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Optimal Design of Horizontal Well Cluster Spacing Based on Extended Finite Element and Numerical Simulation

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Abstract: As a crucial component of volumetric fracturing in unconventional oil and gas reservoirs, the design and optimization of cluster spacing significantly impact the morphology and production of fractures. Therefore, this paper establishes a multi-fracture propagation geological model based on the extended finite element method to study the scale and morphology of fracture propagation. Simultaneously, a gas reservoir model is established using CMG software, guided by production goals, and incorporating rock mechanics and physical parameters from region M to optimize cluster spacing design. The results indicate that smaller cluster spacing results in greater stress shadow effects, hindering the propagation of central fractures, and increasing the overlap of pressure drop zones, leading to possible repeated modifications during construction. Conversely, larger cluster spacing reduces stress shadow effects but may leave some areas between clusters unmodified, affecting production. Thus, through combined simulation optimization using both methods, a cluster spacing of 10-15 meters is recommended for region M, which has shown good on-site application results, significantly reducing the rate of repeated modifications.

Keywords: Extended finite element, cluster spacing, fractures, fracturing, stress.

1. Introduction

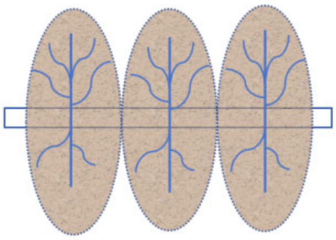
Multistage fracturing in horizontal wells has become a major method for enhancing production in unconventional gas reservoirs such as shale gas, shale oil, deep coalbed methane, and tight oil and gas. Due to the characteristics of unconventional reservoirs, including low permeability, low porosity, and high stress, it is essential to create complex network fractures during fracturing to reduce the initiation pressure of oil and gas and decrease the flow distance of oil and gas, thus enabling effective development[1]. The optimization of cluster spacing is particularly crucial for the propagation of fractures in reservoirs, considering the impact of stress shadowing on the initiation of multiple fractures in horizontal wells.

In recent years, both domestic and international scholars have conducted extensive research on multistage fracturing in horizontal wells and the optimization of cluster spacing. International scholars such as Gordeliy from the United States[2]have studied the influence of stress interference during fracture propagation through experiments and numerical simulations, proposing methods to optimize cluster spacing to minimize mutual interference between fractures and enhance fracturing efficiency. Warpinski et al.[3]have investigated the impact of cluster spacing on fracture oil and gas production. Similarly, domestic researchers have made significant contributions in this field. Chen Qian et al.[4]analyzed the impact of parameters such as the number of fractures and fracture length on production. Zeng Qingdong et al.[5]combined numerical simulation and laboratory experiments to study the fracture propagation patterns under different cluster spacings and provided optimization design recommendations. Zeng Shunpeng et al.[6]developed a multi-fracture induced stress field model based on fracture mechanics and seepage theory to analyze the stress interference between fractures and its effect on fracture propagation, without investigating its impact on production.

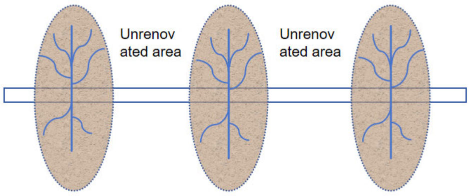
Most previous studies have independently examined fracture propagation and its impact on production, with few studies addressing both aspects simultaneously. Addressing this gap, this paper innovatively optimizes cluster spacing by considering both fracture propagation and its impact on production. Drawing on previous experience and combining the extended finite element method (XFEM) with the multi-fracture induced stress field theory, we developed a numerical simulation model. Our study not only considers the morphology of fracture propagation but also analyzes its impact on oil and gas production, proposing a comprehensive cluster spacing optimization design. Furthermore, we validated the effectiveness of the proposed model and method through practical application, providing new insights and technical support for the efficient development of unconventional reservoirs.

