

Article

Numerical Simulation Study and Field Practice of Balanced Fracture Propagation Under Non-Uniform Perforation: A Case Study of Shale Oil in the Kong'er Member of the Cangdong Sag

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Abstract

Multi-cluster perforation staged fracturing in horizontal wells has become an important means of completion stimulation for unconventional oil and gas reservoirs. However, the non-uniform propagation of multi-cluster hydraulic fractures remains one of the key challenges restricting efficient reservoir stimulation. In this study, based on the finite element method and considering factors such as frictional pressure drop along the wellbore for power-law fluid, perforation friction, and stress interference, a fracture propagation model with dynamic multi-stage flow distribution coupling formation, perforation, and wellbore flow was constructed. The effects of non-uniform perforation schemes, total number of perforations, and perforation non-uniformity coefficient on multi-cluster fracture propagation behavior were systematically investigated, and the characteristics of dynamic flow distribution were clarified. The results show that the order of fluid intake uniformity among different perforation schemes is as follows: spindle-shaped perforation, uniform perforation, and Tapered perforation. Reducing the number of perforations and decreasing the perforation non-uniformity coefficient can improve the uniformity of fracture propagation to a certain extent. The findings of this study can provide a theoretical basis and practical reference for efficient fracturing stimulation of shale oil in the Cangdong Sag.

Keywords: shale oil horizontal well; volume fracturing; perforation parameter optimization; finite element method



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1. Introduction

Unconventional resources such as shale oil have become a crucial strategic replacement energy source for China. As the primary means of unconventional oil and gas development, large-scale hydraulic fracturing still faces technical challenges related to uneven fracture initiation and insufficient stimulated reservoir volume. Previous practices indicate that reducing fracture spacing can enhance fracture network complexity and stimulation effectiveness; however, excessively small spacing intensifies stress interference, leading to restricted propagation or even failure of initiation in certain perforation clusters [1–3]. Therefore, it is necessary to optimize perforation parameters to mitigate inter-cluster stress interference and promote balanced fracture propagation [4–6].

The influence of perforation parameters on fracture propagation uniformity is a prominent issue in fracturing technology for horizontal shale oil wells [7–9]. Zhao Jinzhou et al. [10] determined the perforation friction required for balanced propagation of multi-cluster fractures based on inter-cluster induced stress and optimized the perforation parameters. Wu et al. [11] established a multi-cluster fracture propagation model using fluid–solid coupling principles and recommended appropriately reducing the number of clusters to achieve more uniform fracture growth. Peirce et al. [12] proposed that non-uniform perforation can facilitate balanced fracture propagation. Hu et al. [13] investigated the propagation behavior of multi-cluster hydraulic fractures under different stress differentials and suggested that appropriately increasing the fracturing fluid viscosity and pumping rate can improve the uniformity of fluid intake among clusters to some extent.

The aforementioned studies mainly focus on stress interference phenomena and the analysis of inter-cluster interactions, but have two limitations. First, they typically calculate the wellbore friction and perforation friction first, then assume a fixed flow rate at the fracture inlet, neglecting the dynamic flow distribution under the effect of friction. Second, while these studies have investigated the mechanical mechanisms of multi-cluster fracture propagation, they do not provide a detailed discussion of fracture propagation behavior under non-uniform perforation conditions, such as the influence of the Perforation non-uniformity index. To address these issues, this study builds upon previous findings and establishes a fracture propagation model with dynamic multi-stage flow distribution that couples formation, perforation, and wellbore flow. Using the fluid intake uniformity index as an evaluation criterion, the effects of different perforation schemes, total number of perforations, and perforation non-uniformity coefficient on the competitive propagation of multi-cluster fractures are systematically analyzed and discussed. Finally, the reliability of the proposed model is validated through field tests. The research results provide a theoretical basis for the development of shale oil in the Kong2 Member of the Cangdong Sag.

2. Methods

2.1. Governing Equations

2.1.1. Traction–Separation Criterion

The cohesive element method is employed to simulate fracture initiation and propagation, with the fracture behavior described by the traction–separation law [14]. When an external load is applied to the fracture, the stress increases linearly with the opening/shear displacement until the stress threshold is reached, after which damage initiates at the interface.

Because both tensile and shear stresses exist simultaneously on the upper and lower surfaces of the element, the initiation and propagation processes in the cohesive element model must account for the combined effects of normal and tangential stresses on both surfaces. In this study, the quadratic nominal stress traction–separation criterion (Figure 1) is used to simulate fracture initiation.

When the fracture initiates, the value of the quadratic interaction function equals 1, which can be expressed as follows:

$$\left\{ \frac{\langle t_n \rangle}{t_n^0} \right\}^2 + \left\{ \frac{\langle t_s \rangle}{t_s^0} \right\}^2 + \left\{ \frac{\langle t_t \rangle}{t_t^0} \right\}^2 = 1 \quad (1)$$

where t_n^0 , t_s^0 and t_t^0 represent the critical stresses in the normal, first tangential, and second tangential directions of the cohesive element, respectively, in Pa; and t_n , t_s , t_t represent

the current stresses in the normal, first tangential, and second tangential directions of the cohesive element, respectively, in Pa.

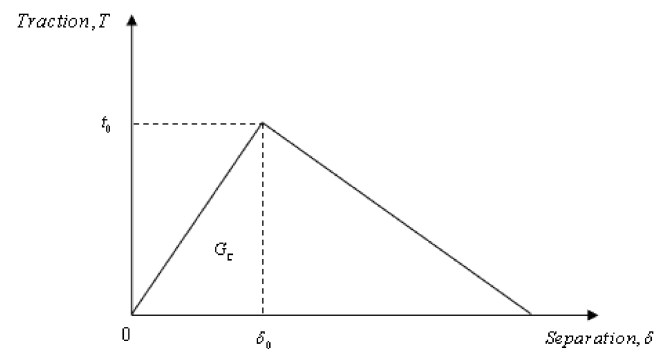


Figure 1. Traction–separation criterion for cohesive elements.

After fracture initiation, the damage evolution is evaluated using fracture energy theory, and the fracture development is described based on the Benzeggagh–Kenane (B–K) fracture criterion:

$$G_n^C + (G_s^C - G_n^C) \left\{ \frac{G_s + G_t}{G_n + G_s + G_t} \right\}^\eta = G^C \quad (2)$$

where G_n^C represents the Mode I critical fracture energy, G_s^C represents the Mode II critical fracture energy, G_n , G_s , G_t represent the fracture energies in the normal, first tangential, and second tangential directions, respectively, and η is a material parameter. When the cohesive element fails, $G_C = G_n + G_s + G_t$.

2.1.2. Fracturing Fluid Flow Equation

During the research process, it is assumed that the fracturing fluid is an incompressible fluid and flows only in the tangential and normal directions within the fracture. In this study, the tangential flow is assumed to follow Newtonian fluid behavior, and its governing equation is derived from the Navier–Stokes equations.

$$q = -\frac{d^2}{12\mu} \nabla p \quad (3)$$

where q is the flow rate inside the fracture, m^3/min ; d is the fracture aperture, mm; μ is the fracturing fluid viscosity, $\text{mPa}\cdot\text{s}$; p is the net pressure inside the fracture, MPa.

