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Study on Distribution Law of Stress and Permeability around Hydraulic Fracturing Borehole in Coal and Rock

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Abstract: By constructing the permeability model to distinguish the fracture zone, plastic zone, and elastic zone around the hydraulic fracturing borehole, we study the influence of some important parameters on the stress distribution around the borehole and the permeability of the coal rock. The research results show that the greater the ground stress, the greater the radial stress in the fracture zone and plastic zone, and the smaller the radial stress in the elastic zone, while the trend of the stress variation in permeability is the opposite to the radial stress. The greater the gas pressure, the greater the permeability of the coal rock in each stress area. The larger the borehole radius, the smaller the radial stress at the same distance from the borehole center, and the greater the permeability of the coal rock. The greater the fracturing pressure, the greater the radial stress on the coal rock at the same distance from the borehole center, and the smaller the permeability of the coal rock. The research results can provide a theoretical reference for hydraulic fracturing construction in coal mines with different reservoir environments.

Keywords: hydraulic fracturing; gas extraction; stress distribution; permeability evolution; elastic strain softening; stress-permeability mode

1. Introduction

As a widely used permeability-improving technology of reservoirs, hydraulic fracturing can significantly improve the gas extraction effect and increase the extraction efficiency by forming a connected fracture network in a coal seam [1]. Hydraulic fracturing as a mature technology has been widely used in the development of unconventional oil and gas since 1947. In this way, plenty of fracturing fluids containing proppants such as sand or ceramics are injected under high pressure, and a fracture network with high conductivity is artificially created to form a high-speed channel for gas acquisition [2]. Hydraulic fracturing is a multi-physical field coupling process involving fracture initiation, fracture propagation, the deformation of the coal rock, and fluid migration. After hydraulic fracturing, the stress distribution and permeability of the coal rock around the fracturing borehole will inevitably change significantly. These changes will not only affect the stability of the extraction borehole but also determine the efficient extraction of coalbed methane. In recent years, many scholars have studied the stress and permeability evolution of the coal rock around the fracturing borehole. Zhang et al., systematically analyzed the relationship between the lateral stress coefficient, rock properties around the hole, and fracturing...
pressure through theoretical derivation [3]. Li et al., analyzed the relationship between reservoir pressure and the law of gas migration through field tests [4]. Li et al., studied the improvement effect of hydraulic fracturing on the permeability of coal seams by comparing gas concentration and flow before and after hydraulic fracturing [5]. Li et al., optimized the fracturing effect by gradually increasing the fracturing pressure. At the same time, he also analyzed the influence of fracturing pressure on the permeability-increasing radius and the permeability coefficient of coal rock [6]. Liu Haibo et al., used the crack-causing and permeability-increasing technology of hydraulic punching and fracturing coupling to study the change law of coal displacement, stress distribution, and permeability in “three soft” coal seams after fracturing [7]. Li Huipeng et al., restored the fracturing process on site through a simulation test of similar materials, and obtained the change law of water injection pressure, coal seam stress, and fracture propagation of coal seams in the fracturing process [8]. By means of numerical simulation and field engineering tests, Gao Song systematically studied the change law of the fracturing fracture range and gas drainage volume from a low permeability coal seam deep to the cross-layer hydraulic fracturing [9]. Sun measured the gas content of each borehole by sampling and analyzed the change law of the gas content in the target coal seam and an adjacent coal seam after hydraulic fracturing in detail [10]. Jiang et al., studied the effect of cyclic fracturing of a high and low-pressure on gas drainage by monitoring gas concentration and flow rate change on-site [11]. Li et al., studied the application of high and low pressure cyclic hydraulic fracturing [12,13]. Ma et al., carried out physical simulation experiments of hydraulic fracture through-layer propagation for lacustrine shale, argillaceous dust, and siltstone and studied the influence of geological and engineering parameters on hydraulic fracture through-layer propagation behavior [14]. The hydraulic fracturing technique has been an indispensable approach to creating artificial fracture networks in shale oil/gas reservoirs. However, due to the difference in the geological conditions of different reservoirs and the strong heterogeneity of shale, the fracture morphology of hydraulic fracturing is very complex. Guo et al., preliminarily discussed the formation mechanism of the hydraulic fracturing fracture network in the Chang 7 continental shale oil reservoir by combining laboratory true triaxial hydraulic fracturing tests with a 3D-visualization model based on computer tomography [15]. Jiao et al. explored the influence of different factors on hydraulic fracture propagation behavior. Taking the hard roof sandstone of the Tashan coal mine as the research object, the extended finite element method was used to simulate the fracture propagation process, and the influence of the horizontal stress ratio, tensile strength, Poisson’s ratio, interval time, liquid injection rate, and fracture spacing on the fracture propagation behavior was analyzed [16]. Zhao et al., studied the pre-existing crack angle optimization of a thick sandstone roof during directional hydraulic fracturing and its application to prevent rock burst [17]. In addition, the adsorption and permeability also drew the focus of researchers [18,19].