The extended finite element method (XFEM) is a finite element method based on element decomposition. Compared with traditional finite element methods, it introduces enhanced shape functions to characterize the displacement discontinuity of fractures[7]. XFEM allows discontinuous structures to be independent of the computational mesh, eliminating the need for local mesh refinement around discontinuities, significantly reducing computational workload. When applied to fracture propagation problems, XFEM can predict fracture propagation in any direction without predefining the fracture path[6]. Therefore, this paper adopts the extended finite element simulation in Abaqus to optimize cluster spacing, providing guidance for field design.

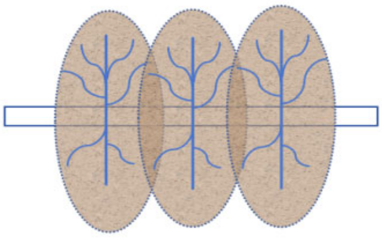
After fracturing operations, a controllable linear flow pressure boundary of hydraulic fractures forms around each bifurcated fracture wing. Within this boundary, linear flow predominates, significantly enhancing the production efficiency of formation fluids compared to radial flow around the wellbore before modification[8]. However, the controllable linear flow pressure boundary of hydraulic fractures is not infinite; formation fluids far from the hydraulic fractures still struggle to participate in linear flow, necessitating densification modifications towards the wellbore direction[9]. If the cluster spacing is too large, there will be unmodified blind spots between clusters, contributing no production,as shown in Fig.1. Conversely, if the spacing is too small, redundant modifications occur, reducing fluid efficiency and significantly increasing modification costs[10-11],



a.Cluster spacing is reasonable



b.Cluster spacing is too large



c.Cluster spacing is too small

Figure 1. Distribution of seepage boundaries at different clusters at production distances

2. Mathematical Models

2.1. Extended Finite Element Method (XFEM) Basic Theory

The extended finite element method (XFEM) consists of standard finite elements and enrichment functions based on the partition of unity method. This approach can more accurately describe discontinuities such as fractures in complex physical fields. The displacement vector function is expressed as follows: [12-17]

$$u = \sum_I N_I(x) u_I + \sum_J N_J(x)\Phi(x) q_J \tag{1}$$

$N_I(x)$ are the standard finite element shape functions, u are the standard nodal degrees of freedom, $\Phi(x)$ is the enrichment function, and q are additional degrees of freedom.

The rock failure criterion uses the maximum principal stress criterion, which states that failure initiates when the maximum principal stress exceeds a critical value:

$$\langle \sigma_{\max} \rangle = \sigma_{0\max} \tag{2}$$

where $\sigma_{0\max}$ is the critical maximum principal stress in MPa; $\langle\rangle$ denotes Macaulay brackets indicating that compressive stress does not induce fracture.

The crack propagation and evolution process after crack opening is described using the BK criterion:

$$G_{equivC} = \mathrm{G_{IC}} + (\mathrm{G_{IIC}} - \mathrm{G_{IC}}) \left[\frac{\mathrm{G}_{III} + \mathrm{G}_{II}}{\mathrm{G}_{III} + \mathrm{G}_{II} + \mathrm{G}_{I}} \right]^n \tag{3}$$

where G_{equivC} is the critical energy release rate in MN/m, $\mathrm{G_{IC}}$ and $\mathrm{G_{IIC}}$ are the fracture toughness values in the normal and first shear directions in MPa·m$^{1/2}$, $\mathrm{G}_I \cdot \mathrm{G}_{II} . \mathrm{G}_{III}$ are the energy release rates in the normal and first shear directions in MN/m, and n represents the work done by the stress on the corresponding displacement.

2.2. Multi-Fracture Induced Stress Field

During multistage fracturing in horizontal wells, the main fractures induce a stress field around them, affecting the surrounding geostress field and altering the local stress distribution at the fracture tips. The superposition of the induced stress field and the geostress field can lead to local stress reversals, influencing the initiation and propagation of subsequent fractures[18-22]. The induced stress field theory is studied based on fracture mechanics under the assumptions of homogeneity, isotropy, and plane strain conditions. Figure 2 illustrates the schematic diagram of the stress field caused by cracks.

