Research Article
Theoretical Study and Numerical Simulation Research on the Effect of Coal-Rock Interface on Multistaged Fracturing in the Roof of Outburst Coal Seam

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Multistaged fracturing in the roof of outburst coal seam is an efficient and creative technology for coalbed methane (CBM) drainage, which can effectively improve the permeability of coal seam. To reveal its mechanism of permeability enhancement, the effect of coal-rock interface on multistaged fracturing in the roof of outburst coal seam was simulated and discussed in this paper. Firstly, the lithological difference between outburst coal seam and roof was compared, and the concept and significance of multistaged fracturing in the roof of outburst coal seam were explained. Then, the mechanical conditions of multiple fractures in the roof traversing coal-rock interface were analyzed. The results indicated that fracturing borehole in adjacent rocks of outburst coal seam is much easier to drill and maintain gas drainage. Considering gas drainage efficiency and avoiding being blocked by coal fines, multistaged fracturing borehole is generally drilled in the stable rock stratum of roof. Whether the multiple fractures in the roof can traverse coal-rock interface is related to mechanical parameters of coal and rock, friction factor of coal-rock interface, angle between horizontal profile and coal-rock interface, cementing strength of coal-rock interface, minimum horizontal stress, and other factors. Higher fracturing fluid pressure contributes to propagating from the reservoir with low elastic modulus to the one with high elastic modulus for hydraulic fracture. Hydraulic fracture is more likely to propagate in the rock stratum with high brittleness index. The research results can improve multistaged fracturing theory and provide technological support for field test.

1. Introduction

Coalbed methane (CBM) is a kind of unconventional natural gas that reserves in coal seam, which has been successfully produced in Ordos, Qinshui, and Junggar basins in China [1–3]. CBM production has the advantages of reducing greenhouse effect, utilizing clearer energy, increasing safety level of coal mining, and improving energy structure [4]. With the concept of “green mining of coal mine” proposed, the mode of integrated coal exploitation and gas extraction has been paid more attention [5]. However, CBM reservoirs in China are characterized by low porosity, low gas saturation, low reservoir pressure, and high in situ stresses, resulting in difficulties in CBM production [6, 7]. More seriously, with the increment of coal mining depth, the outburst coal seams gradually increase, which greatly affect miners’ safety. In China, most outburst coal seams currently achieve methane predrainage and safe mining by means of rock tunnel and cross-measure borehole [8–10]. However, this method has disadvantages of great investment, huge amount of engineering, long construction period, and other bad aspects [11, 12]. To solve the problem during gas drainage in outburst coal seam, improve gas control, and ensure safe mining, Geng et al. proposed transforming the roof of outburst coal seam and enhancing its permeability for building CBM migration channel [13], they suggested to drill a long borehole parallel towards of coal seam in the roof, and then hydraulic strengthening methods were conducted in the borehole, thus forming fracture network that was interlinked in the roof and coal seam. The fracture network
played the role of channel for gas drainage, finally achieving the aim of indirect gas drainage and safe mining in the outburst coal seam. With the development of fracturing technique and device, multistaged fracturing in the roof of outburst coal seam is applied to more and more outburst coal mines for methane predrainage [14–16]. Multistaged fracturing in the roof of outburst coal seam aims to create multiple fractures in the roof, which can traverse the coal-rock interface for building migration channel for methane drainage [17]. Therefore, the research emphasis on mechanism of permeability enhancement by multistaged fracturing in the roof of outburst coal seam mainly focuses on whether the multiple fractures in the roof can form and then traverse the coal-rock interface [18].