In general, scholars have conducted much research on the theoretical analysis, field tests, similar experimental simulation and numerical simulation on gas migration, and analyses of the important parameters of coalbed stress, fracture pressure, and stratum properties in fracturing. However, few scholars have studied the evolution law of the stress distribution and permeability of the coal rock around the hole after fracturing through theoretical modeling systems, and even fewer scholars have studied the impact of various geological and construction parameters on the fracturing effect.

Therefore, based on previous research results, a permeability model of the coal rock around a hydraulic fracturing borehole is reconstructed, Permeability zoning theory and stress distribution theory were innovations. This paper analyzes and studies the distribution laws of stress and permeability around hydraulic fracturing boreholes in coal mines through theoretical modeling and solving in MATLAB to provide theoretical guidance and a reference for the hydraulic fracturing construction of coal seams.
2. Mechanical Model of Coal Rock Fracture

The coal rock around the borehole is divided into three zones: elastic zone, plastic zone, and fracture zone. The radius of the fracture zone is $R_d$, the radius of the plastic zone is $R_p$, and the elastic zone is outside the plastic zone. Assuming that the coal rock around the borehole is in a state of hydrostatic pressure, the model of coal rock fracture is an elastic-strain softening model. The stress state and range division of the coal rock are shown in Figure 1. In Figure 1, $P_0$ is the original stress of the coal seam, $a$ is the drilling radius. The physical and mechanical properties of coal rock during hydraulic fracturing are assumed as follows:

$$
\begin{align*}
\sigma_1 &= K_p \sigma_3 + \sigma_c \quad \text{(Elastic zone)} \\
\sigma_1 &= K_p \sigma_3 + \sigma_c \left( \frac{\sigma_1}{\sigma_c} \right) \quad \text{(Plastic zone)} \\
\sigma_1 &= K_p \sigma_3 + \sigma_c^* \quad \text{(Fracture zone)} \\
K_p &= \frac{1 + \sin \phi}{1 - \sin \phi}
\end{align*}
$$

In the formula, $\sigma_1$ and $\sigma_3$ are the maximum and minimum principal stresses, $\sigma_c$ is the uniaxial compressive strength of coal rock, $K_p$ is the plastic coefficient, $\phi$ is the internal friction angle of coal rock, $\sigma_c^*$ is the uniaxial compressive strength of coal rock after the change in cohesive force, $\sigma_c^*$ is the residual strength of coal rock.

2. The mechanical model is based on an axisymmetric plane strain problem; that is, the mechanical properties of physics and the values of the stress components of coal rock are the same at any point on any circumferential line with the center of the borehole as the circle center, and the stress direction is symmetrical to the center of the borehole.

3. The deformation of coal rock is treated as a plane strain problem and conforms to the assumption of small deformation and small displacement in elastic mechanics, which meets the following geometric equation and equilibrium differential equation.

$$
\begin{align*}
\frac{\partial \varepsilon_r}{\partial r} + \frac{\sigma_r - \sigma_\theta}{r} &= 0 \\
\frac{\partial \varepsilon_\theta}{\partial r} + \frac{\sigma_\theta - \sigma_r}{r} &= 0
\end{align*}
$$

**Figure 1.** Elastic-strain softening model.
In the formula, $\sigma_r$ is the radial stress of coal rock, $\sigma_\theta$ is the tangential stress, $\varepsilon_r$ and $\varepsilon_\theta$ are radial strain and tangential strain, and $u$ is radial displacement.

