Research Article

Investigation of the Ultrasonic Stimulation Performance on Permeability Enhancement in Coal Seam: Field Tests and In Situ Permeability Evaluation

Jinbiao Fei,1 Peng Liu,2,3 LongKang Wang4, Fangxiang Zhong,5 Chenglong Xie,2,3 Yongdong Jiang,2,3 Quangui Li,2,3 and Mingyang Liu1

1College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China
2State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing 400030, China
3College of Resources and Safety Engineering, Chongqing University, Chongqing 400030, China
4Institute of Civil-Military Integration, CCID, Beijing 100048, China
5School of Emergency Management and Safety Engineering, China University of Mining and Technology Beijing, Beijing 100083, China

Correspondence should be addressed to Peng Liu; rocliu@cqu.edu.cn and LongKang Wang; wkmit@163.com

Received 20 December 2021; Accepted 18 March 2022; Published 16 April 2022

Academic Editor: Yanan Gao

Copyright © 2022 Jinbiao Fei et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Power ultrasonic-assisted reservoir modification is a promising technique for enhanced coalbed methane recovery. However, the in-situ performance of ultrasound-assisted CBM production has not yet been revealed. In the current study, the in situ antirefection test was conducted with high-power ultrasound ~18 kW in underground coal seam, and the antirefection performance was investigated by measuring the borehole drainage gas data in the field test zone, and then, the in situ permeability change of the target coal seam was evaluated numerically. The result shows that, within 40 days’ drainage after ultrasonic antirefection in coal seam, the average gas concentration of single borehole in the experimental group increased by 81.4%~227.3% than that in control group, the average borehole gas flowrate has a 20%~106% improvement over the control group, and the pure methane production in single borehole increased by about 3.83 times. The permeability inversion indicates that the in situ coal seam permeability has increased by at least 2.36 times after the ultrasound stimulation within the range of 8 m from the ultrasound source.

1. Introduction

Coalbed methane, commonly known as “coal mine gas,” is an unconventional natural gas associated with coal resources and hosted in coal seams and surrounding rocks [1–3]. It is a clean energy with high calorific value, high-quality energy, and chemical raw materials [4–6]. With the “dual carbon” strategic goals of the Chinese government, the coalbed methane industry shoulders the important tasks of ensuring the safe production of coal mines and making up for the clean energy gap [7–9]. It is understood that CBM has high comprehensive utilization value and can be used as power generation fuel, industrial fuel, vehicle fuel, chemical raw material, and residential fuel [10–12]. Relevant studies have shown that the carbon dioxide released by burning CBM with the same calorific value is 50% less than that of oil and 75% less than that of coal. The pollutants produced during combustion are generally only 1/40 of that of oil and 1/800 of that of coal [13, 14]. The extraction and utilization of coalbed methane is also a powerful and effective strategy for preventing and controlling gas accidents in coal mines [15, 16]. Promoting the “mining of gas first and coal mining later” in coal mines can realize the coordinated and efficient development of coalbed methane and coal [17–19].

High gas pressure, high ground stress, high gas content, and low permeability are the main characteristics of coal seams in China [20, 21]. In particular, due to the influence of complex geological movements, the permeability of coal
seams is generally lower than that of other coal-producing countries in the world and belongs to low-permeability coal seams [22–24]. As a result, the effect of direct construction drilling for gas extraction is not good, and certain additional measures need to be taken to increase the methane production from coal seam [25, 26]. Through extensive research, hydraulic technology such as hydraulic fracturing, hydraulic slitting, and high-pressure water jets have basically matured [27–29]. At the same time, noncontact high-energy antireflection technologies such as directional blasting, carbon dioxide blasting, high-pressure air blasting, and physical field excitation are also being used continuously in the field practices [30–33].

Ultrasonic excitation is a kind of excitation technology that strengthens and improves the extraction rate of coalbed methane [34–36]. As early as the 1950s and 1960s, the United States and the former Soviet Union started the research work on ultrasonic treatment of oil layers, and the research data showed the effect of good effect. In the 1990s, Jiang et al. proposed the research of ultrasound stimulation in coal to increase the CBM production [37]. After that, a series of studies was conducted with focusing on the changes in pore structure, desorption and diffusion behavior, and gas permeability of coal before and after ultrasound treatment. With the application of multiple pore characterization techniques, the pore volume, pore connectivity, pore size, and fracture density in coal were observed to be increased after being ultrasonically treated [38–40]. The influence of water moisture on the coal pores caused by ultrasound treatment was studied, and it showed that the water content in coal helps to boost ultrasonic cavitations and has a positive effect on the development of pore structure [41, 42]. The sorption tests illustrated that gas desorption amount from coal powders increased remarkably with ultrasound treatment, and the higher power ultrasound will promote the sorption stimulating performance on coal [43–45]. With the permeability tests, it was found that coal permeability increase significantly after being subjected to ultrasound, and the induced permeability increment was closely related to the time of ultrasound treatment [46, 47]. However, the field application research of ultrasonic antireflection is relatively small, and the effect of antireflection is still unclear.