To reveal the mechanism of permeability enhancement by multistaged fracturing, many global scholars discussed different aspects and achieved lots of beneficial research results. Bagher et al. [19] analyzed the productivity of multifractured horizontal well in a bounded dual-porosity formation, and the infinite conductivity fracture case was modeled by combining Laplace transform (LT) and finite Fourier cosine transform. Liu et al. [20] revealed the mechanism of casing deformation problems, established a semianalytical model for calculating induced stress along the fault caused by hydraulic fracture, and discussed the effects of fluid pressure, dip angle of fault, scale of fluid stimulated area, and the friction coefficient of fault slippage. Liu et al. [21] established a novel laboratory simulation method for modeling multistaged fracturing in a horizontal well based on a true triaxial hydraulic fracturing simulation system, and the effects of net pressure in hydraulic fracture, stage spacing, perforation parameter, horizontal stress bias, and well cementation quality on the propagation geometry of multiple fractures in a tight sandstone formation were studied. Wasantha et al. [22] discussed fracture containment behavior under varying in situ stress conditions for single-staged and multistaged fracturing using a fully coupled hydromechanical model. Zhou et al. [23] analyzed the influences of pore-pressure field on multifracture propagation during the multistage fracturing cluster fracturing of tight sandstone by laboratory experiments and self-developed 3D coupled fluid-solid numerical simulation method. Lu et al. [24] established a multifracture stress interference model to simulate non-isometric half-length, unequal fracture spacing and arbitrary angle between fracture and wellbore based on displacement discontinuity method, analyzed stress field change, and verified the model by data from a tight sandstone reservoir in Sichuan basin of China.

Fracture initiation, propagation, and geometry of multiple fractures are affected by many factors; although there are many significant reports about the mechanism of permeability enhancement by multistaged fracturing in the roof of outburst coal seam, the mechanical conditions of multiple fractures in the roof traversing coal-rock interface have not been completely understood yet. In this paper, the effects of coal-rock interface on multistaged fracturing in the roof of outburst coal seam were theoretically analyzed and numerically simulated. The research results can improve multistaged fracturing theory and provide technological support for field test.

2. Theoretical Study

2.1. Significance of Multistaged Fracturing in the Roof of Outburst Coal Seam. Compared with outburst coal seam, its adjacent rocks have the advantages of good transformation, high brittleness index, low sensitivity to flow speed, low expansibility, high stability of borehole, and some other beneficial factors. Hydraulic strengthening methods in adjacent rocks can form fracture network and improve permeability; then multiple fractures traverse the coal-rock interface and propagate into outburst coal seam, which transform the adjacent rocks into a high-speed seepage channel. Adjacent rocks are changed to be indirect layer for CBM migration [25, 26]. After being decompressed and desorbed, CBM in outburst coal seam is quickly transported to adjacent rocks through multiple fractures and extracted from fracturing borehole.

Due to the diversity of mechanical parameters between outburst coal seam and adjacent rocks, fracturing borehole in adjacent rocks is much easier to drill and maintain gas drainage. Therefore, for outburst coal seam, horizontal well can be drilled in stable adjacent rocks, and multiple fractures form under the effect of induced stress during multistaged fracturing. It should be noted that if multistaged fracturing is conducted in the floor of outburst coal seam, it is difficult for gas drainage, which will seriously affect gas desorption and release. Meanwhile if multistaged fracturing is carried out in the roof, multiple fractures can avoid being blocked by coal fines. Therefore, multistaged fracturing borehole can be generally drilled in stable rock stratum in the roof, as shown in Figure 1.

Known from the above analysis, multifracturing borehole drilled in the roof of outburst coal seam is better for gas drainage. Based on the mechanical parameters of fracturing stratum, in situ stress, fracturing scale, and requirements, fracturing borehole drilled towards coal seam can acquire multiple fractures using multistaged fracturing in the roof. Affected by induced stress of multiple fractures, the original in situ stress is greatly changed, which is beneficial for fracture reorientation, eventually forming new multiple fractures and quick migration channel for gas drainage. The CBM in outburst coal seam is extracted into fracturing borehole through multiple fractures by means of seepage. The gas pressure and gas content in the outburst coal seam finally decrease. Additionally, multistaged fracturing not only can overcome the shortcomings of small dimension of fracturing device, small fracturing scale, and difficulty of drilling during field test but also can achieve targeted fracturing, form massive multiple fractures, expand the scope of fracturing effect, improve fracture conductivity, and promote gas desorption and diffusion. This new fracturing method can satisfy the requirement of gas control for various coal structures.

