stronger the diffusion and the faster the diffusion process. Substituting the relationship between adsorption time, diffusion coefficient, and shape factor into eq 13, the flux equation for the diffusion and migration of matrix gas to the fracture system can be expressed by eq 15

$$q = \frac{MV_m}{\tau RT} (p_m - p_f) \quad (15)$$

The existing state of gas in the pores of coal generally includes free gas and adsorbed gas, so the average concentration of gas contained in the coal matrix can be expressed by eq 16

$$\bar{c}_m = \frac{Q_{ab} + Q_{fr}}{V_m} = \left( \frac{abp_m}{1 + bp_m} + \frac{\phi_m p_m}{\rho p_0} \right) \cdot \frac{\rho M}{V_M} \quad (16)$$

where  $\bar{c}_m$  is the matrix average gas concentration, g/mL;  $Q_{ab}$  is the adsorbed gas quantity, g;  $Q_{fr}$  is the free gas quantity, g; and  $\phi_m$  is the matrix porosity, %.

The mass conservation equation of gas in the coal matrix is as follows

$$q = -\frac{\partial \bar{c}_m V_m}{\partial t} \quad (17)$$

By combining the above formulas, the variation function of the coal matrix gas pressure with time can be obtained.

$$\frac{\partial p_m}{\partial t} = -\frac{1/\tau \cdot (p_m - p_f)}{\left( \frac{a'b}{1 + bp_m} - \frac{a'b^2 p_m}{(1 + bp_m)^2} + \frac{\phi_m}{\rho p_0} \right) \frac{\rho RT}{V_M}} \quad (18)$$

For coal rock fractures, a large number of studies show that the gas flow mainly follows Darcy's law, that is, the gas velocity in coal has a linear relationship with its pressure gradient

$$v = \frac{k}{\mu} \nabla p \quad (19)$$

where  $k$  is the coal seam permeability, mD and  $\mu$  is the gas dynamic viscosity coefficient,  $1.08 \times 10^{-5}$  Pa·s.

Then, the continuity equation of gas movement can be expressed as

$$\frac{\partial(m_f)}{\partial t} - \nabla \cdot (\rho_g v_g) = q \quad (20)$$

where  $m_f$  is the amount of free gas in the fracture, and it can be calculated by the gas equation.

The right term of the above formula shows that the matrix gas is used as the gas source term in the coal fractures, and the gas mass exchanges with the fractures. Combining the Darcy formula for fracture flow and eq 13, the gas flow continuity equation can be written as

$$\begin{aligned} \phi_f \frac{\partial(p_f)}{\partial t} + p_f \frac{\partial(\phi_f)}{\partial t} - \frac{k}{\mu} \nabla \cdot (p_f \cdot \nabla p_f) \\ - 1/\tau \cdot (1 - \phi_f)(p_m - p_f) \\ = 0 \end{aligned} \quad (21)$$

where  $\phi_f$  is the porosity, %.

Through the gas flow equation, it is not difficult to see that the difficulty of gas flow in coal is mainly determined by the permeability, so the permeability evolution law is very important. The permeability change caused by load change has been characterized by volume stress and damage parameters. In addition, in the process of gas drainage, the gas pressure changes continuously, and the pore pressure of free gas and the deformation caused by adsorbed gas will also affect the fracture permeability. In the past research, many permeability evolution models have been established to describe, including the Palmer–Mansoori (PM) model, Shi–Durucan (SD) model, Cui–Bustin (CB) model, etc.<sup>39–41</sup> The parameters of the PM model are easy to obtain and widely used. Therefore, the PM model is selected to analyze the influence of gas pressure change on permeability. Further, according to the expression of effective stress of coal and the deformation caused by matrix adsorption, the PM model can be improved to

$$\begin{aligned} \phi_f = \phi_{f0} + \frac{(1 + \nu)(1 - 2\nu)}{E(1 - \nu)} (\gamma_f p_f + \gamma_m p_m \\ - (\gamma_f p_{f0} + \gamma_m p_{m0})) - \frac{2(1 - 2\nu)}{3(1 - \nu)} \left( \frac{\varepsilon_{Lv}^s p_m}{p_m + p_L^s} \right. \\ \left. - \frac{\varepsilon_{Lv}^s p_{m0}}{p_{m0} + p_L^s} \right) \end{aligned} \quad (22)$$

The above equations constitute the control equation of coal seam gas movement, in which the fracture porosity and coal permeability are gas–solid coupling parameters, which change with the stress and damage of the coal body.

