Distribution Relationship of Pore Pressure and Matrix Stress during Hydraulic Fracturing

Xinglong Zhao and Bingxiang Huang*

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ABSTRACT: When hydraulic fracturing is utilized to eliminate coal and gas outbursts and rockburst in dynamic disaster coal−rock formations, the stress disturbance of hydraulic fracturing may have negative effects such as causing local stress concentration. The method of combining physical model experiments and numerical simulations is adopted to study the distribution relationship of pore pressure and matrix stress during hydraulic fracturing. The research results show that the pore pressure and matrix stress gradually attenuate farther away from the hydraulic fracture in the process of hydraulic fracturing. The attenuation rate of matrix stress is less than that of pore pressure. The range of the matrix stress disturbance zone is larger than the range of the pore pressure disturbance zone. With the increase of pumping time, the increasing speed of the matrix stress disturbance zone is greater than that of the pore pressure disturbance zone. This indicates that the squeezing force on both sides of the hydraulic fracture increases correspondingly with the increase in crack opening, which causes the range and magnitude of the matrix stress disturbance zone to increase gradually. The stress disturbance zone around the hydraulic fracture includes the pore pressure disturbance zone and the matrix stress disturbance zone. In the pore pressure disturbance zone, the pore pressure and the matrix stress increase and interact at the same time, which together lead to the deformation and failure of coal and rock mass. The relationship between the pore pressure and the matrix stress in this region conforms to the natural logarithmic attenuation relationship. Outside the pore pressure disturbance zone, the deformation and failure of coal and rock mass are mainly caused by the matrix stress effect.

1. INTRODUCTION
Hydraulic fracturing technology is first applied in the petroleum industry to improve the permeability of oil and gas reservoirs and enhance the effect of oil and gas extraction.1−3 In recent years, it has been widely used in the coal industry. Significant results have been achieved in the use of hydraulic fracturing technology for hard roof control, hard top coal weakening, coal seam permeability improvement, coal and gas outburst prevention, and rockburst prevention.4−10

The principle of eliminating coal and gas outbursts by hydraulic fracturing is to inject high-pressure water into the coal seam. Artificial fractures would be formed to increase the coal seam permeability. Therefore, the gas pressure and content of the coal seam will be reduced, and the gas drainage effect can be improved. Consequently, the coal and gas outbursts can be eliminated.11−13 The principle of eliminating rockburst by hydraulic fracturing mainly includes two aspects, stress transfer and surrounding rock weakening. On the one hand, high stress is transferred to the goaf through directional hydraulic fracturing, which can achieve the purpose of pressure relief. On the other hand, the surrounding rock can be weakened through water absorption and wetting of the coal−rock formation. Finally, the risk of rockburst in coal−rock formation can be reduced.14−16

The stress magnitude and distribution around the hydraulic fractures will be changed in the process of hydraulic fracturing, which is called the “stress disturbance” effect of hydraulic fracturing.17,18 This phenomenon is called stress shadowing in the oil and gas industry,19 and there are many research studies on this topic. Stress shadowing affects the subsequent fractures by the change of the stress field; in particular, mostly increased minimum principal stress at the area of subsequent fracturing. This behavior accumulates as the fracturing phase progresses. Hydraulic fractures generated in such altered stress fields are shorter and compact with the orientation deviating significantly from the far-field maximum horizontal stress orientation.20 The stress shadow effect is mainly used to describe the stress increase in the region surrounding the fracture. If a second hydraulic fracture is located in the stress shadow and is parallel to an existing open fracture, it will produce closure stress higher than the original in situ stress. As a result, it
requires a higher pressure to propagate the fracture. The fracture has a shorter length, narrower width, and the orientation of propagation deviates from the maximum principal stress direction.