In conclusion, the advantages of multistaged fracturing in the roof of outburst coal seam can be summarized as the following aspects. (1) Fracturing boreholes can be well
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maintained. (2) The roof has the quality of good transformation. (3) Multiple fractures will not close under the effect of stress sensitivity. (4) Migration channel for gas drainage is difficult to be affected by the sensitivity to flow speed. (5) Avoiding granulated coal and mylonitized coal, the phenomenon of coal fines blocking fracturing borehole reduces. (6) Fracturing degree of CBM reservoir is homogeneous and the effect of reconstruction is good for gas drainage. (7) This new method is applicable to any CBM reservoir.

2.2. Mechanical Conditions of Multiple Fractures Traversing Coal-Rock Interface. The effect of coal-rock interface on mult fracturing in the roof of outburst coal seam is mainly reflected by whether the multiple fractures in the roof can traverse coal-rock interface and continue to propagate in outburst coal seam and final propagating distance. The relative position relationship between multiple fractures and coal-rock interface can be described as the following three aspects: (1) Multiple fractures traverse the coal-rock interface and continue to propagate in the coal seam. (2) Multiple fractures propagate along the coal-rock interface. (3) Multiple fractures no longer propagate when they encounter coal-rock interface. These aspects are all closely related to the elastic modulus of roof and coal seam, vertical stress on coal-rock interface, and properties of coal-rock interface [27]. However, the mechanisms of multiple fractures in the roof of outburst coal seam traversing coal-rock interface are rarely reported.

2.2.1. Coal-Rock Interface Is Well Cemented without False Roof. When multiple fractures induced by multistaged fracturing in the roof of outburst coal seam encounter coal-rock interface, the mechanical properties of coal-rock interface may make the propagation path turn to another direction, consume the propagation energy of multiple fractures, and reduce the probability of multiple fractures propagating into coal seam. When there is no false roof between immediate roof and coal seam, the greater the vertical stress on coal-rock interface, the greater the cementing strength and interface friction factor, and the multiple fractures in the roof are easier to traverse coal-rock interface and propagate into coal seam [27]. Whether the multiple fractures in the roof can traverse coal-rock interface and propagate into coal seam is closely related to the fluid pressure inside fracture. The fluid pressures inside fracture of different rock strata are contrasted and analyzed as follows.

In CBM reservoir, the actual propagation path of hydraulic fracture is three-dimensional. To specifically analyze fracture propagation when coal-rock interface is well cemented without false roof, the CBM reservoir is simplified into a two-dimensional model. The loaded stress and profile of two-dimensional model are as shown in Figure 2.

It is assumed that the coal-rock interface is well cemented and does not slip. According to fracture mechanics theory, fracture initiation in CBM reservoir complies with the following criteria. Hydraulic fracture usually begins to propagate when stress intensity factor \( K_I \) is greater than critical stress intensity factor \( K_{IC} \) [28]:

\[
K_I \geq K_{IC},
\]

where \( K_I \) is the stress intensity factor, MPa·m\(^{1/2} \); and \( K_{IC} \) is the critical stress intensity factor, MPa·m\(^{1/2} \).

By substituting equation (2) into equation (1), it can be concluded that the critical fluid pressures of hydraulic fractures propagating in roof and coal seam are \( p_1 \) and \( p_2 \), respectively:

\[
p_1 = \sqrt{\frac{2E_1\gamma_1}{\pi a(1 - \nu_1^2)}} + \sigma_h,
\]

\[
p_2 = \sqrt{\frac{2E_2\gamma_2}{\pi a(1 - \nu_2^2)}} + \sigma_h,
\]

where \( E_1 \) is the elasticity modulus of roof, GPa; \( \gamma_1 \) is the superficial energy of hydraulic fracture in roof, MPa·m; \( \nu_1 \) is Poisson’s ratio of roof; \( E_2 \) is the elasticity modulus of coal seam, GPa; \( \gamma_2 \) is the superficial energy of hydraulic fracture in coal seam, MPa·m; and \( \nu_2 \) is Poisson’s ratio of coal seam.