In this study, the field test high-power ultrasonic antireflection was carried out in the coal mine site, and the antireflection performance was investigated by measuring gas drainage data, and then, the in situ permeability of the coal seam after the antipenetration operation was numerically evaluated. This study can provide insights for the field application and promotion of the ultrasound technology in enhancing gas recovery from coal seam.

2. Mine Site Application of Enhancing CBM Drainage with Ultrasound

2.1. Mine Site Description. The field application of ultrasound fracturing is conducted in Shuanglong coal mine, Shaanxi Province, China. Shuanglong mine is located in the southwest of Huangling mining area, as shown in Figure 1. The coal-bearing strata is the Middle Jurassic Yan’an Formation, and there are 2 layers of coal in this coal field, with an average thickness of 3.1 m. Among the mineable coal seams, #2 is the primary targeted seam with annual production at ~1.2 million tons/yr in Shuanglong mine. The inclination of the coal seam #2 is between 2° and 5°, the original gas content is 1.517–8.695 m³/t, and the coal temperature is at 22–30°C.

The absolute gas emission of Shuanglong mine is 37.05 m³/min, and the relative gas emission of the mine is 8.72 m³/t, which belongs to the high gas mine. Dense borehole model was used for regional gas drainage with borehole depth of ~120 meters in coal seam #2 of Shuanglong mine. Due to the low permeability of the coal seam #2, the gas drainage efficiency is low, and the gas drainage concentration is 4%–7%. In order to eliminate the influence of mining operation and gas drainage operations in the nearby area, the antireflection test zone was set in the coal pillar at the boundary of the mining panel, and the test site was scheduled at the return entry roadway of 112 working face in Shuanglong coal mine, as shown in Figure 1.

2.2. Arrangement of Field Tests. Three groups of boreholes were drilled in this test, including two experiment groups (zone 1 and zone 2) and one control group (zone 0); the distance between the two adjacent test zones exceeds 30 m, as shown in Figure 2. Ultrasonic antireflection equipment mainly includes ultrasound generators, transducers, and adaptive power supply. The ultrasonic generator provides a maximum power of 18 kW and a frequency of 25–40 kHz. The rod ultrasound transducer was placed in the ultrasonic fracturing boreholes in the experiment group, and other boreholes were used for evaluating the ultrasound antireflection effect.

The diameter of ultrasonic antireflection borehole was 133 mm, and the borehole depth was 80 m, which was sealed with cement mortar, and the sealing length was about 30 cm. The diameter of other boreholes was 94 mm, and the borehole depth was 100 m. The polyurethane expansion material was used for sealing, and the sealing length is 6 m. The high-pressure water pipe was connected with the ultrasonic antireflection borehole to inject water into the borehole, which provided the water bath working environment for the ultrasonic transducer and improved the water content in the coal around the borehole. Other boreholes are connected with gas meters and gas concentration measuring devices to observe the borehole drainage data including the gas flow rate and gas concentration during the test; the antireflection effect can be evaluated by comparing the borehole drainage data of the experimental groups and the control group.

After completing the preparations, turn on the ultrasonic generator to radiate the physical field of the coal body, which will change the pore structure of the coal body, and then, change the desorption diffusion and seepage process of the coal, which should change the amount of gas drainage. The gas flow rate and gas concentration of the gas drainage borehole were measured, and the ultrasonic antireflection effect was investigated by comparing the borehole gas data of the experimental group and the control group.
3. Results of Field Tests

3.1. Change of Drainage Gas Concentration. With the recorded drainage concentration data, the change of gas concentration in drainage borehole of both the experimental groups and the control group was plotted, as shown in Figure 3, and the analysis of drainage concentration data is shown in Table 1.

In Figure 3, it shows that, within 40 days of drainage, the average gas concentration of three boreholes of control group would...
changes between 4% and 8%, and the gas concentration of single borehole of experimental group changes between 5% and 37%. The average gas concentration in single borehole of zone 1 and zone 2 is between 11.62% and 21.34%. Compared with the average concentration in the control group boreholes, the average single borehole gas concentration in zone 1 and zone 2 increases by 81.4%~227.3%, and the increment varies depending on the distances from the antireflection borehole. The closer to the antireflection borehole, the greater the gas concentration increase in the borehole. The results show that the gas drainage concentration has increased significantly with the implementation of the ultrasonic antireflection operations.