Several theoretical models have been proposed to describe the stress shadow effect of hydraulic fracturing. The stress distribution caused by the internal crack opening of an elastic solid under the pressure applied to its surface is analyzed. The stress distribution in the region of an oblate elliptical crack in an elastic solid is also analyzed, and the existence of the stress shadow effect is confirmed. In subsequent studies, it was found that the stress shadow effect can promote crack propagation and form a more complex fracture network. On the other hand, it has also been observed that the stress shadow effect can inhibit the growth of local cracks and even prevent the formation of cracks.

The stress shadow effect alters the magnitude and orientation of the principal stress and can affect the fracture geometry, length, aperture, height, and propagation direction of the crack, which is also confirmed in the field engineering applications. Stress shadow has a significant impact on fracture orientation and fracture length under multicluster perforation fracturing. It can inhibit the expansion of adjacent fractures as well as lead to the divergence of surrounding fractures. In the multwell hydraulic fracturing operation of tight reservoir, the stress shadow effect between multiple wells will affect the development of the hydraulic fracturing networks. In the sequential fracturing of multiple wells, it was found that the obvious interaction between the stress superposition zone and adjacent cracks affects the propagation and spatial morphology of cracks. The stress shadow effect under multicluster simultaneous fracturing is more intense than that under sequential fracturing. Especially in the late stage of fracturing, due to the simultaneous propagation of multiple fractures and the induction of stress field disturbance in a large range, the stress superposition zones appear one after another. The stress shadow effect is larger when applied to unfractured/intact regions of the reservoir. The effect is less when applied to a region where fracturing already took place. A comprehensive numerical study of stress shadow in three-dimensional hydraulic fracturing is carried out. Stress shadow and key influencing factors are investigated for four different scenarios of hydraulic fracturing with or without inclusion, singly or simultaneously. It is demonstrated that the shadow mechanism of hydraulic fractures varies depending on the applied hydraulic pressure magnitude. Stress shadow prediction equations for stress anisotropy, Poisson’s ratio, aspect ratio, and hydraulic pressure are proposed to quantify the stress shadow size in hydraulic fracturing arising in gas shales.

At present, research on stress disturbance of hydraulic fracturing mainly pays attention to the change of matrix stress. In contrast, changes in pore pressure have received almost no attention. The coal–rock formation is a permeable porous medium. During the hydraulic fracturing process, the pressure water penetrates to the surrounding rocks on both sides of the hydraulic fracture, which changes the initial pore pressure distribution. Therefore, the pore pressure and matrix stress of the surrounding rock will increase simultaneously during hydraulic fracturing. The stress disturbance includes pore pressure disturbance and matrix stress disturbance. The distribution relationship of pore pressure and matrix stress is not clear.

When eliminating coal and gas outbursts and rockburst by hydraulic fracturing, the stress disturbance effect of hydraulic fracturing may cause the pore pressure of the outburst coal seams to rise rapidly or produce stress concentration in coal–rock formation with rockburst tendency. There is a potential danger of inducing outbursts and rockburst. At present, hydraulic fracturing is carried out to eliminate outbursts and rockburst in coal and rock formations with dynamic hazard risk. Field technicians just know that injecting high-pressure water into the coal and rock formations will be effective in subsequent outburst elimination and rockburst prevention. However, less attention is paid to the possible negative effects of stress disturbance during hydraulic fracturing, which leads to a certain degree of blindness in the implementation of field hydraulic fracturing. Therefore, it is urgent to study the
distribution relationship of pore pressure and matrix stress in the process of hydraulic fracturing so that when hydraulic fracturing is carried out in coal–rock formation with dynamic hazard risk in underground coal mines, a reasonable hydraulic fracturing pump injection process can be designed to avoid potential risks according to the specific engineering background.

Based on the previous study on the basic law of stress disturbance during hydraulic fracturing, this paper combines the experimental and numerical simulation to analyze the distribution relationship of the pore pressure and matrix stress during hydraulic fracturing. Finally, a preliminary zoning control principle of stress disturbance during hydraulic fracturing will be proposed, which will provide a more comprehensive theoretical basis for eliminating coal and gas outbursts and rockburst by hydraulic fracturing in underground coal mines.