Based on the mechanical parameters of coal and rock, it can be known that the critical fluid pressure of hydraulic fractures propagating in roof \( (p_1) \) is bigger than the one in coal seam \( (p_2) \).

Meanwhile, the fluid pressure for shear failure of hydraulic fracture propagating to coal-rock interface \( p_3 \) can be calculated by the following equation [28]:

\[
p_3 = \frac{c}{K_f} + \frac{\sigma_{HV} - \sigma_h}{2} \left( 1 - \cos 2\theta - \frac{\sin 2\theta}{K_f} \right) + \sigma_h,
\]

where \( c \) is the cementing strength of coal-rock interface, MPa, and \( K_f \) is the friction factor of coal-rock interface.

As shown above, the critical fluid pressure of hydraulic fracture propagating in roof \( (p_1) \) is bigger than the one in coal seam \( (p_2) \), so the fracture propagating modes can be divided into three aspects. (1) If the sequence decreasingly is \( p_3, p_2, p_1 \), based on fluid pressure, the multiple fractures will traverse coal-rock interface and continue to propagate in coal seam. (2) If the sequence decreasingly is \( p_1, p_2, p_3 \) or \( p_1, p_3, p_2 \), based on fluid pressure, multiple fractures will propagate to the direction with low critical fluid pressure between \( p_2 \) and \( p_3 \) after they encounter coal-rock interface. (3) If \( p_2 \) and \( p_3 \) have little difference, partial multiple fractures may propagate along coal-rock interface, and others may traverse coal-rock interface and continue to propagate.
Rapid diffusion and seepage zone in coal seam result in reduced fracturing effect and low gas drainage rate.

Based on equation (3), we can see that when hydraulic fracture traverses coal seam and enters floor, the critical fluid pressure of hydraulic fracture propagating in coal seam is smaller than the one in floor. In other words, once hydraulic fracture propagates into floor, the net fluid pressure of fracture will decrease, and vertical propagation of hydraulic fracture will be limited. The decrease of net fluid pressure will limit the vertical fracture propagating distance in floor.

The results of laboratorial experiments and field tests [25, 26, 29] indicate that, except the effect by cementing strength and loading stress on coal-rock interface, whether hydraulic fracture can vertically traverse coal-rock interface is mainly related to the elastic modulus between roof and coal seam when mechanical parameter is the only considering factor. (1) Hydraulic fracture can traverse coal-rock interface and continue to propagate in coal seam when it propagates from the reservoir with high elastic modulus to the one with low elastic modulus or the elastic moduli of roof and coal seam are similar. This is because the rock with high elastic modulus has strong elastic energy storage capacity before failure and released energy of hydraulic fracture is powerful. Due to the large difference of elastic modulus between roof and coal seam, when the hydraulic fracture in the roof propagates vertically to coal-rock interface, the energy at the tip of hydraulic fracture is released immediately, resulting in obvious pent-up pressure phenomenon in the fracturing curve and different open degree of coal-rock interface, which promotes forming multiple fractures of various direction in coal seam. With the continuous pumping of fracturing fluid, multiple fractures of various directions propagate at the same time, which is beneficial for forming fracture network. That is to say, the greater the diversity of elastic modulus between reservoirs, the more complex the fracture geometry. (2) Hydraulic fracture may stop propagating at the coal-rock interface or turn to the direction of coal-rock interface shaped “T” when it propagates from reservoir with low elastic modulus to the one with high elastic modulus. This is because the fracture width in the reservoir with low elastic modulus is bigger, while fracture height is smaller. When hydraulic fracture propagates to the reservoir with high elastic modulus, the stress intensity factor at the tip of hydraulic fracture upon coal-rock interface is almost zero, hydraulic fracture may stop propagating, and fracture height is still in the reservoir with low elastic modulus.