### 3.2. Establishment and Solution of the Model.

**3.2.1. Establishment of the Model.** Based on the above established control equation of coal seam gas movement after mechanical cavitation, the effect of pressure relief and permeability enhancement and influencing factors are simulated and analyzed by COMSOL Multiphysics software.

COMSOL Multiphysics is a large-scale advanced numerical simulation software for modeling and simulating scientific and engineering problems based on partial differential equations,

which is widely used in scientific research and engineering calculations in various fields. COMSOL Multiphysics software has a powerful interface environment, embedded with rich CAD modeling tools, which can directly perform two-dimensional (2D) and three-dimensional (3D) modeling in the software. Users can easily and freely define the required professional partial differential equations in the graphical interface.

The solid mechanics module and PDE module are used to solve the stress field and gas flow field, respectively, in this paper. To simplify the calculation and analysis, a two-dimensional geometric model of the borehole along the coal seam is established according to the plane strain assumption, as shown in Figure 2. Due to the influence of mechanical

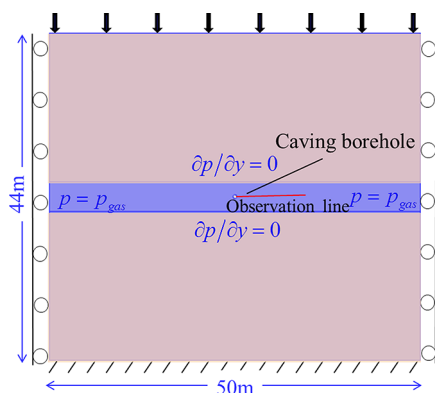


Figure 2. Geometric model and boundary conditions.

cavitation on the coal rock seepage, the mechanical conditions of the model have not been studied too much. The top boundary of the model is the stress boundary, and the load is generated by the gravity of the upper rock mass. The fixed displacement boundary is adopted at the bottom of the model, and the support slip boundary is on both sides. In the flow module, the nonflow boundary is adopted for the roof and floor of the coal seam, and the constant pressure boundary is adopted around the cave-making chamber and both sides of the model coal body.

Model parameters are shown in Table 1.

**3.2.2. Analysis on the Gas Drainage Effect of Mechanical Cavitation.** The gas drainage effect of upward through layer drilling under different cave-making radii and drainage times is shown in Figure 3.

The effective drainage influence radius is an important indicator reflecting the effect of the coal seam gas drainage, which refers to the range within which the coal seam gas pressure of the coal body around the borehole drops to the outburst critical value (0.74 MPa) within a certain drainage time. According to Figure 3, the effective gas drainage influence radius corresponding to different drainage times is obtained, as shown in Table 2.

Under the condition of the same drainage time, the larger the cavitation radius is, the larger the effective influence radius of gas drainage is. For example, with the drainage time being 30 days, when the cavitation radius increases from 0.05 to 0.50 m, the effective gas drainage influence radius increases from 1.00 to 2.20 m, an increase of 1.20 times. For the same cavitation radius, the effective gas drainage influence radius also shows an increasing trend with the increase of drainage time. For example, with the cave-making radius being 0.25 m,

Table 1. Model Parameters

parameters	value	parameters	value
elastic modulus of coal, MPa	3,000.00	original gas pressure, MPa	1.20
Poisson's ratio of coal	0.30	original permeability, m <sup>2</sup>	2.50 × 10 <sup>-17</sup>
bulk density of coal, kg/m <sup>3</sup>	1300.00	original porosity	0.06
coal seam cohesion, MPa	0.90	CH <sub>4</sub> Langmuir volume, m <sup>3</sup> /t	20.00
friction angle in the coal seam, °	30.00	CH <sub>4</sub> Langmuir pressure, MPa <sup>-1</sup>	1.00
critical value of the softening parameter	0.01	relation coefficient with stress, MPa	0.25
elastic modulus of rock mass, MPa	30,000.00	permeability catastrophe coefficient	20.00
cohesion of rock mass, MPa	20.00	critical value of permeability mutation	0.01
Poisson's ratio of rock mass	0.30	maximum volume strain caused by adsorption, %	1.20
friction angle in rock mass, °	40.00	Langmuir pressure, MPa <sup>-1</sup>	1.00
biot coefficient	0.70	gas constant, J/(mol.K)	8.314
apparent density of coal, g/cm <sup>2</sup>	1300.00	CH <sub>4</sub> dynamic viscosity, Pa·s	1.08 × 10 <sup>-5</sup>
coal seam temperature, K	293.00	CH <sub>4</sub> molar mass, g/mol	16.00

