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Research Article

Investigation on Nonuniform Extension of Hydraulic Fracture in Shale Gas Formation

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Hydraulic fracturing with multiple clusters has been a significant way to improve fracture complexity and achieve high utilization of shale formation. This technology has been widely applied in the main shale area of North America. In Changning shale block of China, it, as a promising treatment technology, is being used in horizontal well now. Due to the anisotropy of mechanical property and the stress shadowing effect between multiclusters, fractures would extend nonuniformly and even some clusters are invalid, leading to a poor treatment performance. In this work, based on the geology and engineering characteristics of Changning shale block, different cluster number, cluster spacing, perforation distribution, and flow rate were discussed by the numerical simulation method to clarify multifracture propagation. It is implied that with the reduction of cluster number and the growth of cluster spacing and flow rate, the length and average width of interior fractures are inclined to increase due to the mitigation of stress shadowing effect, contributing to the lower standard deviation (SD) of fracture length, but too small cluster number or too large cluster spacing is not recommended. Besides, the perforation distribution with more perforations in interior fractures can get larger length and average width of interior fractures compared with another two perforation distributions because of more fractional flow rates obtained, which results in more even fracture propagations. In Changning shale block, multicluster hydraulic fracturing with 4-6 clusters in a stage has been employed in 300-400 m well spacing, and diversion technology, limited-entry perforation (36-48 perforations per stage), high flow rate (16 m^3/min), and small-sized ceramic proppant (100 mesh) are used to get better shale gas production. To promote the even propagation of fractures further, nonuniform perforation distribution should be introduced in the target shale area.

1. Introduction

Multistage hydraulic fracturing in horizontal well has been proved to be an efficient technology to stimulate shale formation with extremely low porosity and permeability [1–3]. To enhance production and realize beneficial development, multicluster hydraulic fracturing within a stage has been extensively employed in the main shale area of North America so far. Compared with conventional hydraulic fracturing, this technology can provide more flow paths by perforating more clusters, and takes advantage of induced stress during fracture propagation to increase the fracture complexity between clusters and shorten the distance of gas flow from shale reservoir matrix to hydraulic fractures, improving the utilization of reservoir [4–7], which is shown in Figure 1. However, based on the data from production log and distributed acoustic sensor, one-third of perforation clusters do not extend and cluster efficiency is low, leading to undesirable shale gas production [8, 9].

Uneven extension of hydraulic fractures in multicluster fracturing has been investigated by many scholars. Germanovich and Astakhow and Olson pointed out that the flow rate was dynamically distributed in fractures, and the length and width of interior fractures were restricted during parallel

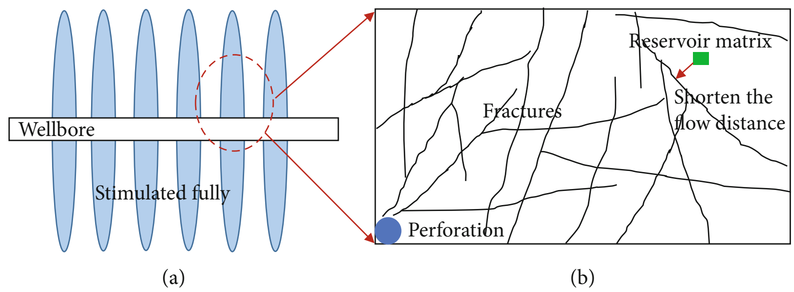

Figure 1: Mechanism schematic diagram of multistage hydraulic fracturing in shale.

fracture extension [10, 11]. Morrill studied the stress field around fracture tip and hydraulic fracture morphology by numerical simulation [12]. Afterwards, a 2D model setup through the displacement discontinuity method (DDM) was used by Bunger et al. and Cheng to discuss stress field distribution and fracture geometry [5, 13]. Peirce and Bunger developed a full coupling model and noted that nonuniform cluster spacing could decrease the uneven propagation of multiple fractures [14]. Shin and Sharma simulated the process of fracture extension by the finite element method and researched on the length and height of hydraulic fracture [15]. Then, Wu and Olson employed the DDM to build pseudo 3D model and demonstrated that fracture geometry was influenced by not only the stress shadowing effect but also the dynamic flow rate [16]. Zhao et al. established a multifracture simultaneous propagation model which coupled elastic deformation of rock, stress interaction, fluid flow, and flow distribution in fractures to optimize cluster spacing based on the sweep area of fractures [17]. Furthermore, a nonplanar 3D hydraulic fracturing simulator was developed by Wu et al. to study fracture width and fracture geometry due to induced stress among clusters [18]. In recent year, Lin et al. applied the DDM to calculate formation stress change and the finite difference method (FDM) to compute reservoir pressure rise, simulating nonplanar propagation of multiple hydraulic fractures [19]. And Wang et al. also studied fracture extension and evolution under different stress conditions [20–23]. As well, a phase-field modeling was used by Alotaibi et al. to study hydraulic fracture in heterogeneous formation with layers [24].

In multicluster hydraulic fracturing, though stress shadowing effect can improve the degree of fracture complexity due to fracture diversion, it restrains the propagation of interior fractures forward. Besides, mechanical properties and in situ stress of shale formation can also lead to uneven fracture extension [25, 26]. In the main shale area of North America, such as Haynesville, Permian Basin, Eagle Ford, and Bakken, multicluster hydraulic fracturing has now developed into a mature and reliable technology [25, 27–29]. And some effective measures, like limited-entry perforation, have been taken to increase perforation cluster efficiency and promote even propagation of fractures. In Changning shale block, one of the most promising shale gas production areas located in Sichuan Basin, China, multicluster hydraulic fracturing as an advanced treatment technology is being used in shale horizontal well. However, there are some different properties of shale formation between two areas which are shown in Table 1, so the extension of multifracture and fracture geometry in the reservoir is likely to exhibit diversely. Additionally, few studies focus on the fracture extension in Changning shale block except Xie et al. who mostly discussed hydraulic fractures in only 3 clusters' perforation within one stage [30]. Therefore, based on the geology and engineering characteristics of Changning shale block, investigation of the effects of cluster number, cluster spacing, perforation distribution, and flow rate on fracture propagation in multicluster hydraulic fracturing by the numerical simulation method is indispensable.

2. Assumptions and Methodology

Hydraulic fracturing is a complex process with multifield coupling, showed in Figure 2. In this study, some assumptions are made to improve computational efficiency: (1) injection fluid is the incompressible Newtonian fluid; (2) the fluid is one-dimensional flow in the fractures, which is effected by Carter filtration; and (3) the formation rock is homogeneous, and it is the liner elastic material. [31, 32]. When multifracture is extended, the balance of flow pressure obeys Kirchhoff's second law, including perforation friction, pressure drop in fractures, and wellbore friction [32]. Based on flow conservation in the clusters, the relationship of pressure and flow is expressed as follows [33, 34]:

$$P_i = p_{\mathrm{perf},i} + \Delta p_{\mathrm{frac},1} + \sum_{j=1}^{i} p_{\mathrm{f},j} - P_{\mathrm{g}} (i \in 1 - n), \quad (1)$$

$$P_{n+1} = Q - \sum_{i=1}^{n} q_i, \quad (2)$$

where $P_{\mathrm{perf},i}$ stands for the perforation friction, $P_{\mathrm{frac},1}$ is the pressure of fracture inlet in cluster i, $P_{\mathrm{f},j}$ is the wellbore friction of segment j, P_{g} is the pressure in well heel, Q is the total flow, and q_i represents the flow of cluster i.