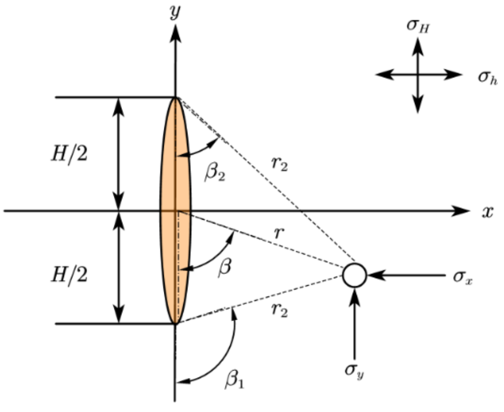


Figure 2. Schematic diagram of the stress field caused by cracks

It is assumed that the fracture is vertical, with an elliptical vertical section, height h ; x is along the horizontal wellbore, and the y is in the direction of the maximum horizontal stress. Tensile stress is positive, and compressive stress is negative. The induced stress at any point is:

$$\begin{cases} \sigma_x = -p\frac{r}{c}(\frac{c^2}{r_1 r_2})^{\frac{3}{2}} \sin\beta \sin[\frac{3}{2}(\beta_1+\beta_2)] + p\left[\frac{r^2}{(r_1 r_2)^{\frac{1}{2}}}\cos(\beta-\frac{1}{2}\beta_1-\frac{1}{2}\beta_2)-1\right] \\ \sigma_z = p\frac{r}{c}(\frac{c^2}{r_1 r_2})^{\frac{3}{2}} \sin\beta \sin[\frac{3}{2}(\beta_1+\beta_2)] + p\left[\frac{r}{(r_1 r_2)^{\frac{1}{2}}}\cos(\beta-\frac{1}{2}\beta_1-\frac{1}{2}\beta_2)-1\right] \\ \sigma_y = v(\sigma_x+\sigma_z) \\ c = H/2 \end{cases} \quad (4)$$

σ_x 、 σ_y and σ_z are the induced stress components , MPa, p is the fluid pressure ,MPa, v is Poisson's ratio. The stress field around later fractures is the sum of the induced stress from earlier fractures and the original geostress[23].

2.3. Reservoir Model

For simulating production dynamics of multistage fracturing in tight sandstone gas reservoirs, the widely used black oil model is selected, with the following assumptions [24]:

1. There is no crude oil in the reservoir, only gas and water phases.

2. There is no mass exchange between gas and water; fluids follow Darcy's law.

3. The reservoir exhibits heterogeneity and anisotropy; formation rock and fluid are slightly compressible.

4. The reservoir is rectangular, with isothermal fluid flow.

5. The horizontal wellbore is completed with casing, and production relies solely on fractures, disregarding the wellbore's impact on production.

6. Capillary pressure is considered, while gravity is ignored.

Gas phase flow equation

$$\frac{\partial}{\partial_x}\left(\frac{K\ K_{rg}\rho_g}{\mu_g}\frac{\partial p}{\partial_x}\right)+\frac{\partial}{\partial_y}\left(\frac{K\ K_{rg}\rho_g}{\mu_g}\frac{\partial p_f}{\partial y}\right)+\frac{\partial}{\partial_y}\left(\frac{K\ K_{rg}\rho_g}{\mu_g}\frac{\partial p}{\partial z}\right)=\frac{\partial}{\partial_t}\left(\rho_g\phi\ S_g\right)(5)$$

Water phase flow equation

$$\frac{\partial}{\partial_x}\left(\frac{K\ K_{rw}\rho_w}{\mu_w}\frac{\partial p}{\partial_x}\right)+\frac{\partial}{\partial_y}\left(\frac{K\ K_{rw}\rho_w}{\mu_w}\frac{\partial p_f}{\partial y}\right)+\frac{\partial}{\partial_y}\left(\frac{K\ K_{rw}\rho_w}{\mu_w}\frac{\partial p}{\partial z}\right)=\frac{\partial}{\partial_t}\left(\rho_w\phi\ S_w\right)(6)$$

Auxiliary equation:

$$\begin{cases} S_g + S_w = 1 \\ P_g = P_c + P_w \\ K_{rg} = K_{rg}(S_g) \\ K_{rw} = K_{rw}(S_w) \\ \phi = \phi(1 + C_f(p-P)) \\ \rho = \rho_l(1 + C_l(p-P_g)) \end{cases} \quad (7)$$

2.4. Fracture Mode

Given the small fracture thickness, a two-dimensional, two-phase model is established for hydraulic fractures, considering fluid flow in the fracture plane while neglecting flow in the fracture width direction [24]

Assumptions

(1) The fracture is homogeneous with isotropic permeability

(2) Gravity effects are ignored.