2. PHYSICAL MODEL EXPERIMENT

2.1. Experimental Program. A large-scale true triaxial hydraulic fracturing experimental system is utilized to perform the physical model experiment on the distribution relationship between pore pressure and matrix stress (Figure 1). The experimental system can realize servo-controlled loading of confining pressure and water pressure. The maximum confining pressure loading can reach 31.5 MPa. The maximum water pressure loading can reach 63 MPa. A cement mortar sample with a size of 500 mm × 500 mm × 500 mm is used to simulate coal–rock mass. Twelve pore pressure sensors and 12 strain bricks are embedded into the sample according to the layout design plan (Figure 2). The dynamic change process of pore pressure and matrix stress inside the sample during hydraulic fracturing can be monitored in real time. The effect of temperature on stress during hydraulic fracturing is not considered. The distribution relationship of pore pressure and matrix stress during hydraulic fracture propagation can be analyzed.

The engineering background of this paper is coal and rock formations with dynamic disasters. It includes both coal seams and rock formations. The research is aimed at the core common problems of hydraulic fracturing in coal and rock formations with dynamic disasters. The reason that utilizes cement mortar test blocks to simulate coal and rock layers is mainly based on two considerations. First, the development of original fissures in natural coal and rock samples will affect the stress disturbance during hydraulic fracturing. Based on the
principle of single-factor analysis, the experiment uses cement mortar samples with relatively good homogeneity. Second, the sensor cannot be prefabricated inside the natural coal and rock sample. In contrast, it can be prefabricated inside the cement mortar. By adjusting the ratio of cement, sand, and water, the physical and mechanical properties of cement mortar samples are similar to real coal and rock.

The pore water pressure sensor is processed by Fuyang Jincheng Testing Instrument Factory in China. The probe diameter is 13 mm and the length is 15 mm. The measurement accuracy is less than or equal to 0.3% F-S. The strain brick is prepared by the same ratio of cement mortar material with the hydraulic fracturing experimental sample, ensuring that the physical–mechanical properties of strain bricks are consistent with the experimental sample. The size of the strain brick is 30 mm × 30 mm × 30 mm. Three strain gauges are arranged on the strain brick along three principle stress load directions to monitor the strain variation separately. The sensitivity of the strain gauge is 2.0 ± 1% and the strain limit is 20 000 μm/m.

During the experiment, a static resistance strain gauge is used to collect the data monitored by the pore pressure sensor and the strain brick. The collection frequency is set to 1 Hz.

Figure 3. Hydraulic fracture morphology: (a) overall profile, (b) maximum principal stress surface, and (c) minimum principal stress surface.

Figure 4. Variation of pore pressure and matrix stress during hydraulic fracturing.
Figure 5. Distribution of pore pressure and matrix stress around the hydraulic fractures: (a) at the front of the hydraulic fracture tip and (b) on both sides of hydraulic fracture.

The collected strain signal is converted into the final pore pressure value by formula 1

\[ P_w = k \times \epsilon \]  

(1)

where \( P_w \) is the pore pressure, MPa, \( k \) is the calibration parameter of the pore pressure sensor, and \( \epsilon \) is the measured strain.

Since the deformation around the hydraulic fracture is complex, it is affected by the deformation coordination of the strain bricks and the sample. The transformation method of strain and stress is simplified and handled by Hooke’s law. At the same time, it is specified that the tensile stress is positive and the compressive stress is negative.

\[ P_m = E \times \epsilon \]  

(2)

where \( P_m \) is the matrix stress, MPa, \( E \) is the elastic modulus of the strain brick, and \( \epsilon \) is the measured strain value, 10\(^{-6}\).