According to the principle of material balance, the injection flow equals fracture volume increment and fluid filtration [31]:

$$\int_0^t Q dt = \sum_1^N \int_0^{L_{\mathrm{f},i}(t)} \frac{\pi}{4} h_{\mathrm{f}} w_{\mathrm{f}} ds + \sum_1^N \int_0^{L_{\mathrm{f},i}(t)} \int_0^t q_{\mathrm{v}}(s.t) dt ds, \quad (3)$$

Table 1: Comparison of the main reservoir geological parameters in Changning and North America shale area.

Shale area	Depth (m)	Total organic carbon (%)	Porosity (%)	Brittle mineral (%)	Pressure coefficient	Horizontal stress difference (MPa)
Changning	2000~4500	2.5~4.8	3.4~7.9	50~80	1.2~2.1	9~20
Haynesville	3000~4700	2.0~7.0	5.0~11.0	65~75	1.6~2.1	3~6
Eagle Ford	1300~3600	2.0~6.5	3.4~14.6	67~87	1.3~2.0	/
Duvernay	3000~4200	2.0~6.0	3.0~6.0	⌧40	1.8~2.1	/

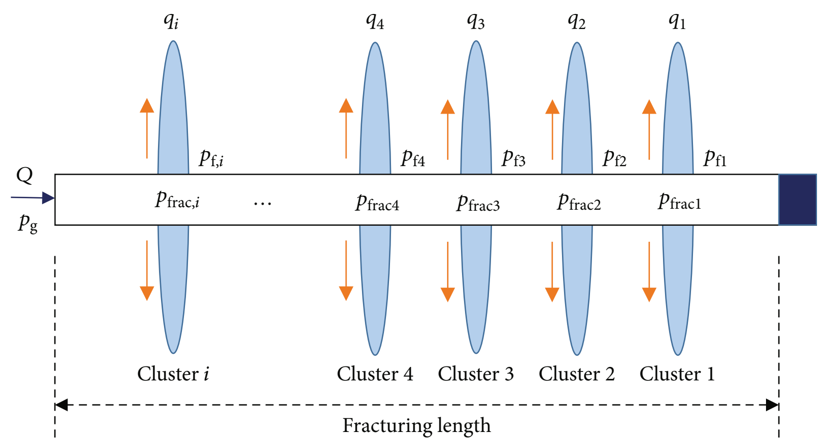

Figure 2: Schematic of multifracture propagation.

where $L_{f,i}$ stands for the fracture length in cluster i, N is the number of fractures, q_v is the viscosity of fluid filtration, h_f is the fracture height, w_f is the fracture width, s is the fracture element, and t is the fracturing time.

The induced stress is caused between clusters during multifracture propagation, and fracture elements are effected mutually. The equation of induced stress field is as follows [32]:

$$\sigma_n^i = \sum_{j=1}^{N} G^{ij} C_{nn}^{ij} D_n^j + \sum_{j=1}^{N} M^{ij} C_{ns}^{ij} D_s^j, \quad (4)$$

$$\sigma_s^i = \sum_{j=1}^{N} G^{ij} C_{ss}^{ij} D_s^j + \sum_{j=1}^{N} M^{ij} C_{sn}^{ij} D_n^j, \quad (5)$$

where σ_n^i and σ_s^i stand for the normal stress and shear stress, respectively, G^{ij} is the 3D correction factor, C^{ij} is the stress of fracture element, D_n^j and D_s^j are the strains of fracture element, and the value of i and j is $1-N$.

The stress intensity factor of fracture tip is calculated firstly when the fracture is extended. Fracture tip increases an element if meeting the condition of fracture propagation. The maximum circumferential stress criterion is expressed by the equivalent intensity factor [35, 36]:

$$K_e = \frac{1}{2}\left[K_I(1+\cos\theta)\cos\frac{\theta_f}{2} - 3K_{II}\sin\theta_f\right] \ge K_{IC}. \quad (6)$$

Based on the DDM, the stress intensity factor of K_I and K_{II} can be calculated as follows [28, 29]:

$$K_I = \frac{\sqrt{2\pi}G}{4\sqrt{a}(1-\nu)} D_n, \quad (7)$$

$$K_{II} = \frac{\sqrt{2\pi}G}{4\sqrt{a}(1-\nu)} D_s, \quad (8)$$

where G stands for the shear modulus of formation rock, ν is the Poisson ratio, a is the half length of discrete fracture element, D_n and D_s represent the normal and shearing displacement discontinuities, respectively.

The normal and shearing displacements are calculated by the induced stress field, and nonlinear equations of stress- and flow pressure-coupled fields are calculated by the Levenberg-Marquardt iteration method.

3. Simulation Results

3.1. Basic Characteristics of Changning Shale. High-quality shale, belonging to the Upper Ordovician Wufeng Formation-Lower Silurian Longmaxi Formations, is well developed in Changning block. Its total organic carbon is 2.5~4.8%, the porosity is 3.4~7.9%, the gas content is 3.1~6.8%, and the brittle mineral content is 50~80%. And its Young's modulus is 34~47 GPa and Poisson's ratio is 0.21~0.3. The horizontal stress difference of shale formation in Changning is 9~20 MP, which is higher than that of North America area. Multicluster hydraulic fracturing technology is being used to improve the efficiency of development in Changning shale block. Based on the geological characteristics and engineering parameters of target shale area in Changning, multifracture extension model was established to study the effects of clusters, cluster spacing, perforation distribution, and flow rate on fracture extension. The main basic model parameters are listed in Table 2.

Table 2: The main basic model parameters.

Parameters	Value
Average maximum horizontal stress (MPa)	88
Average minimum horizontal stress (MPa)	72
Young's modulus (GPa)	41
Poisson's ratio	0.26
Fracture height (m)	15
Total injection rate (m^3/min)	9-15
Cluster number	3-6
Cluster spacing (m)	5-15
Perforation number per stage	48
Fluid viscosity (mPa s)	2

3.2. Effects of Cluster Number on Fracture Propagation. Cluster number and cluster spacing are two vital parameters in the optimization design of multicluster hydraulic fracturing. In this part, effects of cluster number on fracture extension are discussed first. The cluster number is from 3 to 6 within a stage which is consistent with the completion design in Changning shale block. Cluster spacing (5 m), total injection rate (14 m^3/min), and time are kept constant. The fracture geometries of various clusters simulated are showed in Figure 3.