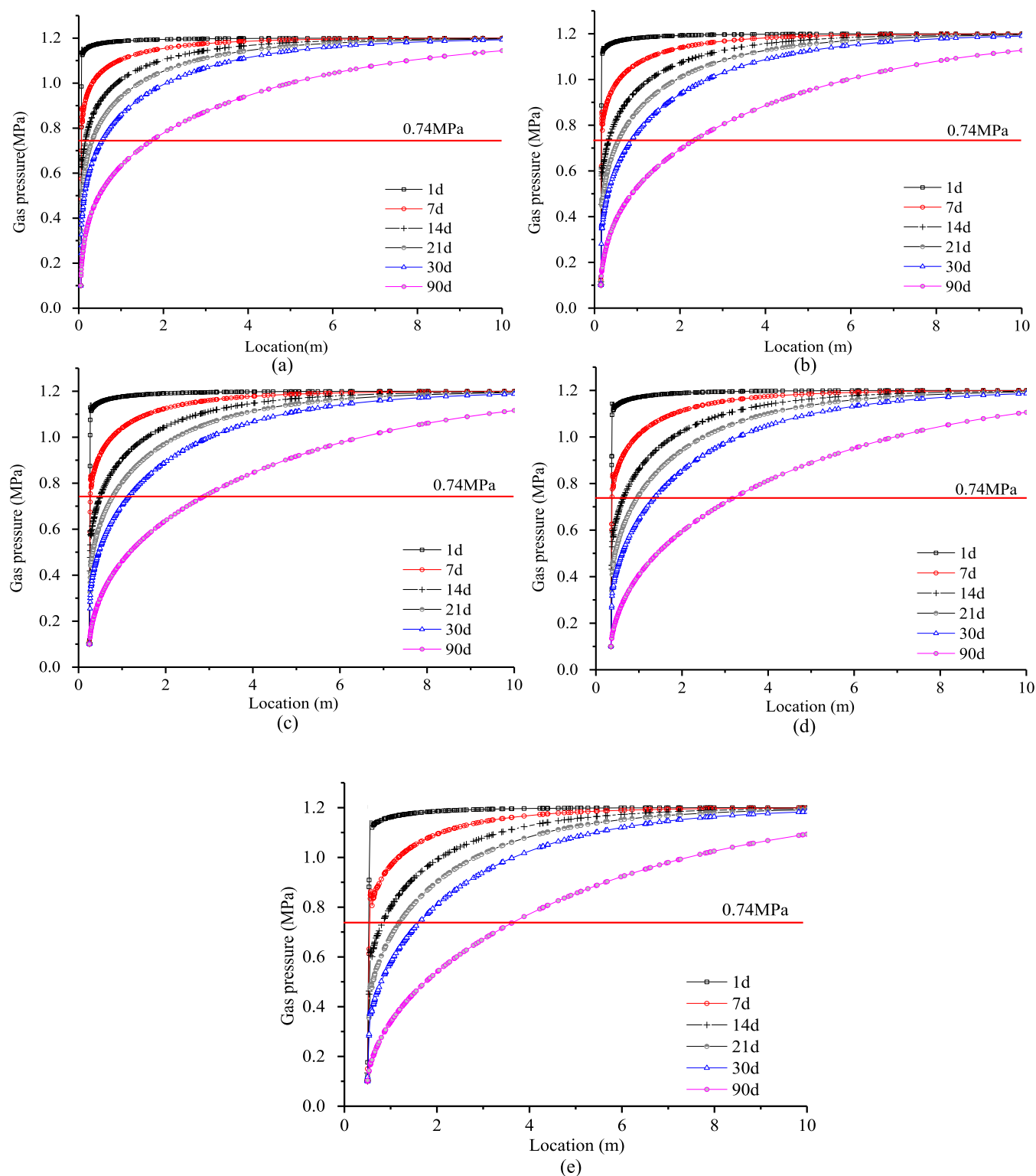
when the drainage time increases from 14 to 21 days, 30 and 90 days, respectively, the effective gas drainage influence radius increases from 0.70 to 1.15, 1.70 and 4.10 m, respectively.