Its mass conservation equation is as follows:

$$\frac{\partial d}{\partial t} + \nabla(qd) + (q_t + q_b) = Q_{inj} \quad (4)$$

where q_t and q_b are the flow rates corresponding to the upper and lower boundaries of the model element, in m^3/min ; Q_{inj} is the injection rate, in m^3/min .

The equation for fracturing fluid filtration from the fracture into the matrix (i.e., normal flow) is as follows:

$$\begin{cases} q_t = c_t(p - p_t) \\ q_b = c_b(p - p_b) \end{cases} \quad (5)$$

where c_t and c_b are the fracturing fluid filtration coefficients at the top and bottom of the element, in $\text{m}/\text{min}^{0.5}$; p_t and p_b are the pressures at the top and bottom of the element, in MPa.

2.2. Dynamic Flow Distribution

Bernoulli's equation is adopted to describe the steady-state flow of fracturing fluid in the horizontal wellbore [15]. The frictional pressure loss along the wellbore can be expressed as:

$$\Delta P_{\text{wellbore}} - \rho g \Delta Z = (C_L + K_i) \frac{\rho V^2}{2} \quad (6)$$

where ΔP is the pressure difference between two nodes, Pa; ΔZ is the elevation difference between two nodes, m; K_i is the local loss coefficient; and C_L is the frictional loss coefficient, $C_L = f/D_h$.

Among them, the Churchill model is used to describe the frictional loss:

$$\begin{cases} f = 8 \left[\left(\frac{8}{\text{Re}} \right)^{12} + \frac{1}{(A+B)^{1.5}} \right]^{\frac{1}{12}} \\ A = \left[-2.457 \ln \left(\left(\frac{7}{\text{Re}} \right)^{0.9} + 0.27 \left(\frac{K_s}{D_h} \right) \right) \right]^{16} \\ B = \left(\frac{37350}{\text{Re}} \right)^{16} \end{cases} \quad (7)$$

where K_s is the absolute roughness of the pipe.

When the fracturing fluid flows from the wellbore into the fracture through perforations, a local pressure loss occurs at the perforation entrance, which can be expressed as follows:

$$\Delta P_{\text{perf}} = 0.807249 \times \rho \left(\frac{Q}{NC_d D_p^2} \right)^2 \quad (8)$$

where Q is the flow rate, m^3/h ; D_p is the perforation diameter, m; N is the number of perforations; and C_d is the perforation shape coefficient.

During staged multi-cluster fracturing in horizontal wells, multiple perforation clusters are arranged. Once the fracturing fluid is pumped in, the multi-cluster fractures initiate simultaneously and propagate competitively. In the model, pipe flow elements are used to simulate the horizontal wellbore, and connector elements are used to simulate the perforations. Based on the principles of flow rate conservation (i.e., the total flow rate equals the sum of flow rates entering each fracture cluster) and pressure equality (i.e., the pressure at a wellbore node equals the sum of the fracture pressure within each cluster and the perforation friction pressure), dynamic flow rate distribution among clusters is ultimately achieved.

2.3. Evaluation Methods

2.3.1. Uniformity Index

To evaluate the uniformity of fractures under different perforation parameters, the fluid intake uniformity index is defined. A larger value of this index indicates a more uniform fluid distribution among the fracture clusters:

$$F_{U.I.} = 1 - \frac{\sqrt{\frac{\sum_{i=1}^n (v_{fi} - \bar{v}_f)^2}{n}}}{\bar{v}_f} \quad (9)$$

where v_{fi} is the fluid intake volume of each fracture cluster, m^3 ; and $\bar{v}_f$ is the average fluid intake volume, m^3 .

2.3.2. Perforation Non-Uniformity Index

In addition, to characterize the difference in the number of perforations per cluster under non-uniform perforation, the perforation non-uniformity index is defined. A larger value of this index indicates a greater difference in the number of perforations among clusters.

$$PE_{U.I.} = \frac{MAX(N_1 : N_i) - MIN(N_1 : N_i) + \left| N_1 + N_i - 2\frac{N}{i} \right|}{N} \quad (10)$$

where $MAX(N_1 : N_i)$ and $MIN(N_1 : N_i)$ represent the maximum and minimum numbers of perforations in a single cluster, respectively, and N is the total number of perforations.

3. Numerical Simulation Scheme

3.1. Establishment of the Numerical Model

During staged multi-cluster fracturing in horizontal wells, fracture propagation is subject to compressive stress interference among clusters. Because the pumped fracturing fluid is dynamically distributed among perforation clusters, the induced stress of each cluster varies dynamically over time, ultimately affecting the geometric morphology of each fracture and resulting in non-uniform propagation. To accurately characterize this phenomenon, a wellbore–perforation–fracture coupled multi-cluster fracture propagation model was established based on the ABAQUS 2017 platform (Figure 2). The model has a height of 50 m, a length of 100 m, and a width of 60 m. Six perforation clusters are arranged in the model with a cluster spacing of 10 m. The model parameters are listed in Table 1.

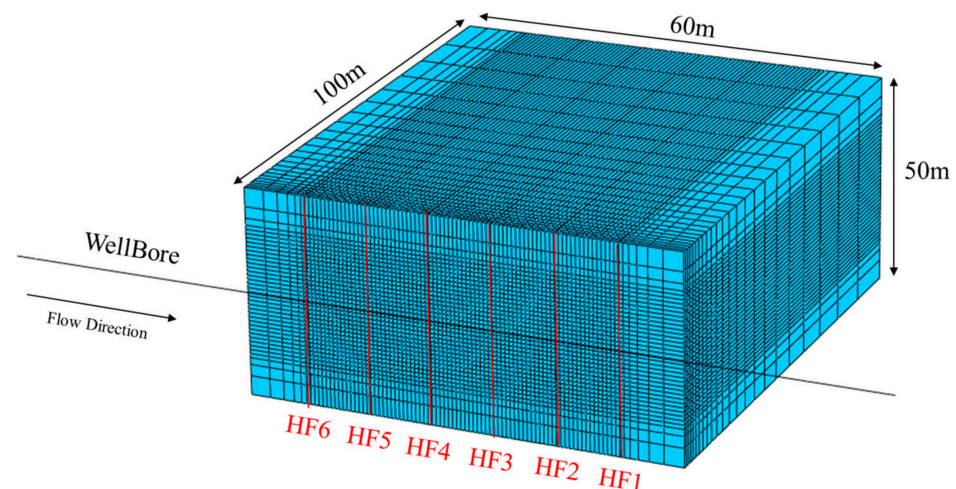


Figure 2. Multi-cluster fracture propagation model sketch.

Table 1. Model calculation parameters.

Parameters	Value
Young's modulus/GPa	32
Poisson's ratio	0.25
Minimum horizontal principal stress/MPa	72
Maximum horizontal principal stress/MPa	76
Vertical stress/MPa	81
Number of perforations	30–48
Perforation diameter/mm	10
Injection rate/m ³ ·min ^{−1}	16

To improve the propagation uniformity of each fracture cluster, two types of non-uniform perforation patterns are designed: spindle-shaped perforation and Tapered perforation. Spindle-shaped perforation means that the toe-end and heel-end clusters have fewer perforations, while the clusters in the middle of the fracturing stage have more perforations. Tapered perforation means that the number of perforations decreases progressively from the toe-end cluster to the heel-end cluster. Both perforation patterns aim to reduce induced stress interference and promote uniform fracture propagation by optimizing the perforation friction.