Based on the stimulation results above, it is implied that the propagation of interior fractures is restricted compared with the exterior fractures. And with the increase in cluster number, the degree of restriction is inclined to heighten. Besides, the length and average width of interior fractures are smaller than those of the exterior fractures (Figure 4). It is likely that stress shadowing effect and stress superposition increase the flow resistance of interior fractures and less fracturing fluid flows into them, inhibiting the interior fracture extension.

3.3. Effects of Cluster Spacing on Fracture Propagation. In this section, effects of cluster spacing on fracture extension are investigated under the 6 clusters. In Changning shale block, the cluster spacing is decreasing in recent years, and the average cluster spacing is less than 20 m. In multifracture propagation model, the cluster spacing are 5 m, 10 m, and 15 m, respectively. Cluster number (6 clusters), total injection rate (14 m^3/min), and time are kept constant. The fracture geometries of various cluster spacing are showed in Figure 5.

The fracture geometry is significantly influenced by cluster spacing according to Figure 5. With the decrease in cluster spacing, the restriction degree of interior factures tends to strengthen remarkably. And the length and average width of two interior factures are shorten compared with those of two exterior fractures in the case of cluster spacing 5 m (Figure 6). The main reasons are that when cluster spacing declines to 5 m, stress shadowing effect between clusters becomes stronger, inhibiting fracturing fluid entering into the interior factures. Moreover, the interior factures are squeezed intensively by the induced stress. Recently, cluster number has been growingly increasing and cluster spacing has been decreasing obviously in shale hydraulic fracturing at field, so the optimization design of construction parameter is particularly important for fracture extension and fracture propping.

3.4. Effects of Perforation Distribution on Fracture Propagation. Perforation parameters, including perforation number, perforation distribution, and phase angle, have a crucial influence on fracture extension in multicluster hydraulic fracturing. In order to promote fracture initiation and consider proper pumping pressure, 48 and 36 perforations per stage with uniform perforation distribution are widely used in Changning shale block. In these cases, 48 perforations with uniform and nonuniform perforation distribution are designed to study fracture extension in a stage with 6 clusters (Table 3). Cluster number (6 clusters), cluster spacing (10 m), total injection rate (14 m^3/min), and time are kept constant. The fracture geometries of different perforation distributions are showed in Figure 7.

From Figure 7, it is clear that compared with the uniform perforation distribution (Case 1), the two interior fractures of Case 2 extend more evenly. But in Case 3, the two interior fractures are inhibited and cannot extend forward. Obviously, the length and average width of the two interior fractures of Case 2 are bigger than those of other two cases (Figure 8). The main reason is that under the same flow rate and total perforation number, the cluster with more perforations can get more fractional flow rates, minimizing the stress shadowing effect, so the fracture expands more easily compared with the fracture in cluster with less perforations.

3.5. Effects of Flow Rate on Fracture Propagation. In Changning shale block, flow rate is usually 10-16 m^3/min. Under the same other parameters, various flow rates (9 m^3/min, 12 m^3/min, and 15 m^3/min) are set to research on fracture extension in a stage with multicluster. Cluster number (6 clusters), cluster spacing (10 m), and total injection volume (1200 m^3) are kept constant. The fracture geometries of different flow rates are showed in Figure 9.

It is obvious that the propagation of interior fractures is restricted severely at the small flow rate. With the growth of flow rate, interior fractures tend to expand forward with the exterior fractures. Furthermore, from Figure 10, the length and average width of interior fractures get larger as the flow rate becomes higher. Based on Equation (4), it is found that perforation friction pressure gets higher due to the increase in flow rate, contributing to higher bottom hole pressure and mitigating stress shadowing effect between clusters, which is beneficial for the even propagation of fractures.

4. Discussion

In multicluster hydraulic fracturing, cluster number, cluster spacing, perforation distribution, and flow rate are significant

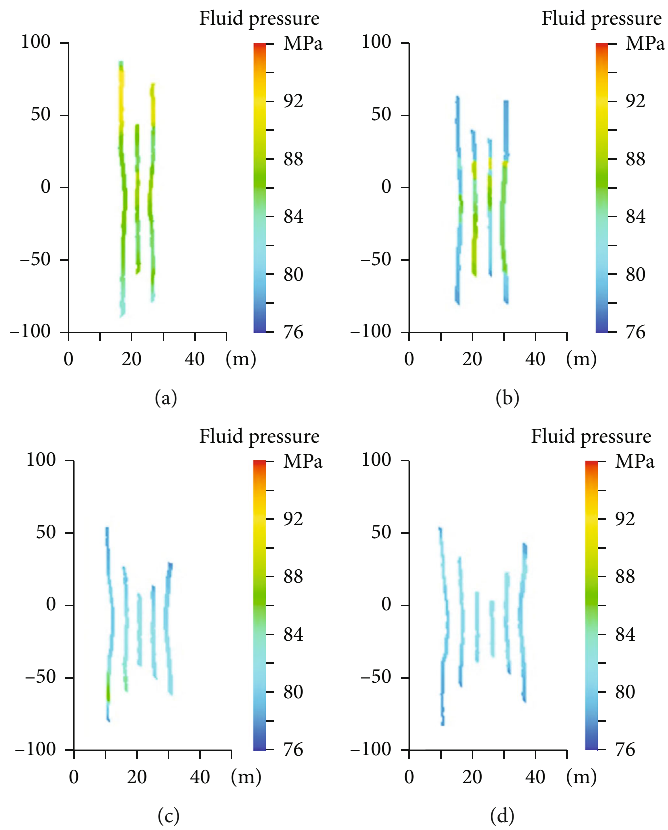

Figure 3: Effects of different numbers of clusters on fracture geometry: (a) 3 clusters, (b) 4 clusters, (c) 5 clusters, and (d) 6 clusters.

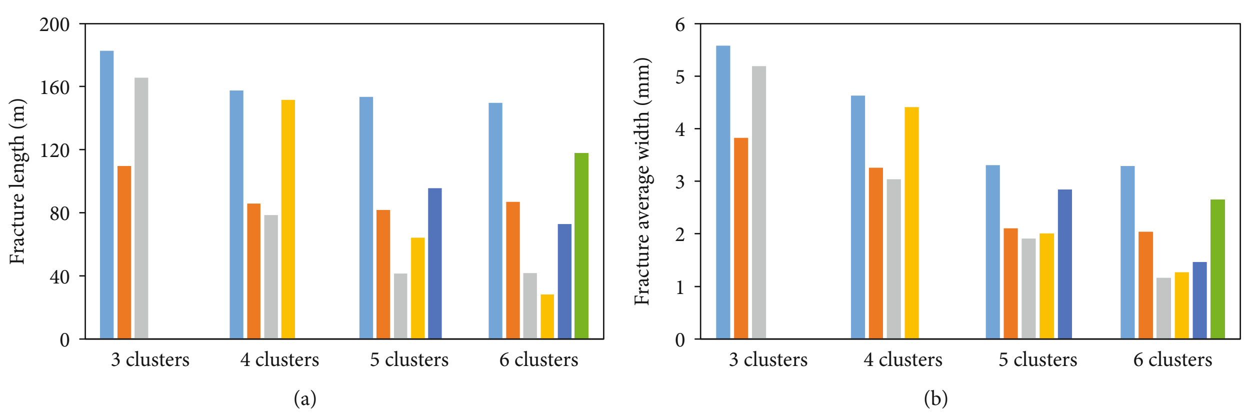

Figure 4: Length (a) and average width (b) of multifracture in a stage with different cluster numbers.

impact factors for fracture extension [18, 37–39]. Based on the simulation results above, standard deviation (SD) is employed to quantitatively evaluate the degree of fracture even extension. A high SD shows that data points distribute over a wider range of the average data value, while a low SD indicates the opposite situation [40].

$$SD = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}(X_i - X)^2}. \quad (9)$$

In this work, SD represents the standard deviation of fracture length and N stands for the number of fractures, and X_i is the length of each fracture and X is the average length of fractures. A lower SD means that fractures extend more evenly. Figure 11 shows the fracture length SD of different impact factors.

