Numerical simulation study on fracture penetration behavior in a reservoir with multiple coal seams

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Abstract. Coal seams are widely deposited in marine-continent transitional facies shale reservoirs. For this type of reservoir, horizontal wells and hydraulic fracturing technology are the main ways to exploit the oil and gas resources. However, multiple layers with uneven thickness and significant differences in physical and mechanical properties among them lead to insufficient vertical fracture propagation, limiting the application of horizontal well and hydraulic fracturing technology. Therefore, to reveal the influence of in situ stress conditions and injection parameters on the vertical propagation of fractures, numerical models with multiple coal seams based on logging lithology were established and the behavior of fractures crossing coal seams under different conditions was studied based on the extended finite element method. In addition, the fracture width and pressure at the injection point were also studied. The simulation results showed that the uneven thickness of the coal seam limited the vertical penetration of the fractures compared with that of a homogeneous formation as the fractures tend to pass through the thinner coal seam. Due to the physical properties difference and stress shadow effect, multiple clusters of fractures were prone to deflection in the coal seam, which made it difficult for hydraulic fractures to grow in height. However, the stress shadow effect in the process of multiple fractures propagation also has a positive side. The stress shadow becomes stronger as the difference in fluid distribution increases, leading to a difference in the growth rate of the fracture up and down, and ultimately improving the overall penetration effect of the fractures. Based on the work presented in this paper, the perforation spacing can be optimized to either avoid the stress shadow effect or effectively utilize its positive influence. Meanwhile, the results can guide the placement of horizontal well and the selection of injection rate.

1. Introduction

Natural gas resources, such as shale gas, have been highly valued over the past decades [1-2]. Recent studies show that marine-continental transitional shale exhibits great exploration potential of shale gas [3-4]. It was evaluated that the recoverable shale gas volume from transitional shale could reach up to $1.29 \times 10^{13} \text{ m}^3$ in China [5]. In this kind of reservoir, shale gas, tight gas, and coalbed methane often coexist and are stored together but the economic benefit is poor when any one is exploited alone. Multilayered mining is an inevitable choice for developing such reservoirs efficiently and economically. Hydraulic fracturing technology has been applied in multilayer mining for passing through multiple pay zones. Therefore, it is important to study the vertical growth of hydraulic fractures in the multilayer formation.

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The vertical growth of cracks in multilayer media is a complicated problem, which has been studied in theory, laboratory experiments, and field tests. Research shows that ground stress is the most important factor affecting the growth of fracture height [6-7]. Cracks in layered strata are difficult to extend because of the mechanical properties and ground stress differences among the layers. Studies have shown that it is easier for fractures to pass from hard rock through soft rock, but the opposite is quite difficult [8-10]. The experimental results show that the layer interface has a significant influence on fracture morphology when hydraulic fractures propagate in a multilithological medium [11-12]. The field measured data found that the actual fracture propagation pattern in layered reservoir is affected by fluid filtration, rock’s physical and mechanical properties, and natural fractures and that the actual fracture height is often less than the predicted height [13]. For lithology association strata, the above studies mainly consider whether fractures can enter or cross adjacent strata. However, multiple sets of thin coal seams are often developed in marine-continental transitional reservoirs, indicating that hydraulic fractures need to pass through them during fracturing. The law of crack extension in strata with frequent soft and hard medium changes needs further study. Therefore, the numerical model of multiple sets of coal seams based on logging lithology was established in the ABAQUS platform. A series of numerical simulations of hydraulic fracturing was carried out to study the propagation behavior of hydraulic fractures in multilayer reservoirs to provide some guidance for the optimization of the fracturing scheme of coal-bearing reservoirs.

2. Numerical model for hydraulic fracturing

2.1. Geological characteristics
The research block is located in the Ordos Basin of China. Many sets of source rocks are deposited in the basin, especially the Permian Shanxi Formation, which has the most complicated lithology. The shale of this layer alternately develops with coal, tight sandstone, and limestone, resulting in poor vertical continuity of the shale. Taking X well as an example, shown in Figure 1, the buried depth of the target layer is 2255–2290 m. Logging results of X well indicate that multiple sets of layers contain hydrocarbons while the thickness of a single layer is only a few meters. Relying on the existing technology, the independent development of a single-layer gas reservoir does not have economic benefits. Therefore, the use of multilayer combined mining is an inevitable choice for the efficient and economic development of this type of gas reservoir.