3.2. Experimental Scheme

The overall scheme is shown in Table 2. Using the numerical simulation scheme with uniform perforation as the control group, the effects of non-uniform perforation pattern, number of perforations, and perforation non-uniformity index on the uniformity of multi-cluster fracture propagation and the inter-cluster fluid intake characteristics were investigated, thereby providing a basis for the optimization of perforation parameters.

Table 2. Numerical simulation schemes for varying perforation parameters.

No.	Perforation Pattern	Number of Perforations	Perforation Non-Uniformity Index	Number of Perforations from Toe to Heel
1	Uniform	30	0	5-5-5-5-5-5
2	Uniform	48	0	8-8-8-8-8-8
3	Spindle-shaped	30	0.2	3-6-6-6-6-3
4	Spindle-shaped	30	0.1	4-5-6-6-5-4
5	Spindle-shaped	48	0.2	5-9-10-10-9-5
6	Spindle-shaped	48	0.1	7-7-10-10-7-7
7	Tapered	30	0.2	7-6-6-5-4-2
8	Tapered	30	0.1	6-6-6-5-4-3
9	Tapered	48	0.2	12-10-8-8-6-4
10	Tapered	48	0.1	10-10-8-8-7-5

4. Results and Discussion

4.1. Effect of Perforation Pattern on Fracture Propagation

To discuss the influence of different perforation patterns on fracture propagation morphology, taking the case of 30 perforations and a perforation non-uniformity coefficient of 0.1 as an example, a comparison of the results of Cases 1, 4, and 8 (Figure 3) shows that for uniform perforation, the fractures at both ends exhibit dominant propagation while the middle fractures are restricted, with a uniformity index of 0.77. For tapered perforation, the toe-end fractures show dominant propagation while the heel-end fractures are restricted, with a uniformity index of 0.72. For spindle-shaped perforation, the propagation advantage of the end fractures is significantly reduced, and the middle fractures are fully developed, yielding the highest uniformity index of 0.79.

Further analysis of the variation of fluid intake per cluster with pumping time under different perforation patterns (Figure 4) reveals the following. In the case of uniform perforation, the initial fluid intake of each cluster is relatively uniform (approximately 20% per cluster). This is attributed to the consistent perforation parameters and identical initial friction across clusters, leading to a balanced near-wellbore stress distribution. However, as pumping time increases, the fluid intake of the middle clusters gradually decreases, resulting in an inter-cluster fluid intake difference (max/min ratio) of 1.33 at the final time. This phenomenon arises from the stress shadow effect during simultaneous propagation of multiple fractures: the middle clusters are compressed by the fractures on

both sides, leading to an increase in induced stress, which hinders further fracture opening and weakens fluid diversion capability. Considering that perforation friction is proportional to the square of flow velocity, near the wellbore, the cumulative flow rate is high, but the number of perforations is small, making perforation friction dominant; at the distal end, the cumulative flow rate is low, but the along-hole frictional pressure drop accumulates [16]. Under uniform perforation conditions, all clusters have the same perforation parameters; however, as pumping time increases, the flow distribution gradually becomes uneven. Clusters with higher flow rates generate higher net pressure and wider fractures, exerting a stronger compressive stress shadow on adjacent clusters, which further suppresses the propagation of the middle clusters.

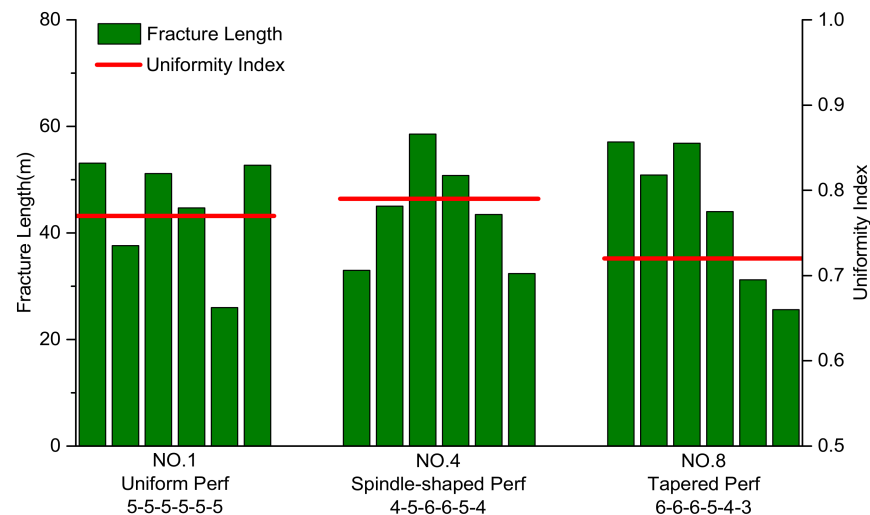


Figure 3. Statistics of fracture length and uniformity index under different perforation methods.

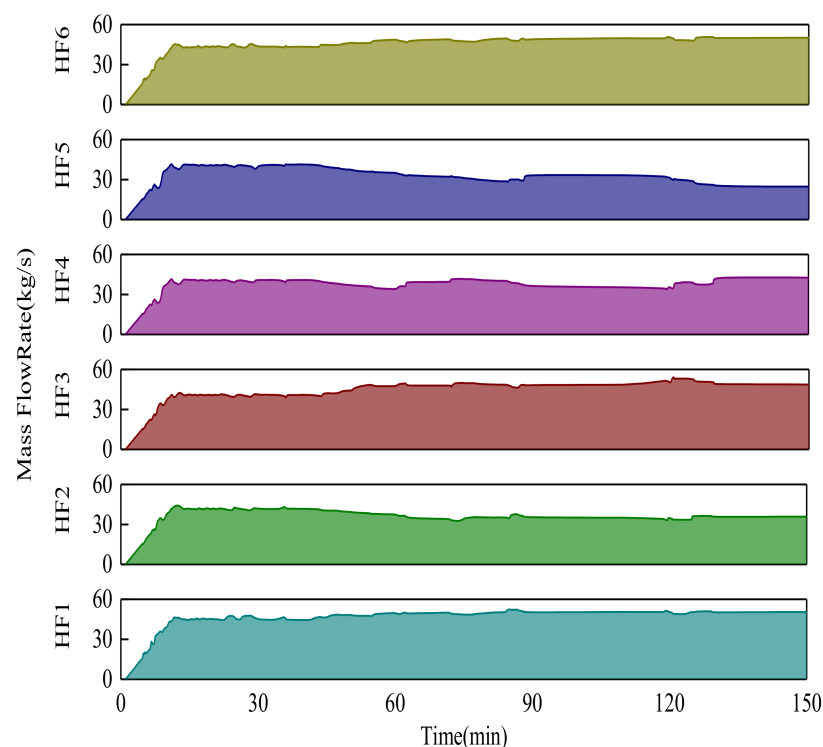


Figure 4. Fluid Distribution Among Clusters Under No. 1 Uniform Perforation.