According to Figures 11(a) and 11(b), it is indicated that with the decrease in cluster number and the increase in cluster spacing, the SD of fracture length tends to be lower, which means the stress shadowing effect is mitigated and fracturing fluid entered into each cluster is more uniform, so the degree of fracture even propagation increases gradually. Similar

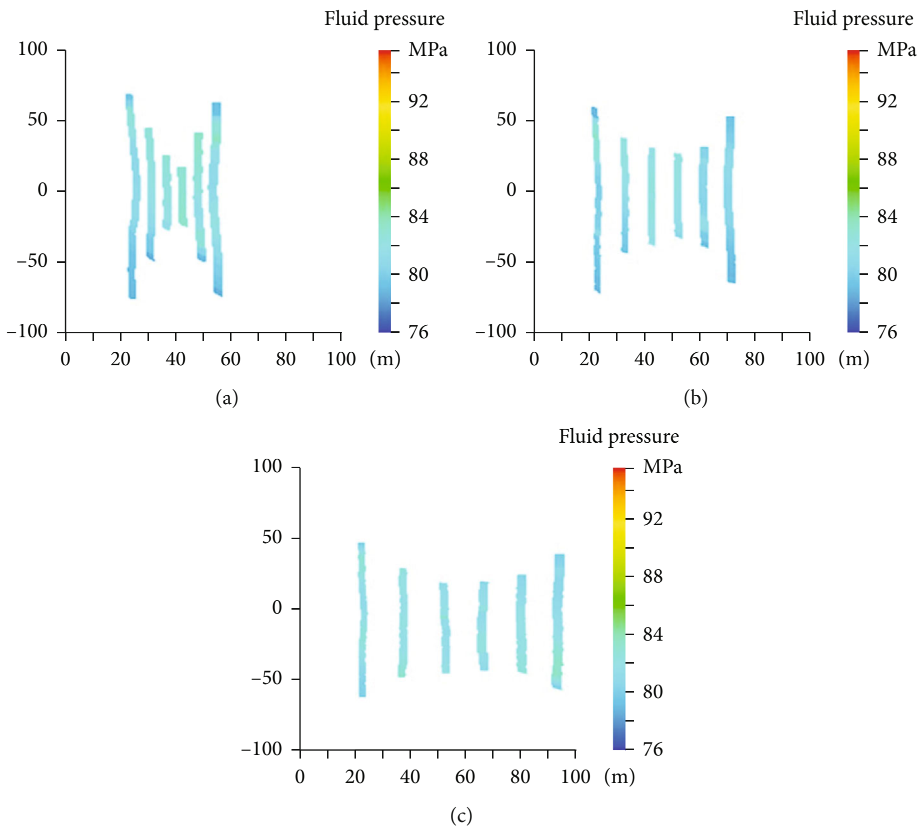

FIGURE 5: Effects of different cluster spacing on fracture geometry: (a) cluster spacing 5 m, (b) cluster spacing 10 m, and (c) cluster spacing 15 m.

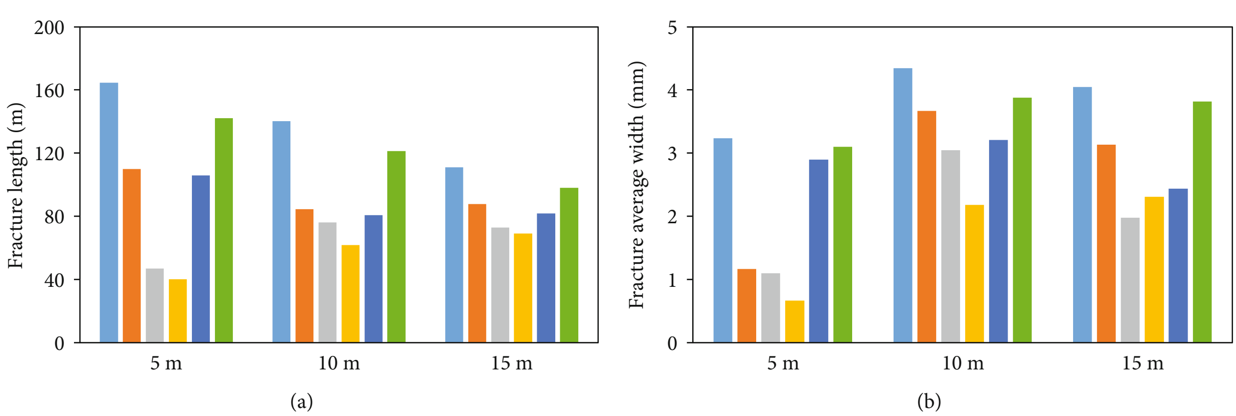

FIGURE 6: Length (a) and average width (b) of multifracture in a stage with different cluster spacing.

TABLE 3: Perforations of each cluster.

Case number	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Case 1	8	8	8	8	8	8
Case 2	7	7	10	10	7	7
Case 3	9	9	6	6	9	9

stimulation results can be found by Lecampion et al. and Wu and Olson [16, 41]. However, it is not wise to design too small cluster number or too large cluster spacing which could lead to low utilization of shale formation between clusters. Besides, Cheng et al. and Li et al. [42, 43] have discussed the effects of perforation distribution on fracture propagation and their study results are consistent with ours, which is that reducing the perforation number of exterior clusters and increasing the perforation number of interior clusters properly are beneficial for the even propagation of fractures (Figure 11(c)). For the flow rate, the lower SD of fracture length can be obtained with larger flow rate which is showed in Figure 11(d). At the smaller flow rate, the bottom hole pressure is lower relatively, which has a negative effect on fracture propagation. In the researches of Green et al. and