(3) Fluid flow in the fracture follows Darcy's law

Fracture mathematical model:

$$\begin{cases} \frac{\partial}{\partial_x}\left(\frac{K_f K_{rgf}}{\mu_g B_g}\frac{\partial p_f}{\partial_x}\right)+\frac{\partial}{\partial_x}\left(\frac{K_f K_{rgf}}{\mu_g B_g}\frac{\partial p_f}{\partial z}\right)=\frac{\partial}{\partial_t}\left(\rho_g\phi\ S_g\right) \\ \frac{\partial}{\partial_x}\left(\frac{K_f K_{rwf}}{\mu_w B_w}\frac{\partial p_f}{\partial_x}\right)+\frac{\partial}{\partial_x}\left(\frac{K_f K_{rwf}}{\mu_w B_w}\frac{\partial p_f}{\partial z}\right)=\frac{\partial}{\partial_t}\left(\rho_w\phi\ S_w\right)(8) \\ S_g + S_w = 1 \end{cases}$$

3. Fracture Propagation Patterns with Different Cluster Spacings

Taking the M block of the Sichuan Basin's tight sandstone gas reservoir as an example, a fracture propagation model is established. The main producing layer is the second member of the Shahejie Formation (Sha-2), with the middle part of the Sha-2-2 sub-member being the key exploration and development target. The reservoir thickness ranges from 8 to 33 meters, and the lithology is primarily medium to fine-grained feldspathic sandstone, with some lithic feldspathic sandstone. The primary storage space type is intergranular pores, followed by intragranular dissolution pores. The average Young's modulus is 2.47×10^4 MPa, Poisson's ratio is 0.23, brittleness index is 36.4%, the maximum horizontal principal stress is 60.2 MPa, and the minimum horizontal principal stress is 52.7 MPa. Porosity ranges from 7% to 15% (average 8.3%), and permeability ranges from 0.01 mD to 1 mD (average 0.57 mD). Formation pressure ranges from 16.37 to 26.52 MPa, with a pressure coefficient between 0.77 and 1.17.

The study uses the extended finite element method (XFEM) in ABAQUS software to analyze the propagation patterns of fractures in horizontal wells. During propagation, fractures alter the original stress field, and the new stress field affects the morphology of subsequent fractures[25]. The model dimensions are set to 50m×50m. The perforation points are defined as initial fractures with a length of 1m, acting as the initial fractures in the model. The horizontal wellbore is aligned with the direction of the minimum horizontal principal stress, and the perforation initial orientation is perpendicular to the wellbore, as shown in Fig. 3