When applying large-diameter mechanical cave-making technology, a large amount of coal was pulled out around the borehole. Finally, a hole with a regular cylindrical shape would be formed, which provides a space for coal expansion, deformation, pressure relief, and displacement. It can be inferred that the fissures in the coal body around the borehole will also proliferate and expand, thus forming a fissure network conducive to the flow of pressure relief gas. That is to say, the process of mechanical cavitation is a process of continuous development of the coal fracture network. The larger the cavitation diameter, the higher the permeability of the coal around the borehole after cavitation.

#### 4. FIELD TEST OF MECHANICAL CAVITATION

The underground test was done in the Sijiazhuang coal mine in the Yangquan mining area of Shanxi province in China (Figure 4). The thickness of the 15# coal seam being mined is 5.12 m, the measured maximum gas pressure is 1.20 MPa, and the measured original gas content is 14.42 m<sup>3</sup>/t. In the past coal mining, several coal and gas outburst disasters occurred, posing a huge threat to employees.

The test working face is the 15114 working face. The gas in the 15114 air inlet roadway is pre-extracted through layer drillings. A group of boreholes is arranged every 4 m in the roadway, with nine boreholes in each group. As shown in Figure 5, for a single drilling hole, all of the coal-penetrating sections with the length being 4.6–9.6 m are mechanically cavitated, and the cavitation diameter is 500 mm. The area of the borehole predrainage is not less than 15 m outside the 15114 air inlet roadway. The borehole diameter should not be less than 113 mm, and the quantities of each group of



**Figure 3.** Variation of gas pressure with time under different cavity radii of upward hole drilling; (a–e) cavitation radius of 50, 150, 250, 350, and 500 mm, respectively.

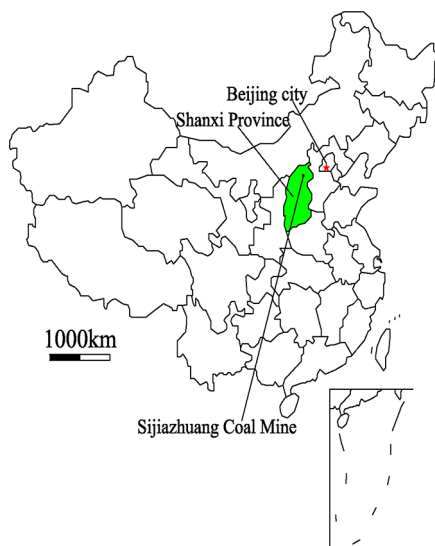
boreholes should be 239 m. The spacing of each group of boreholes is 4 m and it takes about 5 min to make a cave. After statistical analysis, the coal output of mechanical cavitation drilling is about 0.46 t/m.

A comparison of the drainage concentration and purity between mechanical cavitation and ordinary borehole is shown in Figures 6 and 7. The average gas drainage concentration in

the cave-making area can reach about 50%, and the gas drainage concentration can be increased by about two times. The average net amount of gas drainage in the cave-making area can reach 0.38 m<sup>3</sup>/min (within 50 m), and the average net amount of gas drainage in the common drilling area is 0.21 m<sup>3</sup>/min. The net amount of gas drainage in the cave-making area is about 1.8 times that in the common drilling area, as