2.2.2. Coal-Rock Interface Is Not Well Cemented with False Roof. When false roof exists between immediate roof and coal seam, the two interfaces are (a) false roof and coal seam interface and (b) false roof and immediate roof interface. The lower the cementing strength and interface friction factor are, the more the hydraulic fracture in the roof tends to propagate along false roof and immediate roof interface, and the fracturing effect and range decrease; thus gas drainage efficiency is greatly affected. Meanwhile when the cementing strength and interface friction factor are greater, the interface shear strength is bigger than the sum of minimum horizontal stress of false roof and its tensile strength, hydraulic fracture will propagate into false roof, false roof expands when it is immersed in water, and it is not beneficial to communicate with coal seam for hydraulic fracture. In this case, the hydraulic fracture can be promoted to propagate downward into coal seam by means of increasing fracturing fluid displacement. However, hydraulic fracture will traverse some local areas with natural fractures somewhere. When hydraulic fracture encounters the interface between coal seam and false roof, its propagating path is the same as that of the above analysis.

In summary, when multiple fractures in roof propagate to coal-rock interface, whether they can traverse coal-rock interface is related to the mechanical parameters of coal and rock, friction factor of coal-rock interface, angle between horizontal profile and coal-rock interface, cementing strength of coal-rock interface, minimum horizontal stress, and other factors.

3. Numerical Simulation

From the theoretical analysis, we can see that whether multiple fractures in roof can propagate into adjacent stratum is related to elastic modulus of coal seam and adjacent rocks [30]. In this paper, the effect of elastic modulus of rock stratum without false roof on fracture propagation path is numerically simulated by RFPA2D-Flow numerical simulation software. The characteristics of fracture propagation are qualitatively analyzed to provide reference for the selection of fracturing stratum using multistaged fracturing.

Numerical model of 30 meters × 30 meters is established, which is divided into 300 × 300 = 90000 cells, as shown in Figure 3. The radius of fracturing hole at the center of this model is 0.3 meters, the initial fluid pressure is 10 MPa, and each step is increased by 0.5 MPa. Confining pressure is loaded upon this model and mechanical parameter of numerical model is shown in Table 1. The plane simplified model is plane strain model. The parameters of confining pressure are as follows. The vertical loading stress $\sigma_v$ is 9 MPa and lateral loading stress $\sigma_H$ is 14 MPa. The mechanical parameters of numerical model and confining pressure are all based on Zhongmacun Coal Mine in China.
The numerical model is divided into five strata according to lithological characteristics of adjacent rocks in the field. From top to bottom on the stratum, the thicknesses are, in order, 9 meters, 3 meters, 6 meters, 3 meters, and 9 meters. The distances between fracturing hole and adjacent rocks are all the same. In model No. 1, from top to bottom, the lithologies are mudstone, medium sandstone, sandy mudstone, soft coal, and sandy mudstone. Meanwhile, in model No. 2, from top to bottom, the lithologies are medium sandstone, mudstone, sandy mudstone, soft coal, and sandy mudstone, as shown in Figure 3. Different color in numerical model indicates the elasticity modulus of different lithology in adjacent rocks, which can be clearly identified.

4. Results and Discussion

4.1. Results and Analysis of Numerical Model No. 1. As shown in Figure 4, we can see that, with the pumping of fracturing fluid, initial hydraulic fracture appears at step 29-1 and then hydraulic fracture propagates vertically up and down. In Figure 4(b), the distances between fracturing hole and adjacent rocks are all the same. Hydraulic fracture firstly propagates under adjacent rock stratum at step 36-1; this phenomenon indicates that hydraulic fracture easily tends to propagate into the fracturing stratum with low elastic modulus. At step 39-3, hydraulic fracture propagates upwards to the upper adjacent rock stratum and there is an obvious pent-up pressure, which is believed to be related to the fact that the elastic modulus of sandy mudstone is smaller than that of medium sandstone. At step 39-7, hydraulic fracture in soft coal propagates downward to the surface of sandy mudstone and there is an obvious pent-up pressure at step 39-8; the reason is that the elastic modulus of sandy mudstone below is bigger than that of soft coal. At step 39-13, hydraulic fracture propagates upward into mudstone from medium sandstone; and model No. 1 starts to break at the top of the model by step 39-18.