4. The volume of coal rock in the plastic zone does not change, ignoring the effect of expansion.

3. Distribution of Stress and Permeability of Coal Rock around Fracturing Boreholes

3.1. Stress State of Coal Rock around the Borehole

Based on the assumption that the fracture of coal rock around the hydraulic fracturing borehole conforms to the elastic-strain softening model, Li introduced the brittleness coefficient of coal rock and obtained the range and law of the stress distribution of each stress zone around the borehole through the elastic-plastic mechanics theory [20]. When considering the situation of the borehole shrinkage, that is, when the fracturing pressure is less than the ground stress and $\sigma_\theta > \sigma_r$, the stress distribution of the coal rock around the borehole meets the following formula.

\[
\begin{align*}
\sigma_r &= p_0 + \left( \frac{p_0 - \sigma_c - K_p p_0}{K_p + 1} \right) \left( \frac{R_p}{r} \right)^2 \\
\sigma_\theta &= p_0 - \left( \frac{p_0 - \sigma_c - K_p p_0}{K_p + 1} \right) \left( \frac{R_p}{r} \right)^2 \\
\sigma_r &= \frac{2K_p}{K_p + 1} \left( p_0 + \frac{c_r + \beta B_0 K_p - 1}{K_p + 1} \right) \left( \frac{R_p}{r} \right) - \frac{2(\sigma_c + \beta B_0)}{K_p + 1} - \frac{\beta}{K_p + 1} \\
\sigma_\theta &= \frac{2K_p}{K_p + 1} \left( p_0 + \frac{c_r + \beta B_0 K_p - 1}{K_p + 1} \right) \left( \frac{R_p}{r} \right) - \frac{2(\sigma_c + \beta B_0)}{K_p + 1} + \frac{\beta}{K_p + 1} \\
\sigma_\theta &= 0 \\
B_0 &= \frac{1 + \nu}{(K_p - 1)} \left( p_0 + \frac{c_r + \beta B_0 K_p - 1}{K_p + 1} \right) \left( \frac{R_p}{r} \right) - \frac{\beta}{K_p + 1} - \frac{\sigma_c^*}{K_p + 1} \\
t &= \left( \frac{\beta B_0}{\sigma_c^* - \sigma_c} \right)^{1/2}
\end{align*}
\]

In the formula, $\beta$ is the brittleness coefficient of coal rock, $r$ is the distance to the borehole center, $p_0$ is the original stress of the coal seam, $B_0$ and $t$ are constants.

3.2. Range of Fracture Zone and Plastic Zone

As shown in Figure 1, the coal rock around the borehole of gas drainage forms the fracture zone and plastic zone from inside to outside through hydraulic fracturing. The range of the fracture zone is determined by the distance $R_f$ from the borehole center to the outer boundary of the fracture zone. The range of the plastic zone is determined by the distance $R_p$ from the borehole center to the outer boundary of the plastic zone, and the elastic zone is outside the plastic zone. According to the study of Yong [14], the radius of the fracture zone and the radius of the plastic zone are, respectively, $R_f$ and $R_p$.

\[
\begin{align*}
R_f &= a \left\{ 2 \left( \frac{1}{K_p + 1} \left( p_0 + \frac{c_r + \beta B_0 K_p - 1}{K_p + 1} \right) \left( \frac{R_p - 1}{K_p - 1} \right) \right) \right\} \frac{1}{K_p + 1} \\
R_p &= \frac{a}{7} \left\{ 2 \left( \frac{1}{K_p + 1} \left( p_0 + \frac{c_r + \beta B_0 K_p - 1}{K_p + 1} \right) \left( \frac{R_p - 1}{K_p - 1} \right) \right) \right\} \frac{1}{K_p + 1}
\end{align*}
\]

In the formula, $P_f$ is the fracturing pressure, and $a$ is the drilling radius.

3.3. The Evolution of Permeability of Coal Rock around the Borehole

The permeability of coal rock is the result of the combined action of stress state and gas pressure on coal rock. Li et al., put forward a method by which the effective stress is used
to characterize the stress state of gas-bearing coal rock, and then calculate the permeability of coal rock [21]. The effective stress expression is

\[
\sigma' = \sigma - \alpha P
\]  

(5)

In the formula, \(\sigma'\) is the effective stress in a certain direction of the coal seam, \(\sigma\) is the ground stress in this direction, and \(P\) is the gas pressure.