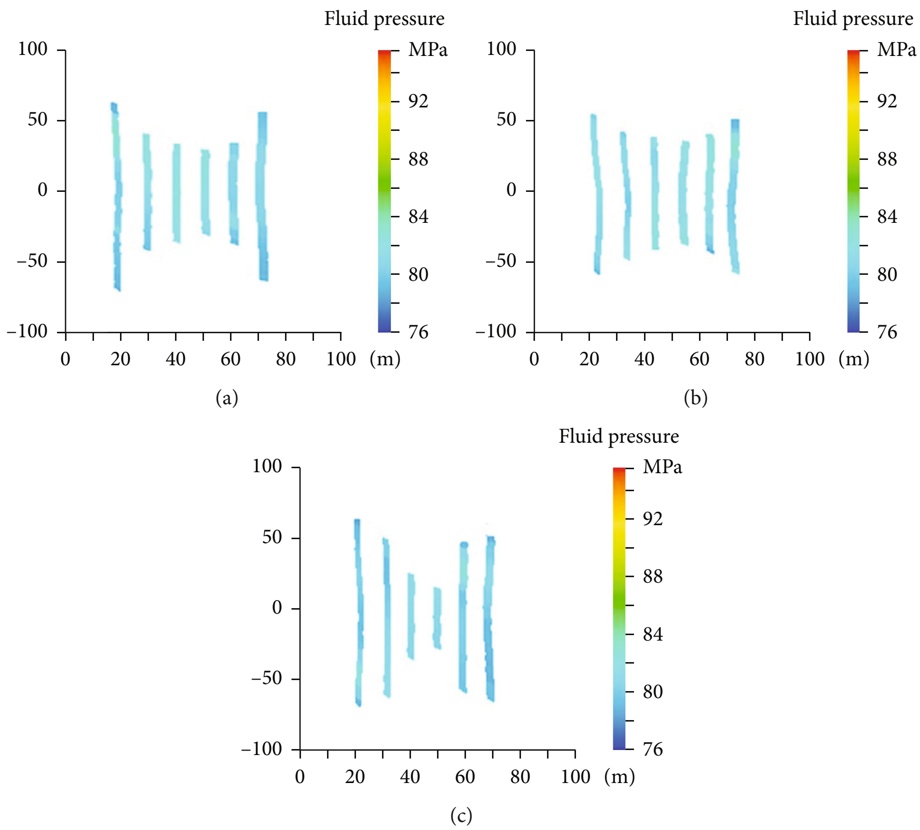

FIGURE 7: Effects of different perforation distributions on fracture geometry.

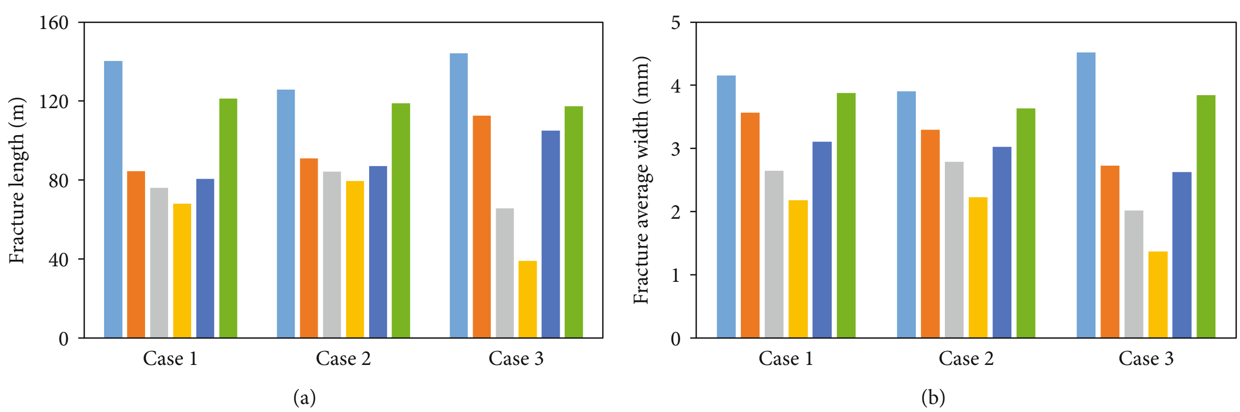

FIGURE 8: Length (a) and average width (b) of multifracture in a stage with different perforation distributions.

Xie et al. [30, 39], larger flow rate in multicluster hydraulic fracturing is recommended as well.

In the main shale area of North America, the well spacing is mostly about 100-300 m. The cluster spacing has shortened to less than 5 m, and the cluster number has increased to more than 15 clusters in a stage to obtain proper fracture length to match the small well spacing [44, 45]. In terms of fracture nonpropagation and fracture uneven propagation due to the mechanical property of shale formation and small cluster spacing, limited-entry perforation and diversion technology are introduced to enhance the cluster efficiency and fracture complexity. And through adopting multistep flow rate, original state of stress is unbalanced to promote fracture propagation further [25, 46, 47]. However, due to the small well spacing and extreme limited-entry perforation, the flow rate is not usually expected to be high in some shale areas.

Compared with the North America area, the well spacing is larger in Changning shale block which is 300-400 m. With the growth of cluster number and the decline of cluster spacing, the average fracture length tends to be shorter. Under the conditions of the larger well spacing, multicluster hydraulic fracturing with 4-6 clusters in a stage has been employed to meet the demands for the well spacing and improve the utilization of shale formation in Changning block.

Also, when the 6 clusters within a stage are designed, diversion technology at the fracture inlet is widely used to

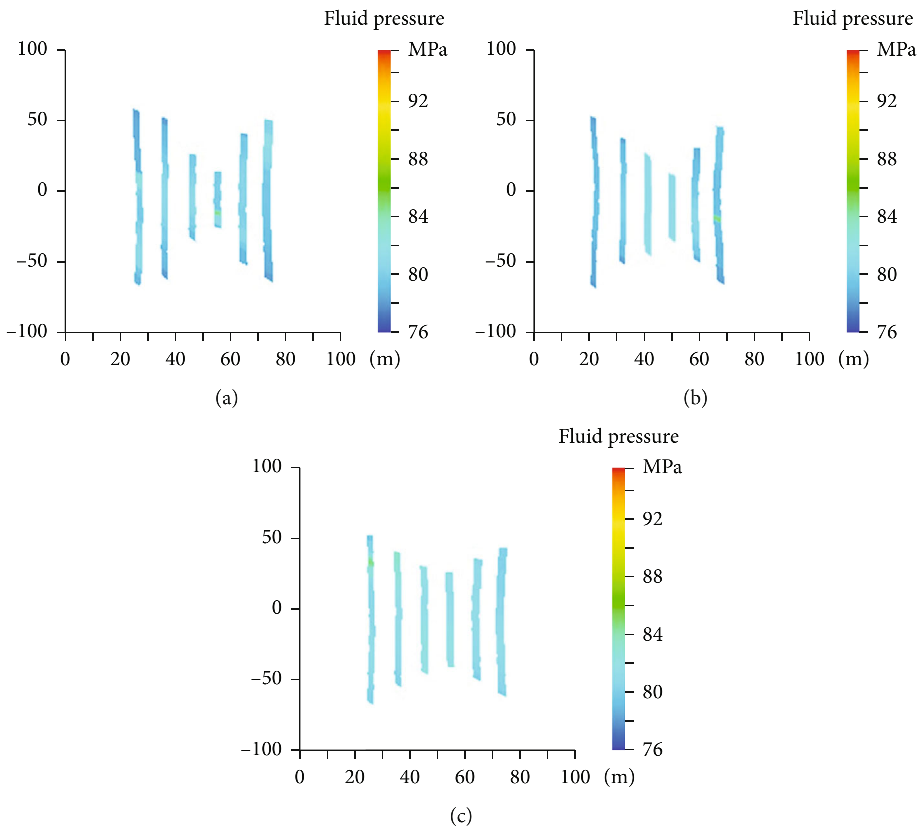

FIGURE 9: Effects of different flow rates on fracture geometry: (a) flow rate 9 m^3/min, (b) flow rate 12 m^3/min, and (c) flow rate 15 m^3/min.