2.2. Results and Analysis. After the experiment, the sample is taken out from the experimental loading frame. The sample is split into two parts along the maximum principal stress. A contoured oval hydraulic fracture can be observed, as well as the pore pressure sensors and strain bricks, on the hydraulic fracture surface. Then, the sample is split into four parts along the minimum principal stress. The pore pressure sensors and strain bricks can be observed on the surface that is perpendicular to the hydraulic fracture surface (Figure 3).

The dynamic change process of pore pressure and matrix stress at the measuring point inside the sample during hydraulic fracturing is shown in Figure 4. As the pumping time increases, the pore pressure and matrix stress fluctuate synchronously with the water pressure, which is the stress disturbance effect of hydraulic fracturing. The changing trend of pore pressure and matrix stress is consistent with water pressure.

The distribution relationship between the pore pressure and the matrix stress at the front of the hydraulic fracture tip and both sides of the hydraulic fracture is shown in Figure 5. The pore pressure and matrix stress distribution at the same time are comparatively analyzed. It is found that the matrix stress increases correspondingly where the pore pressure increases. They gradually decay exponentially along the direction away from the hydraulic fracture. The attenuation rate of the matrix stress is less than the attenuation rate of the pore pressure, which means that the range of the matrix stress disturbance zone at the front and both sides of the hydraulic fracture is larger than the range of the pore pressure disturbance zone.

The rock rupture during hydraulic fracturing is a result of the combined effect of pore pressure and matrix stress. It is closely related to the interaction between pore pressure and matrix stress (fluid–solid coupling effect). Since the physical model experiment can only embed a limited number of pore pressure sensors and strain bricks, the data points for monitoring are very limited. In addition, the monitoring result is affected by the coupling effect of the sensor and the mortar. It is difficult to quantitatively analyze the distribution relationship of the pore pressure and the matrix stress around the hydraulic fracture during the fracturing process. The numerical simulation can obtain the change and distribution of pore pressure and matrix stress over time at all points in the domain. Therefore, based on the physical model experiments, the distribution relationship between the pore pressure and matrix stress around the hydraulic fracture during the fracturing process is further analyzed with numerical calculation methods.

3. NUMERICAL SIMULATION

The combined finite discrete element method (FDEM) numerical calculation method is used to study the relationship of pore pressure and matrix stress during hydraulic fracturing. The numerical model does not consider the structural effects of coal–rock formation, such as internal joints and natural fractures in the coal–rock formation.

3.1. FDEM Numerical Calculation Principle. In the FDEM, the continuum is discretized into three-node triangular elements and four-node interface elements with no thickness initially embedded on the common side of adjacent triangular elements. The constant strain linear elastic triangle element is initially embedded on the common side of adjacent triangular elements and four-node interface elements with no thickness. When a fluid force is applied to the interface element, it is defined and is handled by Hooke’s law. At the same time, it is specified that the tensile stress is positive and the compressive stress is negative.

\[ P_m = E \times \epsilon \]  

(2)

where \( P_m \) is the matrix stress, MPa, \( E \) is the elastic modulus of the strain brick, and \( \epsilon \) is the measured strain value, 10\(^{-6}\).

The nonlinear fracture mechanics is used to simulate the rock rupture during hydraulic fracturing is a result of the interaction between pore pressure and matrix stress (fluid–solid coupling effect). Since the physical model experiment can only embed a limited number of pore pressure sensors and strain bricks, the data points for monitoring are very limited. In addition, the monitoring result is affected by the coupling effect of the sensor and the mortar. It is difficult to quantitatively analyze the distribution relationship of the pore pressure and the matrix stress around the hydraulic fracture during the fracturing process. The numerical simulation can obtain the change and distribution of pore pressure and matrix stress over time at all points in the domain. Therefore, based on the physical model experiments, the distribution relationship between the pore pressure and matrix stress around the hydraulic fracture during the fracturing process is further analyzed with numerical calculation methods.
the fracture tip reaches the tensile strength of the material, a fracturing process zone (FPZ) will be formed in the front of the fracture tip (Figure 6a). The horizontal axis represents the fracture tip development direction and the vertical axis represents the normal bonding stress of the fracture tip. The material force in this region shows a nonlinear behavior. Although the material in the fracturing process zone has been damaged, it can still transmit the load to the fracture wall. In the FDEM, assuming that the fracture surface coincides with the edge of the triangular element, the fracturing process zone is characterized by the four-node cohesive crack element (Figure 6b). According to the local stress and deformation