In the process of gas extraction, the flow of gas along the radial direction of the borehole is mainly studied, and the radial effective stress can be expressed as

\[
\sigma' = \sigma_r - \alpha P
\]  

(6)

According to a large number of previous experimental studies, there is the following relationship between the permeability \(k\) of coal rock and effective stress.

\[
k = k_0 e^{-\tau \sigma'}
\]  

(7)

In the formula, \(k_0\) is the permeability of coal without pressure, and \(\tau\) is a stress-sensitive factor.

Insert Formula (6) into Formula (7) to obtain Formula (8).

\[
k = k_0 e^{-\tau (\sigma_r - \alpha P)}
\]  

(8)

Combining Formula (3) and (7), the permeability distribution of coal rock around the borehole is

\[
\begin{align*}
k_e &= k_0 e^{-\tau \left[p_0 + \left(\frac{\sigma_c - \sigma_P \beta B_0}{\frac{K_p}{\tau} - 1}\right)\left|\frac{P}{P_P}\right|^2 - \alpha P\right]} \\
k_p &= k_0 e^{-\tau \left[\frac{2}{K_p - 1} \left[p_0 + \left(\frac{\sigma_c - \sigma_P \beta B_0}{\frac{K_p}{\tau} - 1}\right)\left|\frac{P}{P_P}\right|\right] - \frac{\sigma_c}{K_p - 1} - \alpha P\right]} \\
k_d &= k_0 e^{-\tau \left[2 \left|\frac{2}{K_p - 1} \left[p_0 + \left(\frac{\sigma_c - \sigma_P \beta B_0}{\frac{K_p}{\tau} - 1}\right)\left|\frac{P}{P_P}\right|\right]\right|\left|\frac{P}{P_P}\right|\left|\frac{\sigma_c}{K_p - 1} - \alpha P\right]\right]}
\end{align*}
\]  

(9)

In the formula, \(k_e\) is the permeability of coal rock in the elastic zone, \(k_p\) is the permeability of coal rock in the plastic zone, and \(k_d\) is the permeability of coal rock in the fracture zone.

4. Study on Geological and Engineering Parameters

From the above theoretical analysis, we can infer that the permeability of the coal rock around the borehole is jointly determined by the parameters of hydraulic fracturing construction and the parameters of the mechanical properties of the physics of gas. In this section, this paper has discussed the spatial evolution law of coal rock permeability around the borehole under different stress, gas pressure, and drilling radius by obtaining a solution in MATLAB, which is based on the stress and permeability model around the fracturing borehole obtained above and combined with the field fracturing construction data of Chongqing Yuyang coal mine [20]. Among them, ground stress and gas pressure are geological parameters that cannot be changed in an engineering operation, while the borehole radius and the fracturing pressure are artificially controllable construction parameters. A comprehensive analysis of the influence of geological parameters and construction parameters on the permeability of coal rock around hydraulic fracturing boreholes can provide theoretical support for the study of practical engineering problems. The basic parameters involved in this section are shown in Table 1.

4.1. Influence of Ground Stress on the Permeability of Coal Rock

Ground stress is also called original rock stress, which is mainly composed of rock gravity, tectonic stress, gas pressure, and thermal stress in coal mines. Ground stress is the fundamental force causing the deformation and fracture of various excavation projects of underground or open-pit rock [22]. In the process of borehole hydraulic fracturing, the
magnitude of the ground stress affects the fracturing pressure and fracture propagation of coal rock, and then affects the permeability of the coal rock around the borehole.