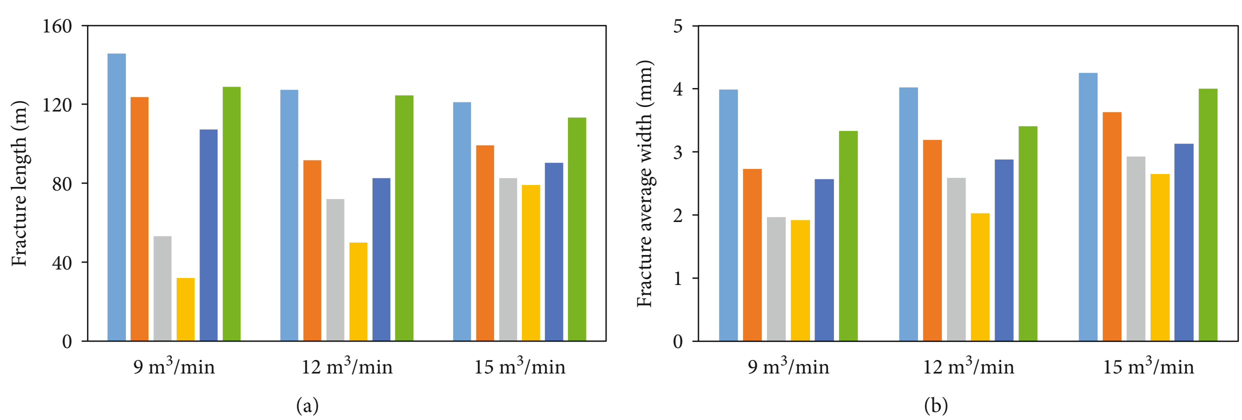

FIGURE 10: Length (a) and average width (b) of multifracture in a stage with different flow rates.

improve the cluster efficiency, promoting fracture propagation uniformly. The 15-19 mm diversion balls are used due to perforation hole erosion during hydraulic fracturing. Considering well extension of fractures, diversion balls are injected at the time of 50-60% total fracturing fluid within a stage to block the dominant fractures, facilitating recessive fractures to expand. Besides, in a certain stage, when the cluster spacing decreases to 10 m with the increase in cluster number, the width of interior fractures becomes smaller compared with exterior fractures based on the study above. In order to effectively prop fractures, small-sized ceramic proppant (100 mesh) is introduced in field, which is beneficial to increase fracture conductivity. Additionally, flow rate is the significant influence factor for hydraulic fracturing effectiveness in this target area, so it should be as high as possible under the normal fracturing treatment at the large well spacing, contributing to the relatively even propagation of multifracture as the study result above shown.

The perforation number per stage decreases to 36 or 48 to enhance the cluster efficiency. Though extreme limited-entry perforation helps fracture to extend simultaneously, reducing perforations further would cause the high wellbore friction

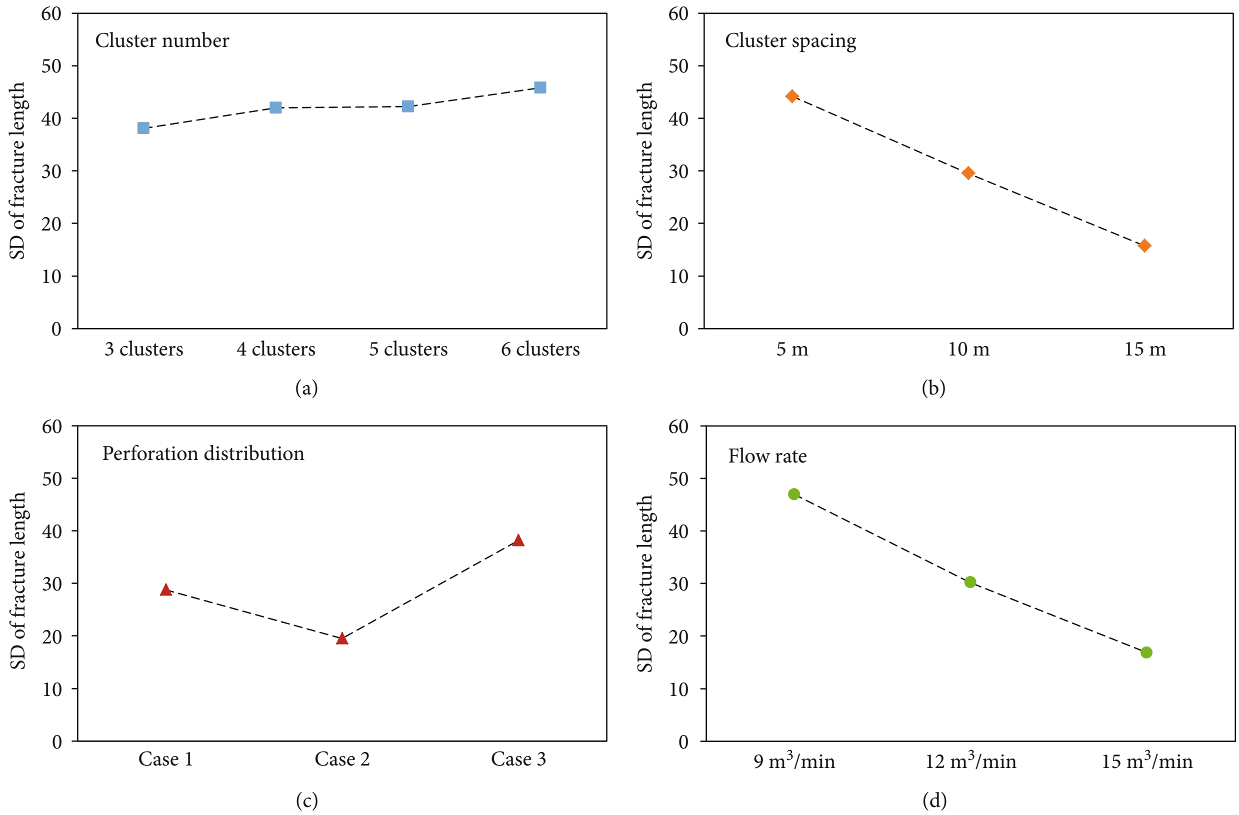

Figure 11: Standard deviation of fracture length: (a) cluster number, (b) cluster spacing, (c) perforation distribution, and (d) flow rate.

pressure P_{per}, increasing the pumping pressure which is not conductive to field operation in Changning shale block (Equation (10)).

$$P_{per} = 0.807 \frac{q^2 \rho}{N_{per} D_{per} C_{per}^2}, \quad (10)$$

where ρ represents the fluid density, N_{per} is the number of perforations, D_{per} is the perforation diameter, q is the flow rate, and C_{per} is the discharge coefficient.