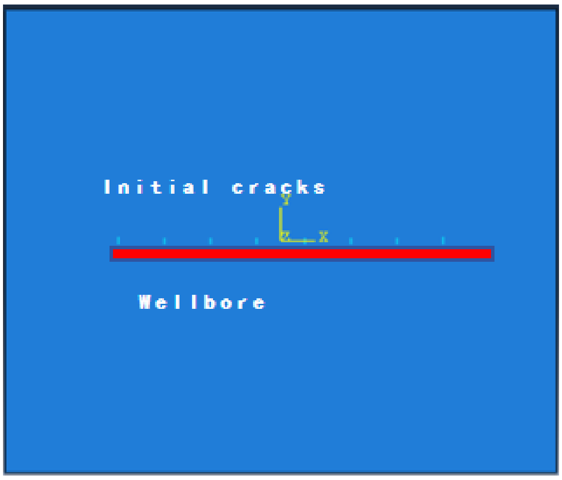
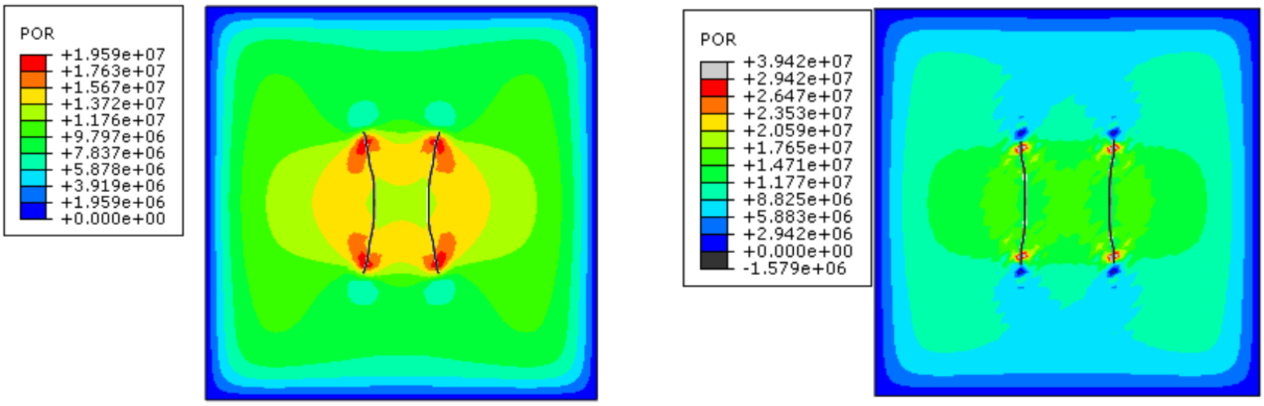


Figure 3. Schematic diagram of the model

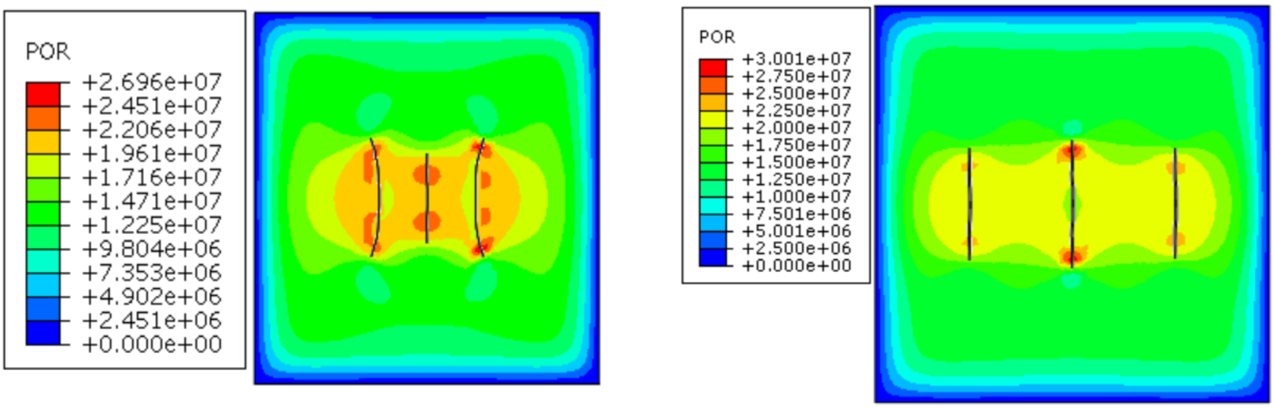
Simulation results for two clusters with different spacings are shown in Fig. 4. As fractures propagate, stress concentration occurs at the fracture tips. The closer the spacing, the greater the stress influence, resulting in larger deflection angles. As the spacing increases, stress interference between fractures decreases, leading to reduced deflection distances and angles. After overcoming the stress at the tips, fractures propagate towards the direction of the maximum principal stress.



a.Spacing 10m b.Spacing 15m

Figure 4. Pore pressure distribution contour of two clusters with different spacing

Simulation results for three clusters with different spacings are shown in Fig. 5. When the spacing is 10 meters, the middle fracture is significantly affected by stress, hindering its propagation and resulting in a shorter length. The outer fractures are also influenced by stress, causing deflection and longer propagation lengths. When the spacing is increased to 15 meters, stress impact is minimal, and all three fractures propagate evenly in the direction of the maximum principal stress. Therefore, based on ABAQUS simulation results, to maximize the stimulated volume and promote even fracture propagation, a cluster spacing of 10-15 meters is recommended.