From the simulated results of model No. 1, we can see that if hydraulic fracture intends to propagate from the reservoir with low elastic modulus to the one with high elastic modulus, a higher fracturing fluid pressure is needed and it is possible for the hydraulic fracture to propagate into the reservoir with high elastic modulus, which is not beneficial for traversing the interface. On the contrary, hydraulic fracture is more likely to propagate into adjacent rock stratum through the interface.

4.2. Results and Analysis of Numerical Model No. 2. From Figure 5(a), it is shown that initial hydraulic fracture appears
Table 1: Mechanical parameters of numerical simulation model.

| Parameters                  | Medium sandstone | Sandy mudstone | Mudstone | Soft coal |
|-----------------------------|------------------|----------------|----------|-----------|
| Mean degree                 | 3                | 3              | 3        | 3         |
| Compressive strength (MPa)  | 90               | 72             | 15       | 2         |
| Elastic modulus (GPa)       | 25               | 13             | 8        | 5         |
| Poisson’s ratio             | 0.22             | 0.31           | 0.31     | 0.33      |
| Coefficient of residual strength | 0.1             | 0.1            | 0.1      | 0.1       |
| Coefficient of porosity pressure | 1               | 1              | 1        | 1         |

Figure 4: Continued.
Figure 4: Elasticity modulus evolution of numerical model No. 1. (a) Step 29-1. (b) Step 36-1. (c) Step 39-3. (d) Step 39-4. (e) Step 39-7. (f) Step 39-8. (g) Step 39-13. (h) Step 39-18.

Figure 5: Continued.
at step 29-1. In Figure 5(b), the distances between fracturing borehole and adjacent rocks are all the same, and hydraulic fracture propagates to the adjacent rock stratams almost at the same time. Figures 5(c)–5(f) indicate that hydraulic fracture is more likely to propagate upward into mudstone and medium sandstone under the effect of fracturing fluid, and it is concluded that the elastic modulus of mudstone is greater than that of soft coal.

In conclusion, when hydraulic fracture propagates to the adjacent rock stratum at the same time, it is more likely to propagate in the reservoir with high elastic modulus. In other words, hydraulic fracture tends to propagate in the rock stratum with high brittleness index. The numerical simulation results can provide theoretical basis for the explanation of the phenomenon that more hydraulic fractures propagate upward in the field.

**5. Conclusion**

To reveal the mechanism of multistaged fracturing in the roof of outburst coal seam, the effects of coal-rock interface on multistaged fracturing in the roof of outburst coal seam were theoretically analyzed and numerically simulated by RFPA2D-Flow numerical simulation software in this paper. The results are as follows:

(1) The reason why multistaged fracturing borehole is drilled in the roof of outburst coal seam is analyzed by comparing the properties of roof and outburst coal seam. Additionally, the advantages of multistaged fracturing in the roof of outburst coal seam are summarized.

(2) Mechanical conditions of multiple fractures in the roof traversing coal-rock interface are deduced, and
whether they can traverse coal-rock interface is closely related to the mechanical parameters of coal and rock, friction factor of coal-rock interface, angle between horizontal profile and coal-rock interface, cementing strength of coal-rock interface, minimum horizontal stress, and other factors.

(3) The effect of elastic modulus of rock stratum without false roof on fracture propagating path is numerically simulated by RFPA2D-Flow numerical simulation software. A higher fracturing fluid pressure is needed for hydraulic fracture propagating from the reservoir with low elastic modulus to the one with high elastic modulus. Hydraulic fracture is more likely to propagate in the rock stratum with high brittleness index.

Data Availability

The data used to support this study can be found in the paper.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors’ Contributions

Fan Zhang performed the numerical simulation. Fan Zhang and Yang Tang analyzed the theoretical study, analyzed the results of numerical simulation, and prepared the manuscript. All authors reviewed the manuscript.

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