![Figure 1. Logging profile of X well in the research block.](image-url)
2.2. Numerical model

Based on the logging lithology profile of X well, the 2260–2280 m coal-bearing shale reservoir was modeled, and a 20 m × 20 m finite element numerical model with six sets of stacked coals’ seams were established. To eliminate the boundary effect as much as possible, a surrounding rock model was built around the numerical model with an overall size of 50 m × 50 m (Figure 2a). The plane stress element (CPE4P) with seepage nodes is used to analyze the fluid–solid coupling effect of fluid in the reservoir during hydraulic fracturing and the mesh is refined in the coal-bearing model to capture the fractures more accurately in the subsequent analysis. The total analysis step time was 60 s. Three perforations are set in the model (Figure 2b), and different perforations are activated in different analyses to study various working conditions.

2.3. Model parameters

To obtain the elastic parameters and strength parameters of coal and shale, triaxial compression experiments and Brazilian splitting experiments were carried out. The results showed that the strength and elastic parameters of coal are much lower than those of shale, and it is a relatively soft medium. In the numerical model, the max failure displacement of coal and shale are both set to 0.001 m. To reduce the effect of the physical properties of coal on the crack path, the permeability and porosity of coal and shale are set to the same values. The pore pressure and ground stress obtained by hydraulic fracturing inversion are used as the boundary parameters. Table 1 shows the basic input parameters for numerical simulation.

![Figure 2. Numerical model with multiple coal seams. The figure on the left (Figure a) is the global model with surrounding rock, and the local model in the middle is mesh encrypted to better capture the crack path; $\sigma_v$, $\sigma_h$, and $P_p$ is the vertical stress, horizontal minimum principal stress, and pore pressure, respectively. The right one is the local model (Figure b), and the coal seams in the model are numbered for subsequent analysis. Three perforations are set in the model to simulate multicluster perforations in a horizontal well.]

| Parameters                  | Value     | Parameters                  | Value     | Parameters                  | Value     | Parameters                  | Value     |
|-----------------------------|-----------|-----------------------------|-----------|-----------------------------|-----------|-----------------------------|-----------|
| Horizontal maximum stress   | 46 MPa    | Maximum failure stress of   | 0.56 MPa  | Maximum failure stress of   | 2.04 MPa  | Porosity of coal & shale    | 0.05      |
| Horizontal minimum stress   | 43 MPa    | coal                         | 10.9 GPa  | shale                       | 27 GPa    | Fluid viscosity             | 50 mPa·s  |
| Vertical stress             | 49 MPa    | Elastic modulus of coal      | 0.31      | Elastic modulus of shale    | 0.25      | Leak off coefficient        | $1 \times 10^{-13}$ m$^2$/Pa·s$^{-1}$ |
| Pore pressure               | 23 MPa    | Poisson’s ratio of coal      | 0.01 mD   | Poisson’s ratio of shale    | 0.01 mD   | Inject rate                 | $2 \times 10^{-3}$ m$^3$/s   |
3. Numerical results and discussion

For multilayer mining, hydraulic fractures should penetrate as many layers as possible during the fracturing process. Geo-stress, physical properties, and fracturing measures are important factors for crack penetration. Therefore, it is important to study the impact of these factors on the extension of hydraulic fractures in coal shale formations. This section covers the characteristics of a single fracture’s penetration pattern along the multilayer system and then focuses on the effect of coal permeability and horizontal minimum stress on fracture propagation. Finally, the penetration pattern of two fractures with different perforation flow allocation methods is studied.

3.1. Comparison of models with and without coal seams

To examine the influence of the coal seam on the propagation path of hydraulic fractures, the propagation law of a single fracture in the coal-bearing shale formation is studied, i.e., perforation 2 is activated, and perforations 1 and 3 are suppressed.