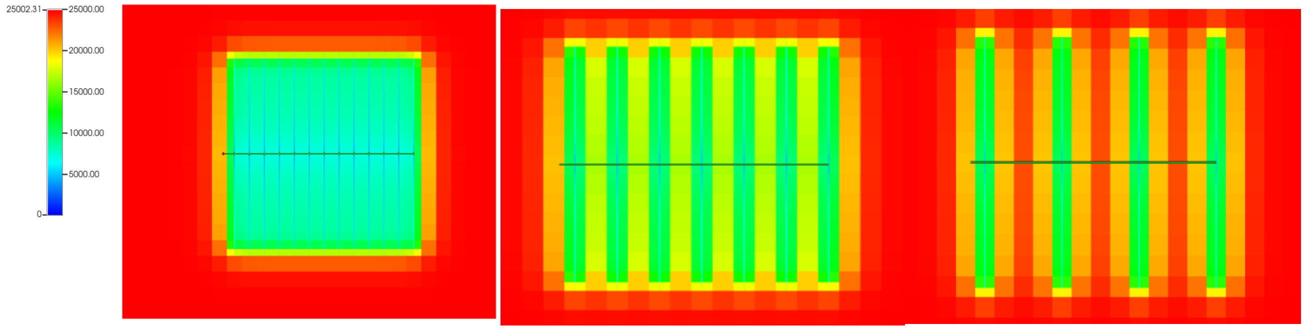


a.Spacing 10m b.Spacing 15m

Figure 5. Pore pressure distribution contour of three clusters with different spacing

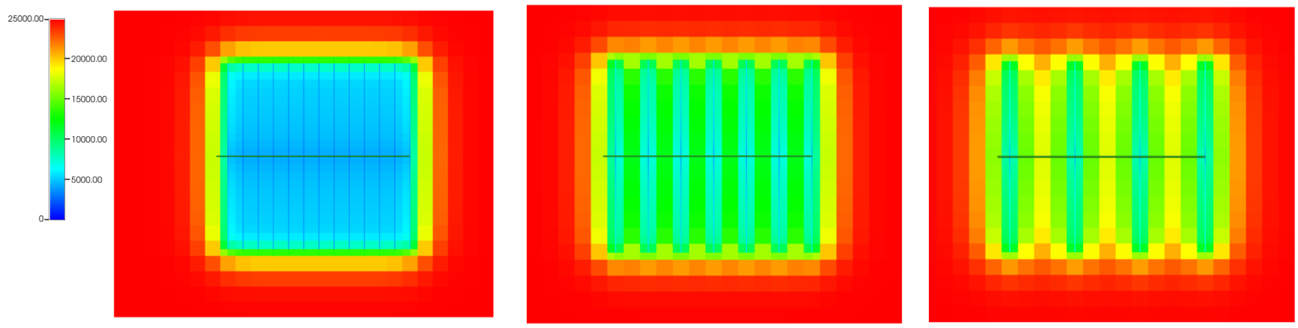
4. Numerical Simulation Optimization

A tight gas geological model is established using the Builder component in CMG software, and the IMEX module is used for solving. Simulations are conducted for each segment of 100 meters, with a fracture half-length of 100 meters, and a given production regime is observed over a certain period to monitor pressure distribution and production. Only the fracture spacing parameter is altered for optimizing cluster spacing, while other model parameters remain unchanged. As shown in Figs. 6-7, a spacing of 10 meters results in excessive clustering, causing severe interference between fractures, overlapping pressure drawdown regions, and higher chances of re-stimulation during fracturing, which is not conducive to reducing construction costs and improving fluid efficiency. After one year of production, the daily output is lower compared to a spacing of 15 meters (Fig. 8). When the spacing is 20 meters, insufficient stimulation of the reservoir occurs, leading to the lowest daily output. Therefore, a spacing of 15 meters balances economic efficiency and production. Thus, it is recommended that the cluster spacing for this block be set between 10-15 meters.