In the case of tapered perforation (Figure 5), the fluid intake increases progressively from Cluster 1 to Cluster 6, with initial proportions of 10.22%, 13.82%, 16.59%, 19.67%,

19.59%, and 20.10%, respectively. Throughout the simulation, Cluster 6 consistently maintains the highest fluid intake, while the intake of the middle clusters remains restricted, yielding an inter-cluster difference of 1.31 at the final time. This is because tapered perforation artificially increases the perforation friction of the front-end clusters, forcing the fracturing fluid to preferentially flow toward the terminal cluster; nevertheless, the middle clusters are still affected by competitive propagation from both sides and cannot significantly increase their intake share. From a pressure balance perspective, when the perforation friction coefficient is high, the flow rate of the near-wellbore clusters is effectively suppressed, and the flow distribution tends to become uniform. However, in tapered perforation, the gradient design of front-end friction increases the flow rate of the terminal cluster, while the middle clusters remain in the superposition zone of stress shadows from both sides, limiting the increase in their net pressure.

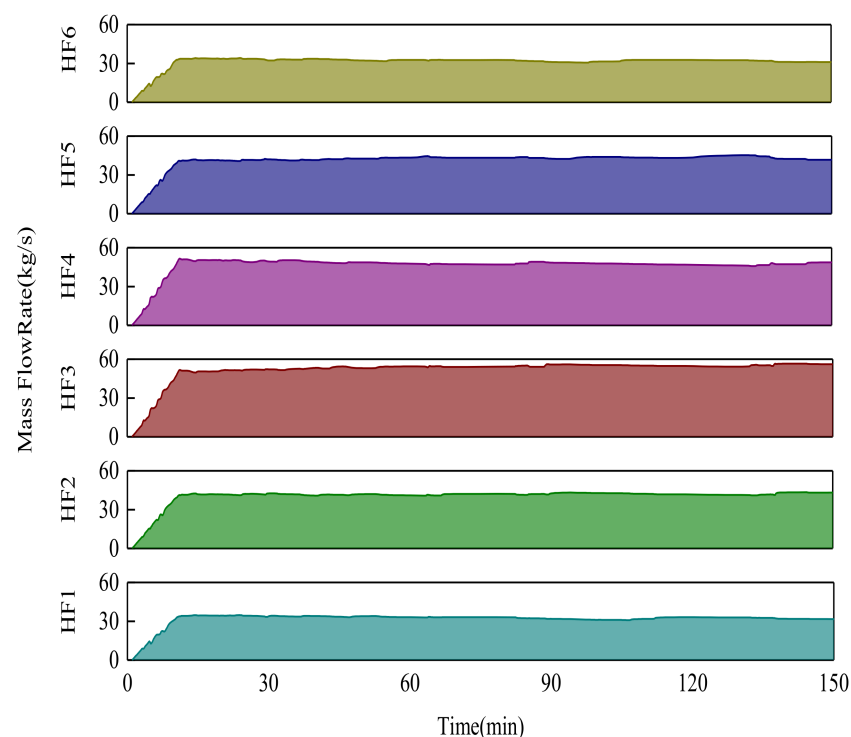


Figure 5. Fluid Distribution Among Clusters Under No. 4 Spindle-Shaped Perforation.

In the case of spindle-shaped perforation (Figure 6), the fluid intake of each cluster is relatively uniform, with an inter-cluster difference of only 1.18 at the final time—the smallest among the three patterns. This results from the targeted increase in perforation friction at the two end clusters, which creates a higher entry resistance near the wellbore, effectively mitigating the compressive effect of stress shadows on the middle clusters. In other words, the induced stress on the middle fractures is significantly reduced, and the propagation of each cluster tends to become more balanced. Further mechanistic analysis reveals that in the spindle-shaped design, the perforation friction of the middle clusters is relatively low, allowing them to obtain a higher flow distribution under the same entry pressure. Meanwhile, the stress interference on the middle clusters from the two side fractures is partially offset (under symmetric placement, the rightward compression from the left fracture and the leftward compression from the right fracture weaken each other to some extent), making the middle fractures easier to propagate. This mechanism enables the middle clusters to maintain sufficient flow rate and net pressure, avoiding the over-suppression of middle clusters observed in the uniform perforation pattern.

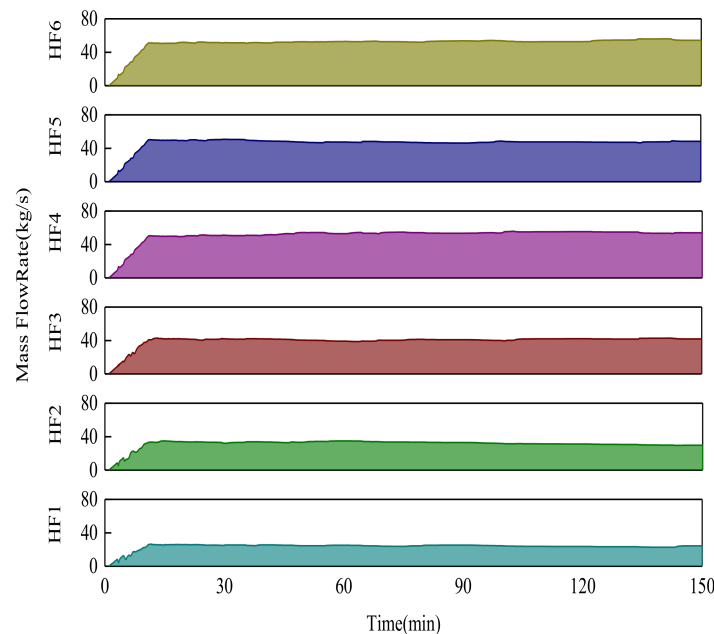


Figure 6. Fluid Distribution Among Clusters Under No. 8 Tapered Perforation.

4.2. Effect of Number of Perforations on Fracture Propagation

To discuss the effect of the number of perforations on fracture propagation morphology, taking a perforation non-uniformity coefficient of 0.1 as an example, a comparison of the results of Cases 4, 6, 8, and 10 (Figure 7) shows that as the number of perforations decreases, both spindle-shaped perforation and tapered perforation exhibit a trend where propagation of the dominant clusters becomes restricted while that of the disadvantaged clusters becomes smoother. Moreover, the uniformity index for the case with a total of 30 perforations (0.79 and 0.72) is higher than that for the case with 48 perforations (0.65 and 0.69).

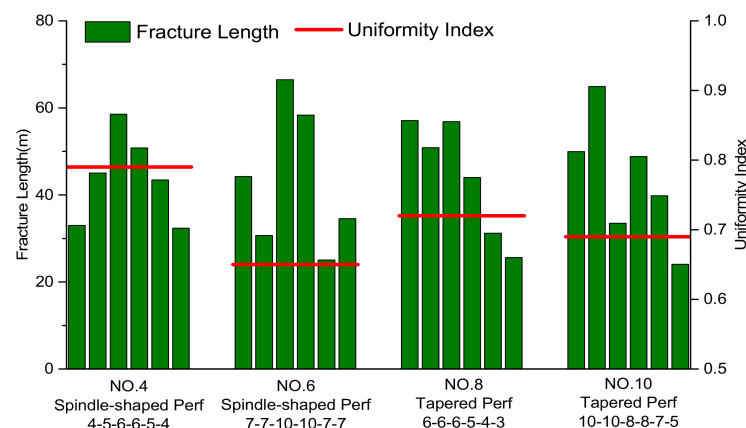


Figure 7. Statistics of fracture length and uniformity index under different numbers of perforations.