3.1.1. Fracture Parameters.

Figure 3 shows the time-history curves corresponding to the fracture height. When the fracture extends to the c-3 coal seam closer to the wellbore, the fracture stops spreading downwards and instead spreads upwards to the c-2 coal seam (Figure 3a). As the injection flow continues to increase, hydraulic fractures penetrate the thinner c-3 coal seam. Finally, the upper crack stops in the c-1 coal seam, and the lower crack stops at the top of the c-5 coal seam with the final fracture heights of 7.5 and 6.75 m, respectively. The homogeneous model finally formed a symmetrical fracture with the upper and lower rallies of 9.25 m. In addition, the distribution of coal seams affects the development of fracture height as well as the final fracture width. The c-2 and c-3 coal seams are close to the wellbore, and the crack width between these two coal seams is greater than that of the homogeneous model while the other widths are relatively narrow. Therefore, compared with the homogeneous model, the existence of coal seams leads to the limited vertical extension of fractures.

![Figure 3.](image)

Figure 3. Fracture parameters of different models. Figure (a) depicts the curves of fracture height versus time, and Figure (b) represents the final fracture height and width.

3.1.2. Pore pressure.

The pore pressure at the crack open mouth, as shown in Figure 4, is compared for the homogeneous and coal seam models. During the injection, the pore pressure increases rapidly to the maximum values of 86.06 and 86.79 MPa for the homogeneous model and coal seams model, respectively, indicating that the fracturing pressure at the injection point is only controlled by the strength of rock around the perforation. Thereafter, the pore pressure decreases to an approximate average value of 45.17 and 48.74 MPa for homogeneous model and heterogeneous model, respectively. We observed that when the fracture started to cross the coal seam, such as at injection times of 10.43 and 25.11 s, it was accompanied by a sudden increase in the pressure at the injection point. Moreover, the pressure distribution of the formation near the fracture is closely related to the location of the coal seam distribution (Figure 5), even though the porosity and permeability of the coal and shale formations are the same in the model setting. This nonuniform pressure distribution is different from the pressure distribution near the fracture in homogeneous strata.
3.2. Effect of coal permeability

There is often an order of magnitude difference between the permeability of coal and that of shale due to differences in the degree of coal cleats’ development. Therefore, the permeability of shale is kept to 0.01 mD and that of coal is set to 0.001, 0.01, 0.1, 1, and 10 mD to investigate the effect of permeability on the crack propagation. The simulation results are shown in Figure 6.

When the permeability of coal rock is lower than that of shale, the evolution pattern of fracture height with injection time is different from when the permeability of coal rock is higher than that of shale. In this case, the permeability of the thick coal seam (i.e., the upper coal seams) has a more significant effect on the fracture height. However, the fracture height in lower coal seams reaches 10 m. Therefore, when fracturing coal shale reservoirs containing uneven thickness, a careful geological study should be conducted to select a suitable borehole trajectory to avoid poor fracturing results in the later development stage.
3.3. Effect of in situ stress

The in situ stress has a significant effect on the crack height. Therefore, numerical simulations were carried out for horizontal minimum principal stresses of 37, 39, 41, 43, and 45 MPa by keeping vertical stress constant. The difference coefficient of stress was defined to investigate the effect of ground stress on crack height (Equation 1). The numerical simulation results are shown in Figure 7.

\[ \delta = \frac{\sigma_v - \sigma_h}{\sigma_h} \]  

where \( \delta \) is the differential coefficient of stress.

Under different stress discrepancy coefficients, all the upper fractures stop at the thickest coal seam c-1; the stress discrepancy coefficient increases from 0.09 to 0.32, and the upper fracture height increases from 7.25 m to 8 m. However, the coal seam crossed by the lower fracture is closely related to the stress discrepancy coefficient; the fracture height increases from 6.75 to 10 m and crosses the lower four sets of coal seams. In addition, the total thickness of the upper two sets and the lower four sets is 3 m. The thickness and location of the upper and lower coal seams lead to competing behavior in the upper and lower extension of the cracks, making the hydraulic fractures pass through multiple sets of thinner coal seams.