3.2. Change of Drainage Gas Flowrate. A gas meter was used to measure the instantaneous flowrate, the change of gas flowrate in drainage borehole of both the experimental groups and the control group was plotted, as shown in Figure 4, and the analysis of drainage concentration data is listed in Table 2.

As shown in Figure 4 and Table 2, within 40 days of drainage, the average gas flowrate in single borehole of the control group is about 0.041 m³/min, the average gas flowrate in single borehole of zone 1 is between 0.0492 and 0.0939 m³/min, which is an increment of 20%~102%; and in zone 2, the average gas flowrate is between 0.0757 and 0.0843 m³/min, that is, an 85%~106% improvement over the control group. The obtained data indicates that gas flow rate in boreholes in the experimental groups is much larger than that in the control group, which infers that ultrasonic stimulation alters the coal pore structure and improve the gas deliverability of coal.

3.3. Change of Pure Methane Flowrate. Due to the roadway excavation and borehole drilling operations, there exists a well-developed fracture network in coal surrounding the drainage borehole. The air in roadway space flows into the borehole through the coal fractures and mixes with the methane released from coal, forming the borehole drainage gas with a certain concentration [48]. The pure methane flowrate in borehole can be estimated with the gas flowrate and gas concentration data measure in the field test. The change curves of pure methane flowrate in single borehole are shown in Figure 5, and the data analysis is listed in Table 3.

As shown in Figure 5 and Table 3, within 40 days of drainage, the average pure methane flowrate in single borehole of control group is about 0.002673 m³/min. For the drainage boreholes in zone 1 and zone 2, the pure methane flowrate in single borehole changes between 0.005758 and 0.01769 m³/min and 0.00992 and 0.01505 m³/min, respectively. In general, the pure methane flow of single borehole in the experimental groups...
Table 2: Data analysis of gas flowrate in borehole.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Borehole</th>
<th>Distance from the antireflection borehole</th>
<th>Average gas flowrate</th>
<th>Increment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 0</td>
<td>Average</td>
<td>/</td>
<td>0.041 m³/min</td>
<td>/</td>
</tr>
<tr>
<td></td>
<td>#1</td>
<td>8 m</td>
<td>0.0492 m³/min</td>
<td>20%</td>
</tr>
<tr>
<td>Zone 1</td>
<td>#2</td>
<td>4 m</td>
<td>0.0791 m³/min</td>
<td>93%</td>
</tr>
<tr>
<td></td>
<td>#3</td>
<td>2 m</td>
<td>0.0829 m³/min</td>
<td>102%</td>
</tr>
<tr>
<td></td>
<td>#1</td>
<td>8 m</td>
<td>0.0757 m³/min</td>
<td>85%</td>
</tr>
<tr>
<td>Zone 2</td>
<td>#2</td>
<td>4 m</td>
<td>0.0836 m³/min</td>
<td>104%</td>
</tr>
<tr>
<td></td>
<td>#3</td>
<td>2 m</td>
<td>0.0843 m³/min</td>
<td>106%</td>
</tr>
</tbody>
</table>

Figure 4: Change curves of the gas flowrate in drainage borehole.

Figure 5: Change curves of the pure methane flowrate in drainage borehole.
has increased by 4.33 times over that in control group during the first 40 days of drainage. It shows that ultrasonic stimulation can improve the drainage efficiency and shorten the predrainage time, which will reduce the cost of gas disaster management and drained gas utilization.

4. The In Situ Permeability Change in Coal Seam with Ultrasound Stimulation

The increase in borehole gas concentration and flow rate is due to the change of gas flow flux in the coal seam, which is closely related to the coal permeability induced by ultrasound stimulation. A mechanism-based model to modeling borehole gas drainage considering air leakage process (as shown in Figure 6) was applied to investigate the permeability change in coal seam with ultrasound stimulation, as shown in Equation (1). The specific introduction of the gas drainage model can be referred to the literature [19].