a.Spacing 10m b.Spacing 15m C.Spacing 20m

Figure 6. Pressure distribution diagram after one year of production



a.Spacing 10m b.Spacing 15m C.Spacing 20m

Figure 7. Pressure distribution diagram after two years of production

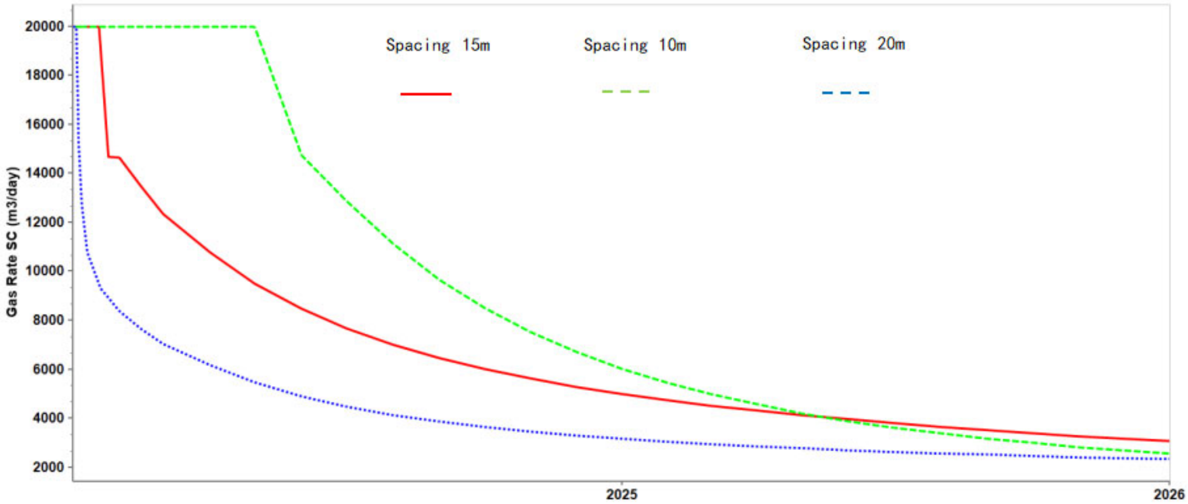


Figure 8. Comparison curve of daily production

5. Field Application Effect

Based on the basic parameters such as logging, physical properties, and mechanics of well M-1, the cluster perforation optimization design for the horizontal section of this well was conducted. Considering fracture propagation morphology and production, it is recommended that the cluster spacing in the M area be 10-15 meters. This spacing design can minimize stress interference while maximizing the coverage of the fracture network and improving oil and gas production. The process involves high flow rates, large fluid volumes, and high sand volumes, with staged fracturing sections of 80-100 meters. The main construction flow rate is 18 m³/min, pumping pressure is 60-66 MPa, average shut-in pressure is 48.3 MPa, sand volume is 6700 tons, fluid volume is 26133 m³, sand intensity is 4.5 tons/m, maximum sand concentration is 480 kg/m³, fluid intensity is 19.5 m³/m, and the overall sand-to-fluid ratio is 17.09%. Microseismic monitoring indicates good fracture propagation, with an average extension length of approximately 369 meters and a total fracture volume of 17.3917 million cubic meters, with an actual total stimulated reservoir volume (SRV) of 12.6548 million cubic meters. The daily production is 235,000 cubic meters, with an overlap ratio of 15.24%. In comparison, a neighboring well with a cluster spacing of 7-10 meters had a sand intensity of 5.1 tons/m, fluid intensity of 21.5 m³/m, an overlap ratio of 26.52%, and a daily production of 229,000 cubic meters. The optimized cluster spacing design not only reduces re-stimulation rates and improves fluid efficiency but also lowers construction scale and costs, achieving cost reduction and efficiency enhancement. Therefore, a cluster spacing of 10-15 meters is more suitable for this block compared to a spacing of 7-10 meters.