Further analysis of the variation of inter-cluster fluid intake with pumping time under different numbers of perforations (Figure 8) reveals the following. For spindle-shaped perforation with a total of 30 perforations, the fluid intake of each fracture cluster remains relatively stable over time, with an inter-cluster fluid intake difference of 1.18 at the final time. This is attributed to the moderate perforation friction at the two end clusters when 30 perforations are used, which effectively balances the entry resistance near the wellbore. Meanwhile, the relatively lower perforation friction of the middle clusters, combined with the partial offset of stress interference from both sides, results in a balanced net pressure

distribution across clusters. As the number of perforations increases, the perforation friction decreases significantly, weakening the flow-limiting effect. In the later stage of injection (at 120 min), the fluid intake of Clusters 2 and 6 decreases, while that of Clusters 3, 4, and 5 increases. This occurs because, with an increased number of perforations, the perforation friction at the two end clusters decreases to a greater extent, reducing their ability to suppress the flow rate of the near-wellbore clusters. At the same time, the middle clusters (Clusters 3–5) are located in the superposition zone of multiple stress shadows, but their perforation friction is relatively lower; under the condition of equal entry pressure, they instead receive a higher distributed flow rate, leading to non-uniform fracture propagation to some extent. Consequently, the inter-cluster fluid intake difference rises to 1.54 at the final time.

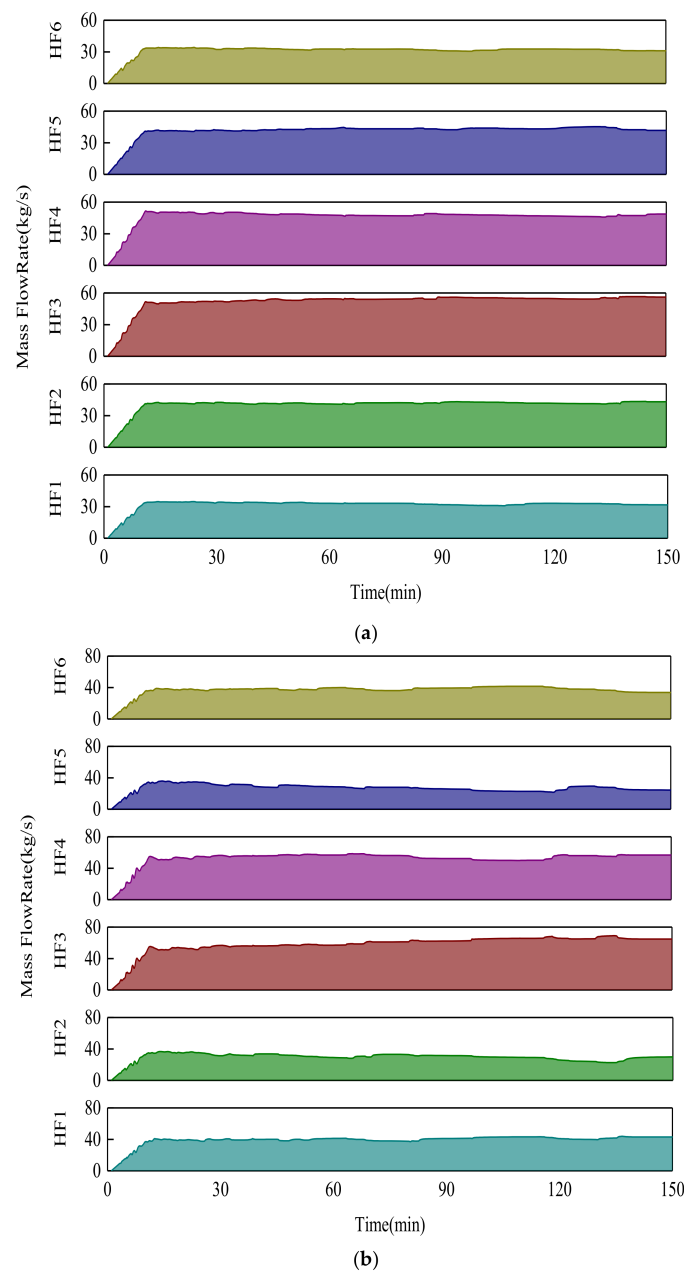


Figure 8. Fluid Distribution Among Spindle-Shaped Perforation Clusters Under Different Perforation Numbers. (a) No. 4 Spindle-Shaped Perforation. (b) No. 6 Spindle-Shaped Perforation.

For tapered perforation with a total of 30 perforations (Figure 9), the fluid intake of each cluster remains relatively stable over time, and the fluid intake gradually increases

from Cluster 1 to Cluster 6, with an inter-cluster fluid intake difference of 1.31 at the final time. This is because, with 30 perforations, the gradient design of perforation friction at the front-end clusters effectively restricts the flow rate of the near-wellbore clusters, forcing the fracturing fluid to divert toward the toe-end clusters. Meanwhile, the middle clusters, affected by competitive propagation due to stress shadows from both sides, do not exhibit excessive concentration of intake share. As the number of perforations increases, the overall perforation friction decreases, and the flow-limiting effect of the front-end clusters gradually deteriorates. In the later stage of injection (at 116 min), the fluid intake of Clusters 5 and 6 accounts for 26.3% and 21.4% of the total intake, respectively, summing to nearly 50%. This is because, under low-perforation friction conditions, the toe-end fractures preferentially propagate. Their net pressure continues to increase, which in turn suppresses the further opening of the middle and front clusters through stress shadows, forming a positive feedback mechanism. Ultimately, the inter-cluster fluid intake difference expands to 1.49.

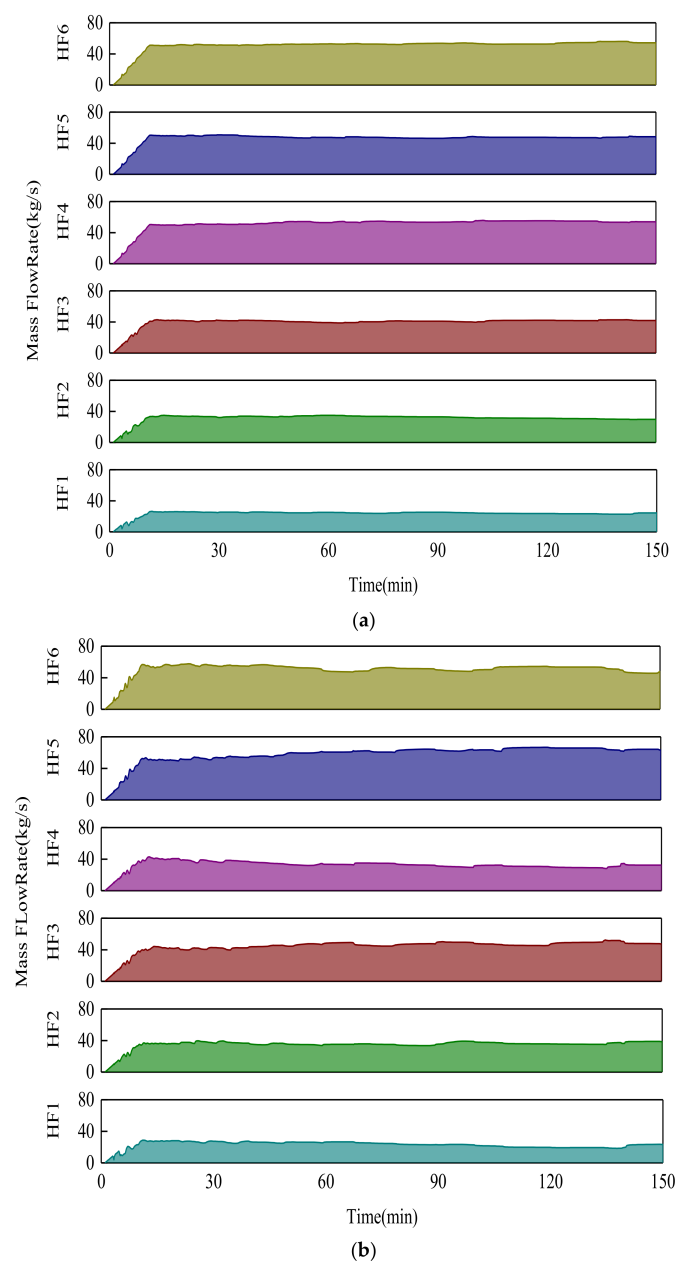


Figure 9. Fluid Distribution Among Tapered Perforation Clusters Under Different Perforation Numbers. (a) No. 8 Tapered Perforation. (b) No. 10 Tapered Perforation.