\[
\begin{align*}
\frac{\partial}{\partial t}(\varphi_i p_i) &= \frac{1}{y \rho (\varphi_i p_i)} \left( \frac{k_i \partial p_i}{\partial x} + \frac{1}{y \rho (\varphi_i p_i)} \left( \frac{\partial}{\partial y} \left( \frac{k_i \partial p_i}{\partial y} \right) \right) + \frac{R_T p_i}{m_i \rho (\varphi_i p_i)} \frac{\partial q_{m}}{\partial t} \right), \\
\frac{\partial}{\partial t}(\varphi_{i2} p_{i2}) &= \frac{1}{y \rho (\varphi_{i2} p_{i2})} \left( \frac{k_{i2} \partial p_{i2}}{\partial x} + \frac{1}{y \rho (\varphi_{i2} p_{i2})} \left( \frac{\partial}{\partial y} \left( \frac{k_{i2} \partial p_{i2}}{\partial y} \right) \right) \right), \\
G(\rho_m) \frac{\partial p_m}{\partial t} &= \frac{\lambda_m}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial p_m}{\partial r} \right), \\
q_m &= \frac{3A_m \rho p_m}{R_m}, \\
P_i &= P_{i1} + P_{i2}.
\end{align*}
\]

(1)

The pure methane flowrate in drainage borehole can be expressed as

\[
\text{Methane rate} = \sum_{i=0}^{M+1} m_i \rho_i \frac{2}{R_D} \frac{\pi x_{i+1} - x_{i-1}}{2} \frac{1}{\mu} (\frac{k_i}{p_n(i + M + 1)} - \frac{k_i}{p_n(i)}),
\]

(2)

where \(m_i\) is the methane molar mass and \(R_D\) is the drainage borehole radius, m.

The gas flow rate in the drainage borehole can be expressed as

\[
\text{Gas rate} = \sum_{i=0}^{M+1} m_i \rho_i \frac{2}{R_D} \frac{2 \pi x_{i+1} - x_{i-1}}{2} \frac{1}{\mu} \frac{k_i}{p_n(i + M + 1)} - \frac{k_i}{p_n(i)}.
\]

(3)

The methane concentration in the drainage borehole can be calculated by

\[
\text{Gas concentration} = \frac{\text{Methane rate}}{\text{Gas rate}}.
\]

(4)

The symbols used in the Equations (1)–(4) are listed and explained in Table 4, and the specific numerical calculation process of gas drainage with in-seam borehole can be referred to the literature [19].

Parameter inversion was used to estimate the permeability in coal seam, in which the calculation results of the theoretical model (Equation (1)) are fitted with the gas drainage data in single borehole to estimate the permeability. Table 5
and Figure 7 show the permeability inversion results in coal surrounding the single borehole in the experimental groups and control group.

With the measured data of drainage gas concentration and gas flow rate in single borehole, the gas permeability in coal around the borehole is obtained using the parameter inversion approach. In the control test region, the average gas permeability is estimated to be $8.537 \times 10^{-14}$ m$^2$, while in the experimental region, the gas permeability is estimated to be $2.023 \sim 6.456 \times 10^{-13}$ m$^2$ in zone 1 and $3.532 \sim 5.77 \times 10^{-13}$ in zone 2, as listed in Table 5. The results show that the in situ gas permeability in coal has increased by at least 2.36 times within 8 meters of the antireflection borehole, and within 2 meters of the antireflection hole, the increment in permeability will exceed 6.73 times, as shown in Figure 7. This should be due to the conductive properties of ultrasonic waves in porous media. In the vicinity of the ultrasonic source, the ultrasonic energy is higher, which can modify the pore structure in coal more efficiently, and is more beneficial to improve the coal permeability. It is inferred that developing more efficient ultrasonic transducer and generator or weakening the ultrasonic conduction attenuation could be one of the keys to further improve the antireflection performance with ultrasound.

5. Conclusions

The ultrasonic excitation technology is a promising method for anhydrous fracturing in the unconventional gas
reservoirs. In the current study, the high-power (18 kW and 25 kHz) ultrasonic antireflection equipment was used to successfully implement the field test of multisegment antireflection in in-seam borehole, and the changes of gas data in drainage boreholes were measured to investigate the antireflection performance. The main conclusions are drawn:

(1) Within 40 days’ drainage after the ultrasonic antireflection operations in coal seam, the average gas concentration of single borehole in the experimental group increased by 81.4%~227.3% than that in control group, the average borehole gas flowrate has 20%~106% improvement over the control group, and the pure methane production in single borehole increased by about 3.83 times. The results show the remarkable performance of powder ultrasound in promoting the in situ gas drainage

(2) Coal pore dilation and enhanced connectivity will improve the gas permeability in coal. Permeability inversion study has shown that the in situ gas permeability of coal has increased by at least 2.36 times within 8 meters of the antireflection borehole after ultrasound stimulation. The research conducts the field application of ultrasonic antireflection in coal seam and initially illustrates the in-site implementability and effectiveness of the ultrasonic antireflection in enhancing methane extraction. Therefore, the ultrasound technology is recommended to be an alternative method for hydraulic fracturing of coal seams

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

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

References