Table 1. Basic parameters of coal and gas.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus of coal/MPa</td>
<td>1500</td>
</tr>
<tr>
<td>Ground stress/MPa</td>
<td>15</td>
</tr>
<tr>
<td>Poisson ratio of coal</td>
<td>0.3</td>
</tr>
<tr>
<td>Internal friction angle</td>
<td>$\pi/6$</td>
</tr>
<tr>
<td>Force of cohesion/MPa</td>
<td>2</td>
</tr>
<tr>
<td>Uniaxial compressive strength of coal rock/MPa</td>
<td>8</td>
</tr>
<tr>
<td>Residual strength of coal rock/MPa</td>
<td>1</td>
</tr>
<tr>
<td>Brittleness coefficient of coal rock</td>
<td>0.5</td>
</tr>
<tr>
<td>Fracture pressure/MPa</td>
<td>0.6</td>
</tr>
<tr>
<td>Radius of drill hole/m</td>
<td>0.1</td>
</tr>
<tr>
<td>Stress sensitivity factor/MPa$^{-1}$</td>
<td>0.37</td>
</tr>
<tr>
<td>Biot coefficient</td>
<td>0.66</td>
</tr>
<tr>
<td>Gas pressure/MPa</td>
<td>2</td>
</tr>
<tr>
<td>Permeability of unpressurized coal rock/mD</td>
<td>0.2</td>
</tr>
</tbody>
</table>

According to Formulas (3), (4) and (9) and the parameters given in Table 1, when the ground stress $P_0$ is 15 Mpa, 20 Mpa, and 25 Mpa, respectively, we study the permeability of the coal rock around the borehole, and calculate the change in radial stress around the gas drainage borehole as shown in Figure 2. The changes in coal permeability and ground stress are shown in Figure 3.

Figure 2. Variation in radial stress around a borehole under different ground stresses.

Figure 3. Variation in the permeability of coal rock around a borehole under different ground stresses.
We can see from Figures 2 and 3 that the radial stress of the coal rock increases with distance from the borehole, and finally approaches the ground stress. The permeability of the coal rock decreases with distance from the borehole, and the permeability of the fracture zone and the plastic zone are much higher than that of the elastic zone. This is because hydraulic fracturing leads to many connected fissures within a certain range around the borehole, which makes the radial stress around the borehole much smaller than the original stress, and the connected fissures network maintain the surrounding coal rock permeability at a high level. In general, the larger the ground stress, the larger the radius of the fracture zone and plastic zone, and the smaller the radial stress of coal rock around the borehole (fracture zone and plastic zone), while the radial stress of coal rock far from the borehole increases with the increase in ground stress. This is because, near the fracturing borehole, the water pressure acting on the borehole wall makes the coal rock bear radial compressive stress, and the ground stress is opposite to the fracturing pressure. When the position of the coal rock is far away from the borehole, the stress state of the coal rock becomes smaller under the influence of fracturing pressure. At this moment, the radial stress of the coal rock is closer to the ground stress. In Figure 2, the area far from the borehole center shows a phenomenon whereby the greater the ground stress, the greater the radial stress.

4.2. Influence of Gas Pressure on the Permeability of Coal Rock

In the coal seam, the gas pressure and the radial effective stress borne by the coal rock skeleton jointly constitute the radial stress of the coal rock, and the radial stress is not directly related to the gas pressure. Gas pressure affects the permeability of coal rock by affecting the effective stress of coal rock. In this section, the gas pressure $P_g$ is 2 Mpa, 4 Mpa, and 6 Mpa, respectively, under the condition of keeping the other parameters unchanged. It is concluded that the permeability of the coal rock around the drainage borehole changes with the distance from the borehole center and the ground stress as follows:

According to the effective stress Formula (6), the greater the gas pressure, the smaller the effective stress. Combining Formula (7) with Figure 4, we can see that an increase in gas pressure reduces the radial effective stress of the coal rock, and then results in an increase in permeability. In addition, the greater the gas pressure, the more obvious the decline of the permeability of the coal rock in the fracture zone and plastic zone, and the influence of gas pressure on the permeability of the fracture zone and the plastic zone is much greater than that on the permeability of the elastic zone. Combined with Figure 2, we can see that the reason is also that in the fracture zone and plastic zone, the radial stress of the coal rock is far less than the ground stress, which makes the effective stress decrease with the reduction in distance from the borehole.

![Figure 4](image-url)  
Figure 4. The change in coal rock permeability around the borehole under different gas pressure.