4.3. Effect of Perforation Non-Uniformity Coefficient on Fracture Propagation

To discuss the effect of the perforation non-uniformity coefficient on fracture propagation morphology, taking a total of 48 perforations as an example, a comparison of the results of Cases 5, 6, 9, and 10 (Figure 10) shows that as the perforation non-uniformity coefficient increases, spindle-shaped perforation exhibits an increase in the length of the middle fractures and a decrease in the length of the two end fractures, with the uniformity index decreasing from 0.65 to 0.63. Tapered perforation exhibits an increase in the length of the toe-end fractures and a decrease in the length of the heel-end fractures, with the uniformity index decreasing from 0.69 to 0.51, a more significant reduction.

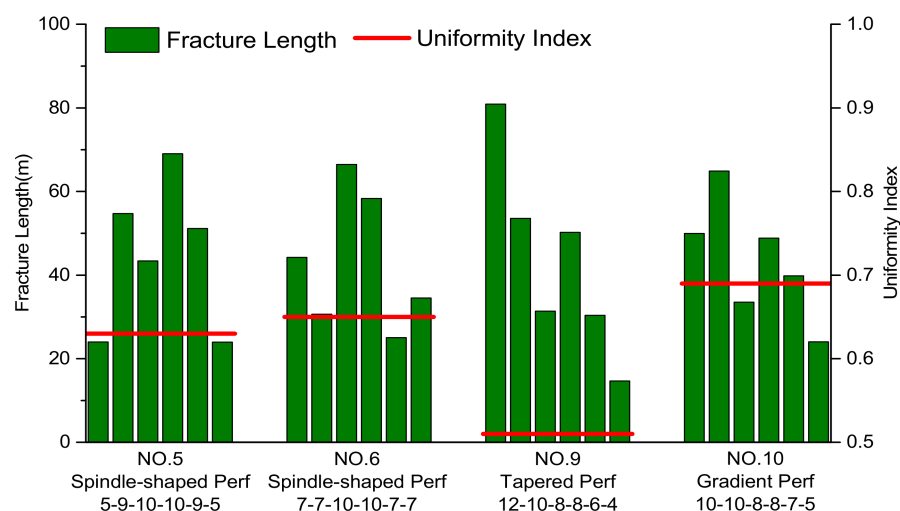


Figure 10. Statistics of fracture length and uniformity index under different perforation non-uniformity coefficient.

Further analysis of the variation of inter-cluster fluid intake under different perforation non-uniformity coefficients (Figure 11) shows that for spindle-shaped perforation, as the perforation non-uniformity coefficient increases, the perforation friction of the end fractures increases significantly. The end clusters, due to their excessively high perforation friction, require a greater pressure drop to overcome the friction, resulting in a reduction in net pressure within the fractures. This implies that, in addition to the perforation friction needed to balance the inter-cluster induced stress, there exists “excessive” perforation friction that instead suppresses the propagation of the end fractures. Meanwhile, the middle clusters have relatively lower perforation friction and can obtain a higher distributed flow rate under the same entry pressure. However, because the propagation of the end clusters is restricted, their stress shadow on the middle clusters weakens, and the advantage in net pressure of the middle clusters does not significantly alter the overall uniformity. Consequently, the inter-cluster fluid intake difference at the final time increases slightly from 1.54 to 1.56, indicating that the negative impact of excessive friction on uniformity is not yet pronounced.

For tapered perforation (Figure 12), a similar trend is observed: an excessively high perforation friction design adversely affects the uniformity of fracture propagation. The physical mechanism lies in the fact that, for tapered perforation, the perforation friction decreases progressively from the heel end to the toe end. When the perforation non-uniformity coefficient becomes too large, the perforation friction at the heel-end clusters increases sharply, severely suppressing their flow rate. In contrast, the toe-end clusters, with extremely low perforation friction, receive a large amount of flow driven by pressure balance, and their net pressure continues to increase. This, in turn, further suppresses the propagation of the heel-end and middle clusters through stress shadows. Compared with

spindle-shaped perforation, the difference in perforation friction in this tapered perforation case is more pronounced (the perforation friction of the heel-end clusters is nine times that of the toe-end clusters), so this effect is stronger. As a result, the increase in the inter-cluster fluid intake difference at the final time is larger, rising from 1.49 to 1.85.