Figure 6. Numerical calculation principle of the FDEM: (a) theoretical fracturing process zone model (PFZ), (b) numerical representation of the theoretical FPZ model in the FDEM, and (c) fracture model implemented in the FDEM.

Figure 7. Numerical model for the relationship of pore pressure and matrix stress.
field, the crack element will yield and fail. There are three failure modes, namely, mode I tensile failure, mode II shear failure, and mixed-mode I–II failure,\(^{40,42}\) which are shown in Figure 6c. For the mode I tensile failure graph, the horizontal axis represents the opening of the fracture tip and the vertical axis represents the tensile stress of the fracture tip. For the mode II shear failure graph, the horizontal axis represents the tangential slip distance between the fracture units and the vertical axis represents the shear stress of the fracture tip. For the mixed-mode I–II failure graph, the horizontal axis represents the opening of the fracture tip and the vertical axis represents the tangential slip distance between the fracture units.

3.2. Numerical Simulation Scheme. The geometric size of the model is set as a block of 200 mm × 200 mm to eliminate the influence of the boundary effect of the model on the propagation of hydraulic fractures. A mesh refinement area of 80 mm × 80 mm is set within the range of the fracture propagation. The mesh size is 0.5 mm. The influence of borehole size on the near-well area is ignored in the model. The fluid will be injected through the point in the middle of the model. An anisotropic stress field is applied to simulate the in situ stress, and the boundary conditions are displacement constraints. It is assumed that the coal–rock formation is an anisotropic and homogeneous material (Figure 7).

The model loading stress field is the same as the physical model experiment. The maximum principal stress \(\sigma_1\) is 12.5 MPa, the minimum principal stress \(\sigma_3\) is 7.5 MPa, the fluid bulk modulus is \(5 \times 10^7\) Pa, the kinematic viscosity is \(1.004 \times 10^{-6}\) m\(^2\)/s, and the pumping rate is 0.4 L/s. The input parameters of the model are shown in Table 1.

![Figure 8. Variation of pore pressure and matrix stress at 0.4 m away from fracture during hydraulic fracturing.](https://doi.org/10.1021/acsomega.1c04268)

Table 1. Input Parameters for the FDEM Model

| parameters                        | value       |
|-----------------------------------|-------------|
| density (g/cm\(^3\))              | 2.67        |
| Young’s modulus (GPa)             | 20.00       |
| Poisson’s ratio                   | 0.24        |
| friction coefficient (MPa)        | 37.06       |
| cohesive (MPa)                    | 10.00       |
| tensile strength (MPa)            | 11.57       |
| mode I fracture energy (N/m)      | 172.00      |
| mode II fracture energy (N/m)     | 1720.00     |
| permeability (m\(^2\))            | \(2.2 \times 10^{-12}\) |

3.3. Simulation Result Verification. The change curve of pore pressure and matrix stress at 0.4 m on both sides of the hydraulic fracture during fracturing is shown in Figure 8. It can be seen that the pore pressure and matrix stress on both sides of the hydraulic fracture fluctuate synchronously with the pumping fluid pressure, that is, the stress disturbance effect of fracturing, which is consistent with the monitoring results in the physical model experiment. It shows that the numerical simulation results are credible.

The hydraulic fracture propagation process and the distribution of pore pressure and matrix stress at different times during the fracturing process are shown in Figure 9. With the initiation of hydraulic fractures, the pore pressure and matrix stress state around the hydraulic fracture change. The pore pressure and horizontal matrix stress on both sides of the hydraulic fracture show an elliptical distribution with the fracture as the major axis. In addition, with the propagation of hydraulic fractures, the disturbance zone of pore pressure and matrix stress continues to expand.