**Table 2. Relationship between Cavitation Radius and Effective Gas Drainage Influence Radius**

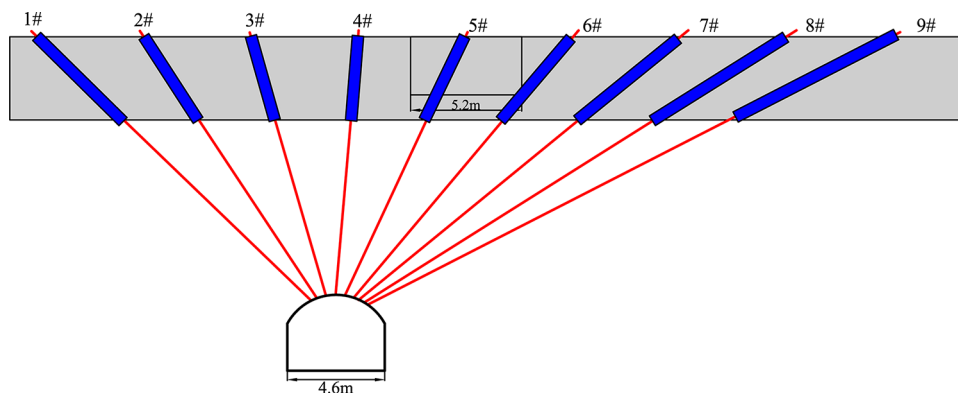
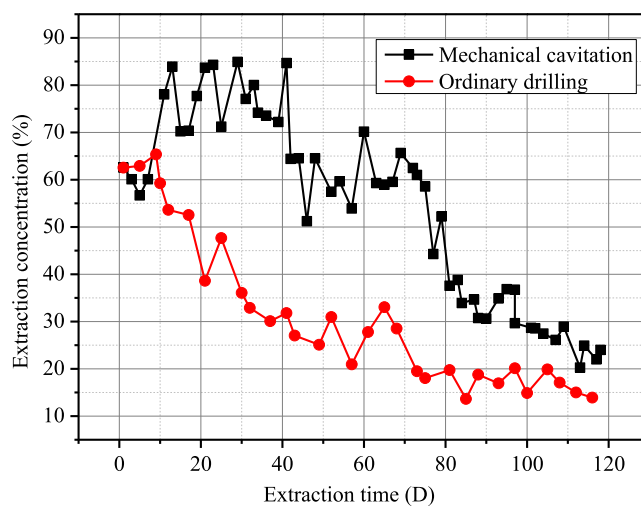
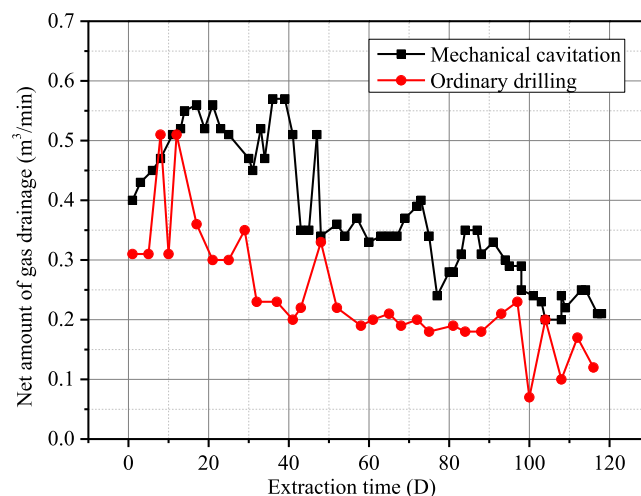
drainage time [d]	cavitation radius [m]				
	0.05	0.15	0.25	0.35	0.50
14	0.40	0.55	0.70	0.95	1.15
21	0.60	0.90	1.15	1.35	1.70
30	1.00	1.35	1.70	1.90	2.20
90	2.70	3.40	4.10	4.35	4.90

**Figure 4.** Test coal mine location.

shown in Figure 4. After five months of gas drainage in the ordinary drilling area, a total of 45,360 m<sup>3</sup> of gas is pumped. After four months of gas drainage in the mechanical cavitation building area, a total of 60,480 m<sup>3</sup> of gas is pumped, which is about 1.3 times the gas drainage in the ordinary drilling area.

## 5. CONCLUSIONS

This paper presents a new permeability improvement technology in a coal seam. According to the numerical simulation results of the gas drainage effect of mechanical cavitation drilling, under the condition of the same drainage time, the larger the cavitation radius is, the larger the effective influence radius of gas drainage is. For the same cavitation radius, the effective gas drainage influence radius also shows an increasing trend with the increase of drainage time.

**Figure 5.** Layout of mechanical hole drilling.**Figure 6.** Comparison of the drainage concentration between mechanical cavitation and ordinary borehole.**Figure 7.** Comparison of the drainage purity between mechanical cavitation and ordinary borehole.

Through the field investigation of large-diameter cave-making technology, it can be seen that the time of single cave-making is about 5 min, and the speed of cave-making is fast. The coal output of a single cave is approximately 0.42 t/m, and the pressure relief effect is obvious. When the measurement

range is 50 m, the average gas concentration for the mechanical cavitation drilling is 50%. The net amount of gas drainage is 0.38 m<sup>3</sup>/min. The net volume of single cycle drainage is 60,480 m<sup>3</sup>. Compared with ordinary drilling, the gas drainage concentration of mechanical cavitation drilling increased by 2 times and the net amount of drainage increased by 1.8 times.

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### Author Contributions

J.L. analyzed the results, L.W. and F.A. conducted the numerical simulation study, and H.C. coordinated the study and helped draft the manuscript. All authors gave final approval for publication.

### Notes

The authors declare no competing financial interest.

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