3.4. Effect of stress shadow

It has been long observed in field tests that the extension of a hydraulic fracture cause changes in local ground stress, which affect the extension path and fracturing pressure of other hydraulic fractures. These induced stress fields are referred to as stress shadow. The stress shadow between two cracks often cause fractures to deflect. To study the influence of stress shadow on the propagation path of hydraulic fractures, perforation 2 was suppressed, and perforations 1 and 3 were activated. In this section, the stress effects under different flow distribution ratios of perforations 1 and 3 were studied. Three scenarios were analyzed while keeping the total injection volume consistent with that under a single cluster of perforation. In case I, perforations 1 and 3 were both injected at a flow rate of 1 \( \times 10^{-3} \) m³/s; in case II, perforations 1 and 3 were injected at a flow rate of 0.8 \( \times 10^{-3} \) m³/s and 1.2 \( \times 10^{-3} \) m³/s, respectively; in case III, perforations 1 and 3 were injected at a flow rate of 0.6 \( \times 10^{-3} \) m³/s and 1.4 \( \times 10^{-3} \) m³/s, respectively. The simulation results are shown in Figures 8 and 9.

Fracture 1 is defined as the fracture that propagates from perforation 1, and fracture 3 corresponds to perforation 3. Figure 8 shows that the contour of the horizontal principal stress at 10 s and the same graph limits were adjusted in these three cases. The contours show that tensile stress is concentrated at the tip of the crack, whereas a compressive zone exists on both sides of the fractures. The compressive stress values in the stress shadow zones at the location of perforation 2 were determined as 30.19, 28.34, and 28.16 MPa, respectively, under the three cases. The compressive stress decreased from case I to III, indicating a decrease in the stress shadow effect.
Figure 8. Horizontal principal stress distribution in different cases.

Figure 9 shows the final crack path and pore pressure distribution under the three cases. With a uniform distribution of flow, fractures 1 and 2 are symmetrically distributed. Under unequal flow distribution, there is a competitive behavior of fracture propagation with fracture 1 preferentially extending upward and fracture 2 extending downward. Fracture 1 is deflected after encountering the c-2 coal seam. The larger the flow difference becomes, the greater is the degree of deflection. However, the total fracture heights of 13.75 and 13.5 m in Cases II and III, respectively, are only 0.5 and 0.75 m less than the total fracture height of 14.25 m for a single fracture. This indicates that the hydraulic fractures can be made to pass through multiple coal seams using the competing behavior of different fractures. In addition, the closer the perforation spacing, the stronger is the stress shadow effect. The perforation spacing can be optimized to either avoid the stress shadow effect or effectively utilize its positive influence.

Figure 9. Fracture paths and pore pressure distribution in different cases.

4. Conclusion

Based on extended finite elements, the behavior characteristics of hydraulic fractures through coal seams in coal-bearing reservoirs were studied. The vertical extension law of fractures was compared for coal-bearing and non-coal-bearing reservoirs, and the effects of coal seam permeability, ground stress characteristics, and stress shadow on the effect of hydraulic fractures through the seam were investigated. The main conclusions are as follows:

The presence of soft coal seams limits the vertical extension of hydraulic fractures. When coal seams exist above and below the wellbore, the width of the inter-seam hydraulic fractures is greater than the width of the fractures above and below the coal seams, which in turn creates a narrow opening near the coal seams.

The greater the coal seam permeability and the stress difference coefficient, the greater is the fracture seam height. Compared with thin coal seams, the thick coal seams have a stronger influence...
on the vertical extension of the hydraulic fracture, and the hydraulic fracture propagation process tends to stop at the thick coal seam.

The characteristic of the stress-shadowing effect is that it may not always inhibit the vertical extension of the fractures. Competitive behavior between cracks due to the stress shadow effect can be used to promote hydraulic cracks through multiple sets of coal seams, which is almost as effective as that of a single crack through the seam.

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