4.3. Influence of Drilling Radius on the Permeability of Coal Rock

The size of the borehole radius not only affects the range of the coal rock fracture zone and plastic zone around the borehole but also determines the construction parameters such
as the fracturing pressure and the effective drainage radius in the later stage. This paper discusses the change in the permeability of the coal rock around the borehole when the radius of the extraction borehole is 0.1 m, 0.15 m, and 0.2 m, respectively.

From Figure 5, we can see that when the other parameters remain unchanged, the larger the borehole radius, the smaller the radial stress at the same distance from the borehole center, and the larger the drilling radius, the larger the range of the fracture zone and plastic zone. Figure 6 shows that the permeability of coal rock at the same distance from the borehole center increases with the augmentation of the borehole radius. However, just as with the radial stress on coal rock, the size of borehole radius has little effect on the variation trend of the permeability of the coal rock around the fracturing borehole.

![Figure 5](image1)

**Figure 5.** The change in radial stress around borehole under different borehole radiiuses.

![Figure 6](image2)

**Figure 6.** The change in coal rock permeability around the borehole under different borehole radius.

### 4.4. Influence of Fracturing Pressure on the Permeability of Coal Rock

Fracturing pressure is the most important construction parameter in hydraulic fracturing. The size of fracturing pressure determines the range of fracturing permeability (radius of fracture zone and plastic zone), and the expansion and contraction of the borehole. Keeping other parameters unchanged, we studied the change in coal rock permeability around the borehole when the fracturing pressure $P_h$ was 0.6 MPa, 0.9 MPa, and 1.2 MPa, respectively, in this section.

We can see from Figure 7 that the greater the fracturing pressure, the greater the radial stress of coal rock at the same distance from the borehole center. The reason is that the fracturing pressure directly acts on the borehole wall, increasing the radial stress on the coal rock, and its influence on the radial stress decreases with the increase in the distance from the borehole center. The gap between the different radial stresses shown in Figure 7 is getting smaller and smaller, and it is gradually approaching the ground stress in the elastic zone. From Figure 8, we can see that a larger fracturing pressure corresponds to a larger...
radial stress, resulting in a greater radial effective stress of the coal rock, and a smaller permeability of coal rock at the same distance from the borehole center. In addition, the figure shows that the larger the fracturing pressure, the smaller the range of the fracture zone and plastic zone, which reflects that typically the fracturing pressure is far less than the ground stress. In the process of hydraulic fracturing, the plasticity of the coal rock does not always exist, but decreases first and then increases with the increase in fracturing pressure, which corresponds to the shrinkage and expansion of drilling.

Figure 7. Variation in radial stress around borehole under different fracturing pressures.

Figure 8. The change in coal rock permeability around borehole under different fracturing pressure.

5. Conclusions

In this paper, we construct a permeability model to distinguish the fracture zone, plastic zone, and elastic zone around a hydraulic fracturing borehole, and to study the influence of geological parameters and construction parameters on the stress and permeability of the coal rock around the borehole, which is based on previous research results on the stress distribution around a hydraulic fracturing borehole, introducing the stress-permeability empirical model. The main conclusions are as follows:

1. The greater the ground stress, the greater the radial stress of the coal rock in the fracture zone and plastic zone around the borehole. The smaller the radial stress in the elastic zone, and the larger the range of fracture zone and the plastic zone, and the changing trend of permeability with ground stress is the opposite to that of radial stress.

2. The greater the gas pressure, the greater the permeability of the coal rock in each stress zone. In addition, the influence of gas pressure on the permeability of the fracture zone and plastic zone is much greater than that on the permeability of the elastic zone.

3. The larger the borehole radius, the larger the range of fracture zone and the plastic zone, and the smaller the radial stress at the same distance from the borehole center, while the permeability of the coal rock remains relatively larger at this location.
4. The larger the fracturing pressure, the smaller the range and radius of fracture zone and plastic zone, the greater the radial stress of the coal rock at the same distance from the borehole center, and the smaller the permeability of the coal rock.

5. The overall trend of radial stress is shown as follows: From the borehole wall to the elastic zone, the radial stress gradually increases from the fracturing pressure and approaches ground stress. The overall trend of permeability is shown as follows: The permeability in the fracture zone and the plastic zone is much higher than that in the elastic zone; from the borehole wall to the elastic zone, the permeability of the coal rock gradually decreases and approaches a low level.

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