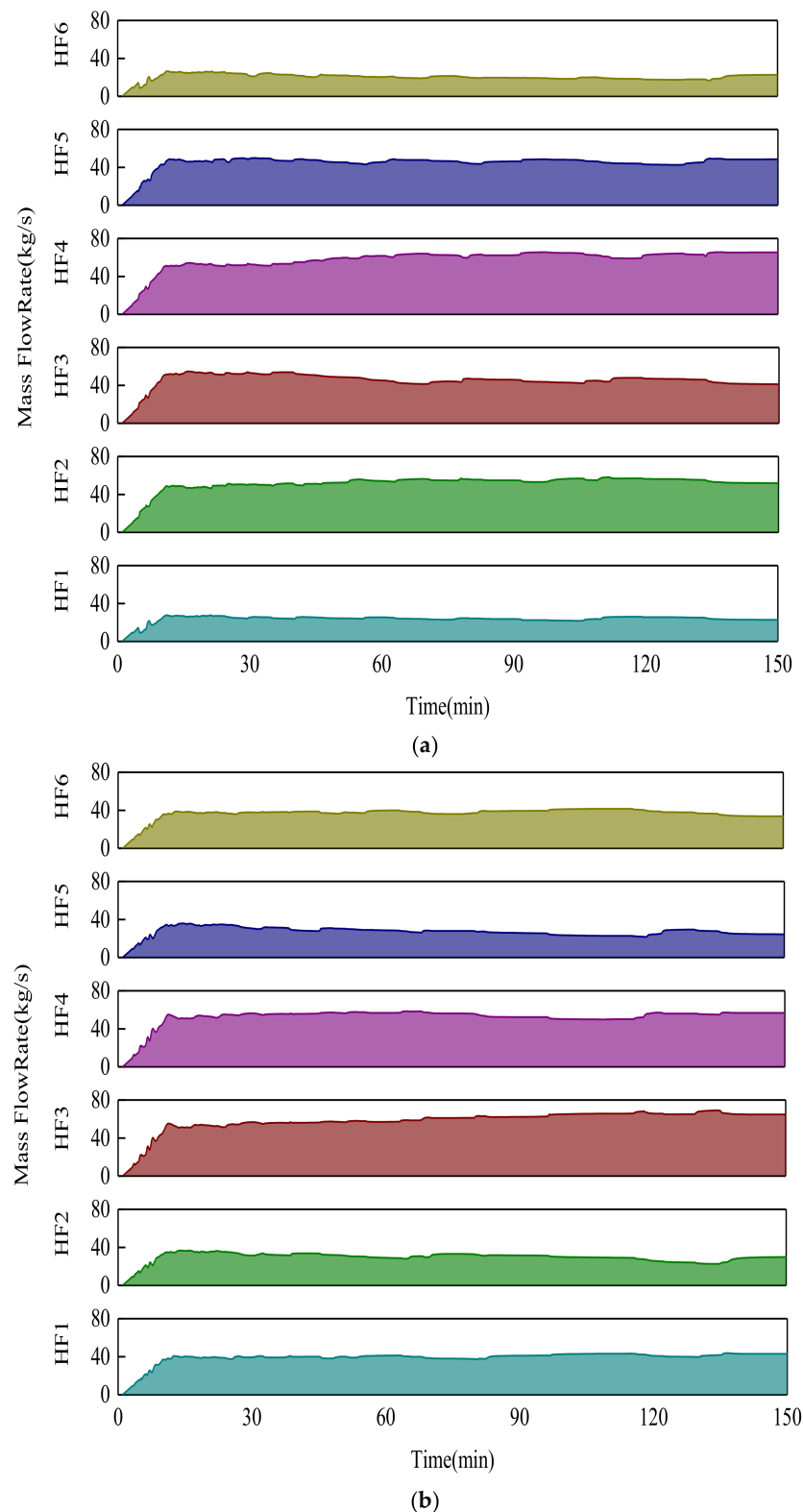


Figure 11. Fluid Distribution Among Spindle-Shaped Perforation Clusters Under Different Perforation Non-Uniformity Index. (a) No. 5 Spindle-shaped Perforation. (b) No. 6 Spindle-shaped Perforation.

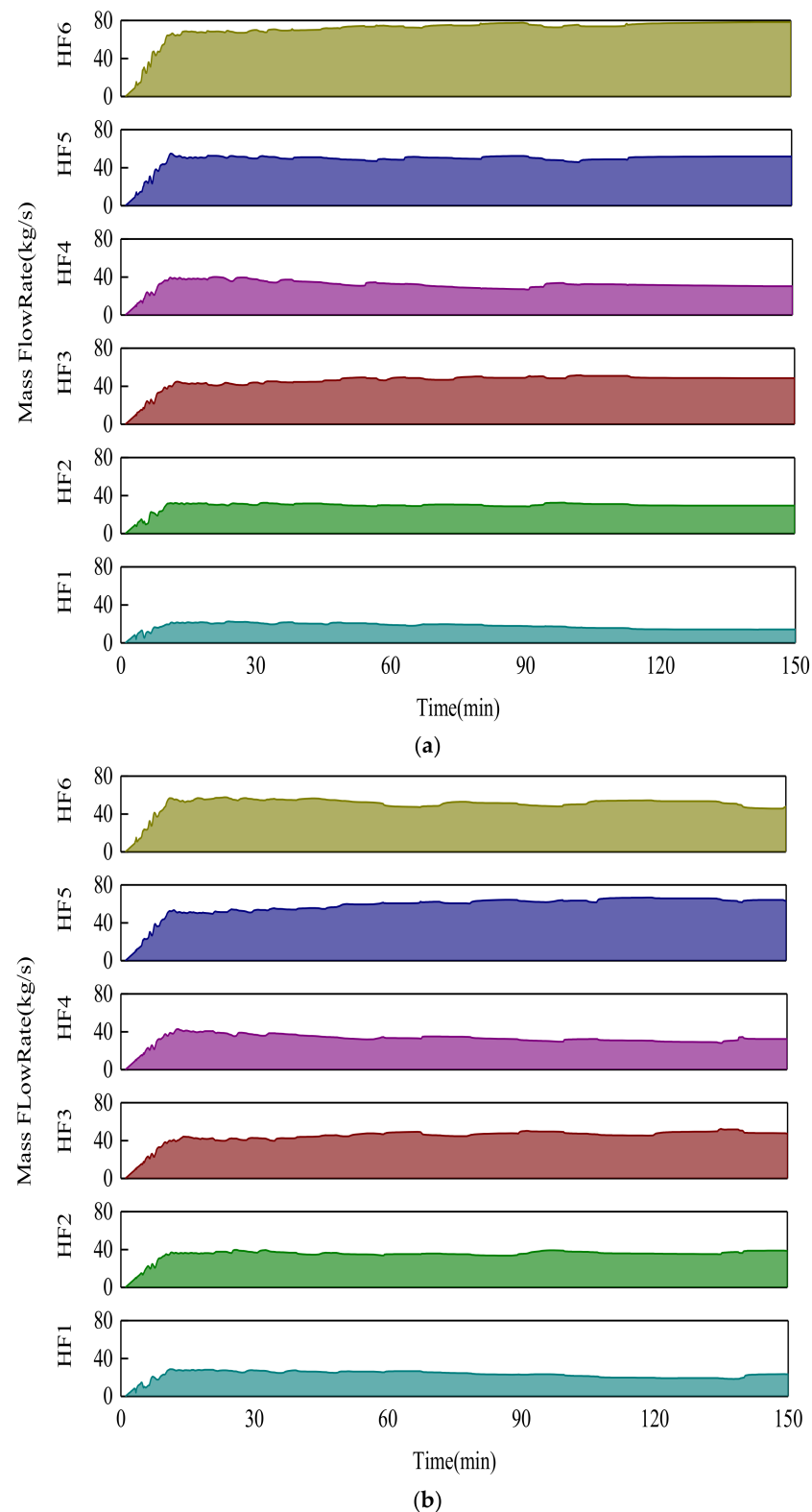


Figure 12. Fluid Distribution Among Tapered Perforation Clusters Under Different Perforation Non-uniformity Index. (a) No. 9 Tapered Perforation. (b) No. 10 Tapered Perforation.

5. Field Test

To further validate the effect of perforation parameters on fracture propagation, a field test was conducted in Well GY-1, which was equipped with out-casing fiber optics. Based on the laboratory study results, the fracturing stage length was set to 60 m, with six clusters per stage and a cluster spacing of 10 m. The number of perforations per stage ranged from

30 to 36, with a fracturing fluid volume of 1950 m³ per stage, a proppant volume of 180 m³, and a pumping rate of 14 m³/min.

Six test fracturing stages were designed in this well. In Stages 2, 3, and 4, the total number of perforations was 36, with perforation patterns of uniform, tapered, and spindle-shaped perforation, respectively, and perforation non-uniformity coefficients of 0, 0.1, and 0.1, respectively. In Stages 5, 6, and 7, the total number of perforations was 30, with perforation patterns of uniform, tapered, and spindle-shaped perforation, respectively, and perforation non-uniformity coefficients of 0, 0.1, and 0.1, respectively.

Figure 13 shows the fluid intake proportion per cluster for Stages 2 to 7. Under uniform perforation (Stages 2 and 5), the middle clusters were strongly squeezed by the induced stress from the clusters at both ends, resulting in a significant reduction in fluid intake. The inter-cluster fluid intake difference at the final time was 1.74 and 1.62, respectively.