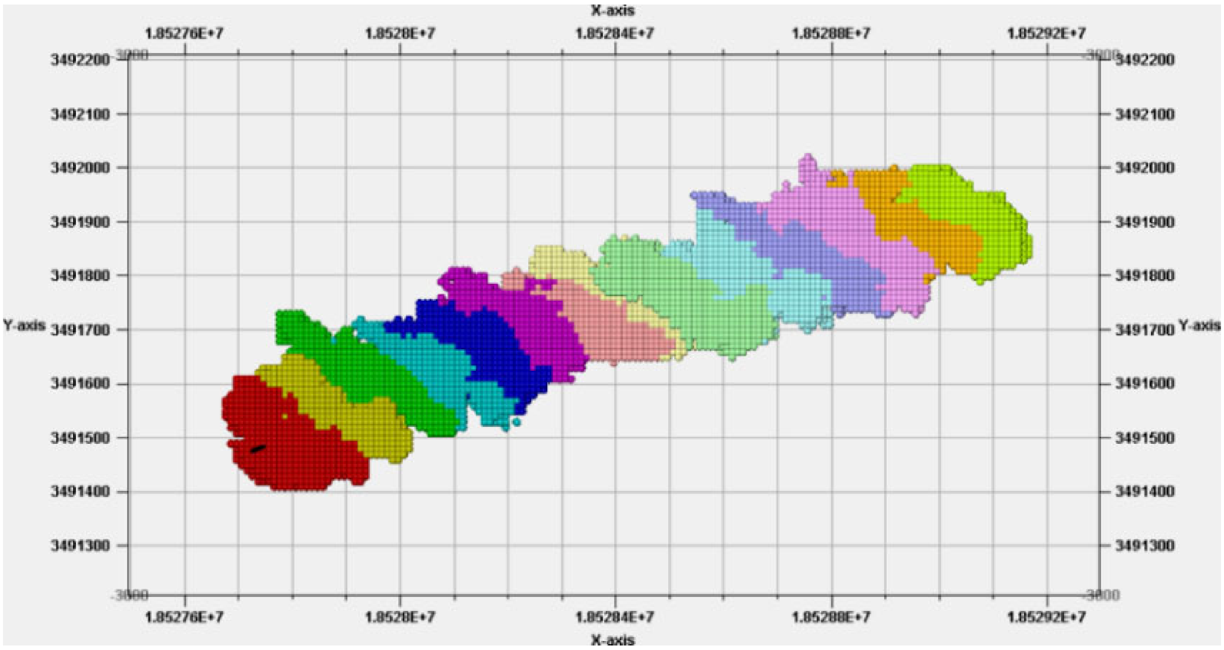


Figure 9. Microseismic monitoring results of Well M-1

6. Conclusion

1. Analysis of Fracture Propagation Using Abaqus Extended Finite Element Method: The study analyzed the fracture propagation patterns in Block M under different cluster spacings. The results indicate that smaller cluster spacing leads to a greater influence of combined in-situ and induced stresses on the fractures, causing significant fracture deflection. The middle fractures, in particular, are heavily impacted by adjacent fractures, resulting in hindered propagation and shorter lengths. Conversely, larger cluster spacing results in less fracture deflection and smoother propagation of the middle fractures.

2. Optimization of Cluster Spacing through Numerical Simulation: Numerical simulation results reveal that a cluster spacing of 10 meters leads to substantial overlap in pressure diffusion boundaries between fractures, potentially causing repeated modifications during field operations. In contrast, a spacing of 20 meters creates insufficiently stimulated areas between clusters, adversely affecting production. Therefore, an optimal cluster spacing of 10-15 meters is recommended for Block M to balance the effectiveness of stimulation and construction costs.

3. Field Application Results: Field application results from Well M-1 demonstrate that a cluster spacing of 10-15 meters effectively reduces the rate of repeated modifications, significantly lowers construction costs, and enhances oil and gas production, achieving the goal of cost reduction and efficiency improvement. Specific data indicate that the optimized cluster spacing design has yielded excellent results in actual production, validating the feasibility and superiority of the optimization scheme.

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