4. RELATIONSHIP AND DISTRIBUTION VARIATION OF PORE PRESSURE AND MATRIX STRESS

4.1. Relationship between Pore Pressure and Matrix Stress. The distribution relationship between the pore pressure and the matrix stress on both sides of the hydraulic fracture at 10 s is shown in Figure 10, which shows that the matrix stress increases at the position where the pore pressure increases. With the increase of the distance from the hydraulic fracture, the pore pressure and the matrix stress attenuate exponentially, and the attenuation rate of the matrix stress is less than the attenuation rate of the pore pressure. The distribution and the relationship between the pore pressure and the matrix stress around the hydraulic fracture obtained by the numerical simulation are consistent with the results of the physical experiment. It indicates that the numerical simulation results are credible. Therefore, the numerical simulation data will be used to quantitatively analyze the relationship between the pore pressure and the matrix stress around the hydraulic fracture during the fracturing process.

The areas on both sides of hydraulic fractures are divided into stress disturbance zone and undisturbed zone. The stress disturbance zone includes the pore pressure disturbance zone and the matrix stress disturbance zone. The range of the matrix stress disturbance zone is larger than the pore pressure disturbance zone. In the pore pressure disturbance zone, the pore pressure and the matrix stress interact and influence each other. Due to the increase in pore pressure, the pore structure is swelled and deformed, which squeezes the matrix and causes the matrix stress to increase. Meanwhile, after the hydraulic fracture initiation, the squeezing of the high-pressure water in the fracture causes the fractures to open. The two sides of the hydraulic fracture are squeezed, which causes the matrix stress and pore pressure to increase. Therefore, in the pore pressure disturbance zone, the increase in matrix stress is mainly caused by the increase in pore pressure and the extrusion formed by the opening and movement of hydraulic fractures. Outside the pore pressure disturbance zone, the increase in matrix stress is mainly caused by the continuous deformation of the matrix.

The relationship between the pore pressure and the matrix stress in the pore pressure disturbance zone on both sides of the hydraulic fracture is shown in Figure 11. It can be seen that...
the higher the pore pressure, the higher the matrix stress. As the pore pressure decreases, the matrix stress is correspondingly smaller, and the decay rate gradually decreases. The changing relationship of the pore pressure and the matrix stress on both sides of the hydraulic fracture conforms to the natural logarithmic attenuation relationship (eq 3)

$$\sigma_x = \ln(a + bP)$$

where $\sigma_x$ is the matrix stress on both sides of the hydraulic fracture perpendicular to the direction of fracture propagation, $P$ is the pore pressure on both sides of the hydraulic fracture, $a$ is the parameter related to the initial matrix stress, and $b$ is the parameter related to permeability. The larger the permeability, the greater the pore pressure at the same distance from the hydraulic fracture and the greater the corresponding matrix stress disturbance.

4.2. Distribution Variation of Pore Pressure and Matrix Stress with Pump Injection Time. The distribution of pore pressure and matrix stress on both sides of hydraulic fractures at different pumping times is shown in Figure 12. As the pumping time increases, the propagation range of hydraulic fractures increases and the range of stress disturbance zones on both sides of the fractures increases accordingly. The increasing speed of the matrix stress disturbance zone is greater than the increasing speed of the pore pressure disturbance zone. It shows that as the pumping time increases, the crack opening increases. The squeezing force on both sides increases correspondingly, which causes the matrix stress in the stress disturbance zone to gradually increase and the scope gradually expands.

5. DISCUSSION

The conceptual diagram of the distribution range of the stress disturbance zone of hydraulic fracturing is shown in Figure 13. From the fracturing section to the outside, the boundary of the hydraulic fracture zone, the boundary of the pore pressure disturbance zone, the boundary of the matrix stress disturbance zone, and the undisturbed zone are in sequence. The stress disturbance zone around the hydraulic fracture includes the pore pressure disturbance zone and the matrix stress disturbance zone.
disturbance zone. The range of the matrix stress disturbance zone is larger than that of the pore pressure disturbance zone.