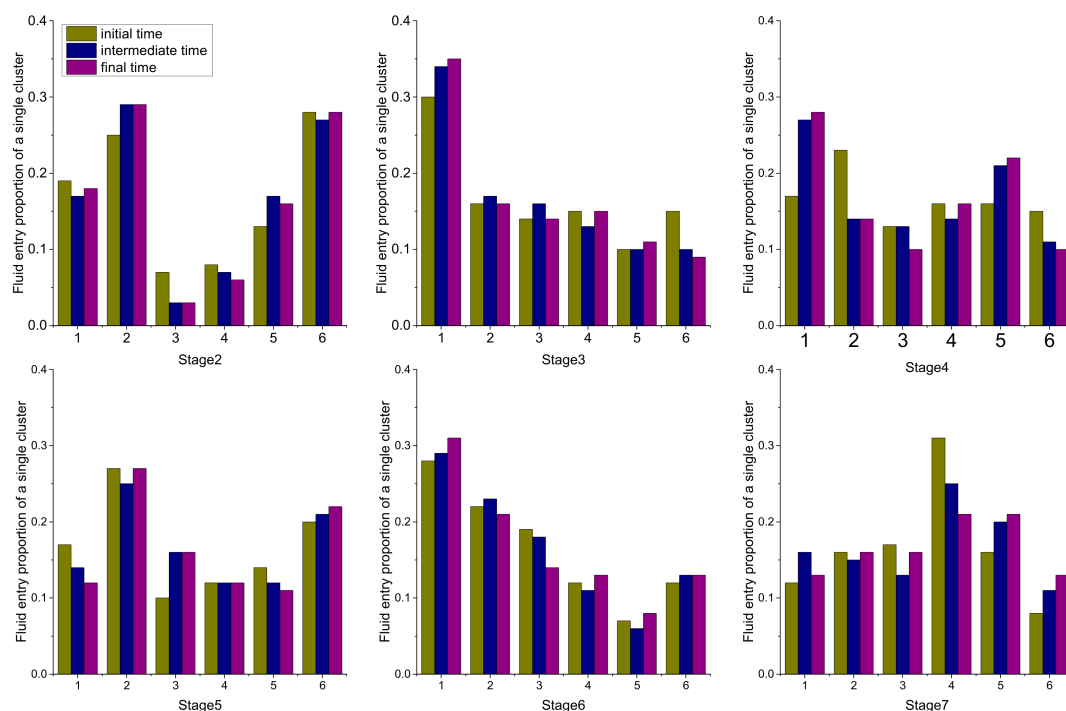


Figure 13. Single-cluster fluid intake proportion for varying perforation numbers and patterns.

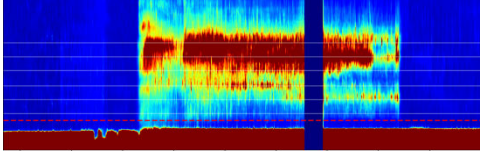
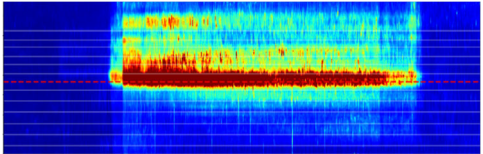
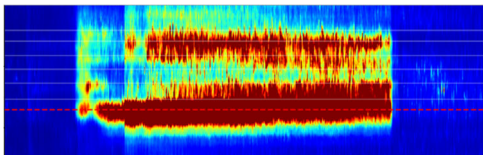
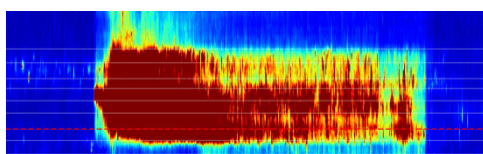
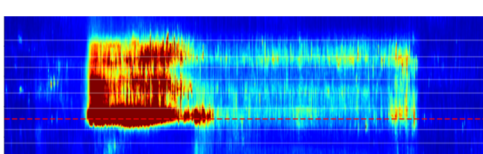
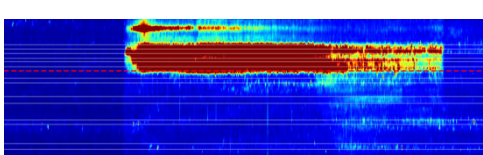
Under tapered perforation (Stages 3 and 6), the overall trend showed higher fluid intake in the toe-end clusters and lower intake in the heel-end clusters. This is because the perforation friction at the toe end is lower, allowing more extensive fracture propagation and greater fluid intake. The inter-cluster fluid intake difference at the final time was 2.1 and 1.86, respectively. This observation is consistent with the numerical simulation results. It is worth noting that in Stage 6, Cluster 1 maintained the highest fluid intake throughout the fracturing process, which may be attributed to perforation erosion leading to failure of the flow-limiting effect [17].

Under spindle-shaped perforation (Stages 4 and 7), with more perforations in the middle clusters and fewer at the two ends, the induced stress on the middle fractures was significantly lower than that under the other two perforation patterns. Moreover, the higher perforation friction at the two end clusters not only alleviated inter-cluster stress interference but also restricted fluid intake into the end clusters, thereby mitigating the limited fluid intake of the middle clusters and ultimately improving fracture propagation uniformity. The inter-cluster fluid intake differences were 1.6 and 1.26, respectively.

Finally, the fluid intake uniformity index was calculated based on the fiber optic monitoring results. From the statistical results (Table 3), it can be seen that as the number

of perforations decreases, the fracture uniformity under different perforation patterns improves. Based on the current monitoring results, the order of fluid intake uniformity for the different perforation patterns is as follows: spindle-shaped perforation > uniform perforation > tapered perforation. It should be noted that the validation data in this study are derived from a specific block, and the generalizability of the proposed model to different geological conditions requires further verification. In future work, we will continue relevant research, including collecting more field cases, to further validate and improve the model.

Table 3. Calculation of uniformity index based on fiber optic monitoring results.

Fracturing Stage	Perforation Pattern	Number of Perforations	Perforation Non-Uniformity Coefficient	DAS	Uniformity Index
2	Uniform	36	0		0.41
3	Tapered	36	0.1		0.48
4	Spindle-shaped	36	0.1		0.61
5	Uniform	30	0		0.64
6	Tapered	30	0.1		0.55
7	Spindle-shaped	30	0.1		0.80

6. Conclusions

(1) Non-uniform perforation can improve fracture propagation uniformity by controlling perforation friction. The calculation results of this study show that spindle-shaped perforation yields the best fracture propagation uniformity (0.79), followed by uniform perforation (0.77) and tapered perforation (0.72).

(2) In this study, adopting spindle-shaped perforation, appropriately reducing the number of perforations (from 48 to 36), and decreasing the perforation non-uniformity coefficient (from 0.2 to 0.1) can improve fracture propagation uniformity to a certain extent. The fluid intake uniformity index increases from 0.65 to 0.79.

(3) Field fiber optic monitoring results indicate that when the total number of perforations is reduced from 36 to 30, the fluid intake uniformity index for uniform perforation, spindle-shaped perforation, and tapered perforation increases by 31.1%, 56.1%, and 14.5%, respectively. The order of fluid intake uniformity among different perforation patterns is as follows: spindle-shaped perforation (0.80), uniform perforation (0.64), and tapered perforation (0.55).

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