Furthermore, nonuniform perforation distribution could not only promote cluster initiation simultaneously under different mechanical properties of shale formation but also render fractures extend more evenly. Therefore, a field test should be taken in target shale area to obtain better fracturing effectiveness and higher production.

5. Conclusion

There are many factors influencing the fracture propagation in multicluster hydraulic fracturing. Based on the geology and engineering characteristics of Changning shale block, cluster number, cluster spacing, perforation distribution, and flow rate were discussed to clarify the extension and geometry of multifracture by the numerical simulation method. The main conclusions can be summarized as follows:

(1) The fracture geometry is influenced by cluster number, cluster spacing, perforation distribution, and flow rate diversely. With the reduction of cluster number and the growth of cluster spacing and flow rate, the length and average width of interior fractures are inclined to increase due to the mitigation of stress shadowing effect between clusters. In the perforation distribution with more perforations in interior fractures, the length and average width of interior fractures are larger than those of another perforation distributions

(2) The SD of fracture length is introduced to evaluate the degree of fracture even extension quantitatively. Employing small cluster number, large cluster spacing, nonuniform perforation distribution, and high flow rate can obtain the low SD of fracture length, which indicates that multifracture propagates more evenly. But too small cluster number or too large cluster spacing is not recommended in a stage because of the low utilization of shale formation between clusters

(3) Multicluster hydraulic fracturing has now developed into a mature and advanced technology in the main

shale area of North America. In Changning shale block, multicluster hydraulic fracturing with 4-6 clusters in a stage has been in use based on its own geology and engineering characteristics, and diversion technology, limited-entry perforation, high flow rate, and small-sized ceramic proppant are employed to get better shale gas production. To promote fracture even extension further, nonuniform perforation distribution should be introduced

Data Availability

The data is available in the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgments

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References

[1] A. Daneshy, "Multistage fracturing using plug-and-perf systems," *World Oil*, vol. 232, no. 10, pp. 1–6, 2011.

[2] J. B. Curtis, "Fractured shale-gas systems," *AAPG Bulletin*, vol. 86, no. 11, pp. 1921–1938, 2002.

[3] X. Weng, "Modeling of complex hydraulic fractures in naturally fractured formation," *Journal of Unconventional Oil and Gas Resources*, vol. 9, pp. 114–135, 2015.

[4] N. Modeland, D. Buller, and K. Chong, "Statistical analysis of the effect of completion methodology," in *North American Unconventional Gas Conference and Exhibition*, The Woodlands, Texas, USA, 2011.

[5] Y. Cheng, "Impacts of the number of perforation clusters and cluster spacing on production performance of horizontal shale gas wells," in *SPE Eastern Regional Meeting*, Morgantown, West Virginia, USA, 2012.

[6] Q. Wu, Y. Xu, X. Wang, T. Wang, and S. Zhang, "Volume fracturing technology of unconventional reservoirs: connotation, optimization design and implementation," *Petroleum Exploration and Development*, vol. 39, no. 3, pp. 352–358, 2012.

[7] Y. Xu, Q. Lei, M. Chen et al., "Progress and development of volume stimulation techniques," *Petroleum Exploration and Development*, vol. 45, no. 5, pp. 874–887, 2018.

[8] C. K. Miller, G. A. Waters, and E. I. Rylander, "Evaluation of production log data from horizontal wells drilled in organic shales," in *North American Unconventional Gas Conference and Exhibition*, The Woodlands, Texas, USA, 2011.

[9] B. Wheaton, J. Miskimins, D. Wood, T. Lowe, and R. Barree, "Integration of distributed temperature and distributed acoustic survey results with hydraulic fracture modeling: a case study in the Woodford Shale," in *Unconventional Resources Technology Conference*, Denver, Colorado, 2014.

[10] L. N. Germanovich and D. K. Astakhow, "Fracture closure in extension and mechanical interaction of parallel joints," *Journal of Geophysical Research*, vol. 109, no. 9, pp. 2208–2222, 2004.

[11] J. E. Olson, "Multi-fracture propagation modeling: applications to hydraulic fracturing in shales and tight sands," in *42nd US Rock Mechanics Symposium and 2nd US-Canada Rock Mechanics Symposium*, San Francisco, 2008.

[12] J. C. Morrill and J. L. Miskimins, "Optimizing hydraulic fracture spacing in unconventional shales," in *SPE Hydraulic Fracturing Technology Conference*, The Woodlands, Texas, USA, 2012.

[13] A. P. Bunger, X. Zhang, and R. G. Jeffrey, "Parameters affecting the interaction among closely spaced hydraulic fractures," *SPE Journal*, vol. 17, no. 1, pp. 292–306, 2012.

[14] A. Peirce and A. P. Bunger, "Interference fracturing: nonuniform distributions of perforation clusters that promote simultaneous growth of multiple hydraulic fractures," *SPE Journal*, vol. 20, no. 2, pp. 384–395, 2014.

[15] D. H. Shin and M. M. Sharma, "Factors controlling the simultaneous propagation of multiple competing fractures in a horizontal well," in *SPE Hydraulic Fracturing Technology Conference*, The Woodlands, Texas, USA, 2014.

[16] K. Wu and J. E. Olson, "Mechanisms of simultaneous hydraulic fracture propagation from multiple perforation clusters in horizontal wells," *SPE Journal*, vol. 21, no. 3, pp. 1000–1008, 2015.

[17] J. Zhao, W. Xu, Y. Li, K. Cai, and M. Xu, "A new method for cluster spacing optimization of multi-cluster staged fracturing in horizontal wells of low-permeability oil and gas reservoirs," *Natural Gas Industry*, vol. 36, no. 10, pp. 63–69, 2016.

[18] K. Wu, J. E. Olson, M. T. Balhoff, and W. Yu, "Numerical analysis for promoting uniform development of simultaneous multiple fracture propagation in horizontal wells," in *SPE Annual Technical Conference and Exhibition*, Houston, Texas, USA, 2015.

[19] R. Lin, L. Ren, J. Zhao, Y. Tao, X. Tan, and J. Zhao, "Hydraulic fractures simulation and stimulated reservoir volume estimation for shale gas fracturing," in *SPE Europec Featured at 81st EAGE Conference and Exhibition*, London, England, UK, 2019.

[20] Y. Wang, D. Liu, J. Han, C. Li, and H. Liu, "Effect of fatigue loading-confining stress unloading rate on marble mechanical behaviors: an insight into fracture evolution analyses," *Journal of Rock Mechanics and Geotechnical Engineering*, vol. 12, no. 6, pp. 1249–1262, 2020.

[21] Y. Wang, W. Feng, and C. Li, "On anisotropic fracture and energy evolution of marble subjected to triaxial fatigue cyclic-confining pressure unloading conditions," *International Journal of Fatigue*, vol. 134, p. 105524, 2020.