The pore pressure and the matrix stress increase at the same time and interact in the pore pressure disturbance zone, which together leads to deformation and destruction of coal–rock formation. The pore pressure does not change in the matrix stress disturbance zone outside the pore pressure disturbance zone where the pressure water does not reach. The deformation and destruction of the coal and rock masses in this zone are mainly caused by matrix stress.

The key point is that measures have to be taken to control the stress magnitude in the pore pressure disturbance zone when hydraulic fracturing is carried out to eliminate coal and gas outbursts. The risk of coal and gas outbursts induced by excessively high coal seam pore pressure during hydraulic fracturing can be reduced. Also, as another key point, measures have to be taken to control the stress magnitude in the matrix stress disturbance zone when hydraulic fracturing is carried out to eliminate rockburst in the coal–rock formation with rockburst tendency. The risk of rockburst induced by stress concentration during hydraulic fracturing can also be reduced.

Previous studies on the stress disturbance effect of hydraulic fracturing only focused on the change of the matrix stress. Through physical simulation experiments and numerical simulations, this paper finds that there are pore pressure disturbance zone and matrix stress disturbance zone in the hydraulic fracturing process; in addition, the matrix stress disturbance zone is larger than the pore pressure disturbance zone. The distribution relationship between the pore pressure disturbance zone and the matrix stress disturbance zone is revealed. Based on this, the zoning control principle of stress disturbance during hydraulic fracturing is proposed for different engineering backgrounds. It will provide a more comprehensive theoretical basis for eliminating coal and gas outbursts and rockburst by hydraulic fracturing in underground coal mines.

6. CONCLUSIONS

(1) With the increase of the distance from the hydraulic fracture, the pore pressure and the matrix stress attenuate exponentially, and the attenuation rate of the matrix stress is less than the attenuation rate of the pore pressure. The range of the matrix stress disturbance zone in the stress disturbance zone is larger than the pore pressure disturbance zone.

(2) In the pore pressure disturbance zone, the higher the pore pressure, the higher the matrix stress. As the pore pressure decreases, the matrix stress is correspondingly...
smaller, and the decay rate gradually decreases. The changing relationship of the pore pressure and the matrix stress on both sides of the hydraulic fracture conforms to the natural logarithmic attenuation relationship.

(3) With the increase of the pumping time, the increasing speed of the matrix stress disturbance zone is greater than the increasing speed of the pore pressure disturbance zone. It shows that as the pumping time increases, the crack opening increases. The squeezing force on both sides increases correspondingly, which causes the matrix stress in the stress disturbance zone to gradually increase and the scope gradually expands.

(4) From the fracturing section of the borehole to the outside, the boundary of the hydraulic fracture zone, the boundary of the pore pressure disturbance zone, the boundary of the framework stress disturbance zone, and the undisturbed zone are in sequence. The stress disturbance zone around the hydraulic fracture includes the pore pressure disturbance zone and the matrix stress disturbance zone.

(5) In the pore pressure disturbance zone, the pore pressure and the matrix stress increase at the same time and interact, which together lead to deformation and destruction of coal–rock formation. The pore pressure does not change in the matrix stress disturbance zone outside the pore pressure disturbance zone, where the pressure water does not reach. The deformation and destruction of the coal and rock masses in this zone are mainly caused by matrix stress.

■ AUTHOR INFORMATION

Corresponding Author

Bingxiang Huang — State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China; orcid.org/0000-0003-3399-0285; Email: huangbingxiang@cumt.edu.cn

Author

Xinglong Zhao — State Key Laboratory of Coal Resources and Safe Mining, China University of Mining and Technology, Xuzhou, Jiangsu 221116, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.1c04268

Notes

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