[22] Y. Wang, S. Gao, D. Liu, and C. Li, "Anisotropic fatigue behaviour of interbeded marble subjected to uniaxial cyclic compressive loads," *Fatigue & Fracture of Engineering Materials & Structures*, vol. 43, no. 6, pp. 1170–1183, 2020.

[23] Y. Wang, C. Li, and J. Han, "On the effect of stress amplitude on fracture and energy evolution of pre-flawed granite under uniaxial increasing-amplitude fatigue loads," *Engineering Fracture Mechanics*, vol. 240, p. 107366, 2020.

[24] T. E. Alotaibi, C. M. Landis, and M. J. AITammar, "Phase-field modeling of hydraulic fracture propagation in mechanically heterogeneous formations," in *International Petroleum Technology Conference*, Dhahran, Kingdom of Saudi Arabia, 2020.

[25] B. Johnston and N. Volkmer, "Predicting success in the Haynesville Shale: a geologic, completion, and production analysis," in *SPE/AAPG/SEG Unconventional Resources Technology Conference*, Houston, Texas, USA, 2018.

[26] Y. Wang, S. H. Gao, C. H. Li, and J. Q. Han, “Investigation on fracture behaviors and damage evolution modeling of freeze - thawed marble subjected to increasing - amplitude cyclic loads,” *Theoretical and Applied Fracture Mechanics*, vol. 109, p. 102679, 2020.

[27] J. Barraza, C. Capderou, C. J. Matthew et al., “Increase cluster efficiency and fracture network complexity using degradable diverter particulates to increase production: Permian Basin Wolfcamp Shale case study,” in *SPE Annual Technical Conference and Exhibition*, San Antonio, Texas, USA, 2017.

[28] S. Evans, S. Siddiqui, and J. Magness, “Impact of cluster spacing on infill completions in the Eagle Ford,” in *The Unconventional Resources Technology Conference*, Houston, Texas, USA, 2018.

[29] K. Ling, X. Wu, G. Han, and S. Wang, “Optimizing the multistage fracturing interval for horizontal wells in Bakken and Three Forks Formation,” in *SPE Asia Pacific Hydraulic Fracturing Conference*, Beijing, China, 2016.

[30] J. Xie, H. Huang, Y. Sang et al., “Numerical study of simultaneous multiple fracture propagation in Changning Shale Gas Field,” *Energies*, vol. 12, no. 7, p. 1335, 2019.

[31] U. C. GA, P. T. Huckabee, M. M. Molenaar, B. Wyker, and K. Somanchi, “Perforation cluster efficiency of cemented plug and perf limited entry completions; insights from fiber optics diagnostics,” in *SPE Hydraulic Fracturing Technology Conference*, The Woodlands, Texas, USA, 2016.

[32] S. T. Castonguay, M. E. Mear, R. H. Dean, and J. H. Schmidt, “September. Predictions of the growth of multiple interacting hydraulic fractures in three dimensions,” in *SPE Annual Technical Conference and Exhibition*, New Orleans, Louisiana, USA, 2013.

[33] R. Manchanda, E. C. Bryant, P. Bhardwaj, P. Cardiff, and M. M. Sharma, “Strategies for effective stimulation of multiple perforation clusters in horizontal wells,” *SPE Production & Operations*, vol. 33, no. 3, pp. 539–556, 2017.

[34] Q. Zeng, Z. Liu, T. Wang, Y. Gao, and Z. Zhuang, “Fully coupled simulation of multiple hydraulic fractures to propagate simultaneously from a perforated horizontal wellbore,” *Computational Mechanics*, vol. 61, no. 1-2, pp. 137–155, 2018.

[35] B. Lecampion and J. Desroches, “Simultaneous initiation and growth of multiple radial hydraulic fractures from a horizontal wellbore,” *Journal of the Mechanics and Physics of Solids*, vol. 82, pp. 235–258, 2015.

[36] A. Peirce and A. Bunger, “Interference fracturing: nonuniform distributions of perforation clusters that promote simultaneous growth of multiple hydraulic fractures,” *SPE Journal*, vol. 20, no. 2, pp. 384–395, 2014.

[37] G. Xu and S. Wong, “Interaction of multiple non-planar hydraulic fractures in horizontal wells,” in *International Petroleum Technology Conference*, Beijing, China, 2013.

[38] S. H. Fallahzadeh, M. M. Hossain, A. J. Cornwell, and V. Rasouli, “Near wellbore hydraulic fracture propagation from perforations in tight rocks: the roles of fracturing fluid viscosity and injection rate,” *Energies*, vol. 10, no. 3, p. 359, 2017.

[39] S. Green, G. Xu, B. Forbes, G. Green, J. McLennan, and D. Work, “Early time fracture growth and cluster spacing effects,” in *52nd US Rock Mechanics/Geomechanics Symposium*, Seattle, Washington, 2018.

[40] Z. Zhao, X. Li, J. He, T. Mao, B. Zheng, and G. Li, “A laboratory investigation of fracture propagation induced by supercritical carbon dioxide fracturing in continental shale with interbeds,” *Journal of Petroleum Science and Engineering*, vol. 166, pp. 739–746, 2018.

[41] B. Lecampion, J. Desroches, X. Weng, J. Burghardt, and J. E. Brown, “Can we engineer better multistage horizontal completions? Evidence of the importance of near-wellbore fracture geometry from theory, lab and field experiments,” in *SPE Hydraulic Fracturing Technology Conference*, The Woodlands, Texas, USA, 2015.

[42] C. Cheng, A. P. Bunger, and A. P. Peirce, “Optimal perforation location and limited entry design for promoting simultaneous growth of multiple hydraulic fractures,” in *SPE Hydraulic Fracturing Technology Conference*, The Woodlands, Texas, USA, 2016.

[43] X. Li, L. Yi, and Z. Yang, “Numerical model and investigation of simultaneous multiple-fracture propagation within a stage in horizontal well,” *Environmental Earth Sciences*, vol. 76, no. 7, p. 273, 2017.

[44] O. A. Jaripatke, J. G. Ndungu, G. W. Schein et al., “Review of Permian completion designs and results,” in *SPE Annual Technical Conference and Exhibition*, Dallas, Texas, USA, 2018.

[45] F. Alimahomed, R. Malpani, R. Jose et al., “Stacked pay pad development in the Midland Basin,” in *SPE Liquids-Rich Basins Conference-North America*, Midland, Texas, USA, 2017.

[46] P. Weddle, L. Griffin, and C. M. Pearson, “Mining the Bakken II – pushing the envelope with extreme limited entry perforating,” in *SPE Hydraulic Fracturing Technology Conference and Exhibition*, The Woodlands, Texas, USA, 2018.

[47] Y. Rodionov, C. Defeu, K. Gakhar et al., “Optimizing of infill well development using a novel far-field diversion technique in the Eagle Ford Shale,” in *SPE/AAPG/SEG Unconventional Resources Technology Conference*, pp. 1160–1172, Austin, Texas, USA, 2017.