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Optimization of Multi-Cluster Fracturing Model under the Action of Induced Stress in Horizontal Wells

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Abstract

Volume fracturing in shale gas forms complex fracture networks and increases stimulated reservoir volume through large-scale fracturing operation with plug-perforation technology. However, some perforation clusters are stimulated unevenly after fracturing. This study aims to solve this problem by analyzing the shortcomings of the conventional fracturing model and developing a coupled model based on the 2D fracture motion equation, energy conservation law, linear elastic mechanics, and stress superposition principle. First, a multi-fracture in-situ stress model was built by studying the induced stress produced by the fracture initiation to deduce the multi-fracture induced stress impact factor on the basis of the stress superposition principle. Then, the classical Perkins–Kern–Nordgren model was utilized with the crustal stress model. Finally, a precise fracturing design method was used to optimize perforation and fracturing parameters under the new model. Results demonstrate that the interference effect among fractures is the major factor causing the non-uniform propagation of each fracture. Compression on the main horizontal stress increases the net pressure. Therefore, both the degree of operation difficulty and the complexity of fracture geometry are improved. After applying the optimal design, the production is increased by 20%, and the cost is reduced by 15%.

Keywords: shale gas, induced stress, cluster perforation, stress superposition, staged fracturing, coupling

1. Introduction

The revolutionary development and large-scale application of horizontal well completion and volume fracturing technology allow shale gas resources to be exploited efficiently[1,2]. However, the production logging data in six large field areas of shale gas reservoir in USA shows that the production distribution of some perforation clusters in fractured horizontal wells is seriously uneven, and almost 25% of clusters do not contribute to the production[3]. This finding may be attributed to the fact that the accumulation, transfer, and interference of stress result in the poor stimulation of some perforated intervals. For example, the stress shadow effect might apply extra compression on neighboring fractures, leading to increased net pressure and limited width expansion and fracture propagation[4–8]. In current fracturing designs, the mechanism by which stress interference affects the width expansion and growth of multi-fractures simultaneously remains unclear. In addition, coupling research on the optimization of induced stress field model and fracturing model is lacking. Hence, a modified model is required to improve fracturing optimization in shale gas reservoirs.

The remainder of this paper is organized as follows. Section 2 describes the research status of induced stress effects on fracture propagation. Section 3 presents the establishment of a new fracture model based on the linear elastic mechanics and stress superposition principle to improve the stimulation of a shale gas reservoir. Section 4 provides an analysis of the proposed model after a number of simulations and presents a case study on the field application of the model. Conclusions are summarized in Section 5.

2. State of the art

Scholars at home and abroad have conducted much research on the rules of multi-fractures propagation and induced stress field. Warpinski[9] studied the effects of single fracture induced stress field, proposed the concept of dimensionless spacing, and provided analytical formulas of the impact factor φ of single fracture induced stress field. Davidson et al[10] discussed the rules of multi-fracture propagation in natural fracture reservoirs on the basis of the test results of certain straight wells with minimal fracturing; they found that complex fracture growth might significantly increase operation pressure. Weng[11] established a numerical model of multi-crack fracturing and propagation in inclined wells and pointed out that optimizing the number of fractures might weaken the negative effect produced by interference among fractures. Olson [12–14] found that the width of newly opened fractures was smaller than that of old ones through on-site microseism data, suggesting that new fractured cracks were affected by compressive stress generated from old cracks. Lecampion[15,16] combined a pseudo-3D fracturing model and linear elastic mechanics to establish a numerical model of multi-fractures in shale gas

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horizontal wells. Bo Cai[17] neglected the stress shadow effect in maximum principal stress direction and built a fracturing description model of the stress shadow effect on the basis of the stress superposition principle. Basing from previous results and considering the effect of multi-crack induced stress, the present study used the stress superposition principle to deduce the multi-crack-induced stress impact factor coupled with the 2D Perkins–Kern–Nordgren (PKN) fracturing model. This study also analyzed key impact factors. The new model may serve a guide to understand the production increase of shale gas volume fracturing.

3. Methodology

3.1 Model Assumptions

The PKN model (Nordgren 1972) with single fracture induced stress impact factor (Warpinski 1987) is used to deduce the coupling model. General assumptions in this study include the following: 1) the fracture initiation and propagation model conforms to the PKN theoretical model; 2) the horizontal wellbore is perpendicular to the maximum principal stress direction; 3) only transverse fractures from the wellbore are considered; 4) shale gas reservoirs are homogeneous and infinite; 5) formation temperature exerts no impact on fluids in fractures; 6) fracture fluids are Newtonian fluid and are considered as 1D flows along the fracture length; and 7) rock burst meets the yield criterion of Mohr–Coulomb, and both fracture toughness and rock creep are neglected.

3.2 Calculation of Fracture Pressure

In case of simultaneous fracturing and propagation of multi-clusters in the shale gas horizontal well, the volume conservation and pressure balance principle were followed, and the interference effect over the pressure system among fractures was considered.

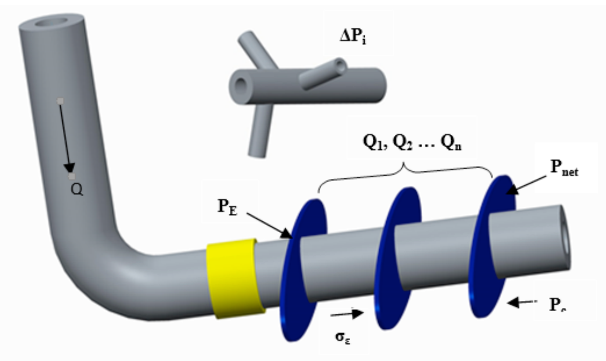

Fig. 1. Flow Distribution and Pressure System of Each Single Cluster Crack of Staged Fracturing

Material Balance. As shown in Figure 1, the total volume that flows into each cluster is equal to the pumping volume. Therefore, the following relationship is obtained between multi-cluster cracks:

$$\Delta P_i = P_W - P_E - P_{pipe} = f_p Q_i^2 \tag{1}$$

$$f_p = C_1 \times \frac{\rho_f}{n_p g D_p^4 g C^2} \tag{2}$$

$$Q_{Total} = \sum_i^n Q_i \ , \ i = 1,2\cdots,n \tag{3}$$

Formula (3) was substituted into Formula (1) to obtain:

$$\sum_i^n P_{wi} - \sum_i^n P_{Ei} - \sum_i^n P_{pipe} = \sum_i^n f_{pi} Q_i^2 \tag{4}$$

where P_w is the bottom-hole flowing pressure (MPa), P_E is the propagation pressure at the fracture tip (MPa), P_{pipe} is the pipeline friction (MPa), ΔP_i is the perforation friction (MPa), Q_{Total} is the total flow (m^3/min), Q_i is the distribution flow of each facture (m^3/min), C_1 is the unit conversion coefficient, n_p is the number of perforations, D_p is the diameter of the perforation hole(cm), ρ_f is the fluid density (kg/m^3), and C is the release coefficient related to the perforation shape.

Pressure Balance. Considering the effect of induced stress field on the pressure system, we combined the PKN model to obtain pressure balance:

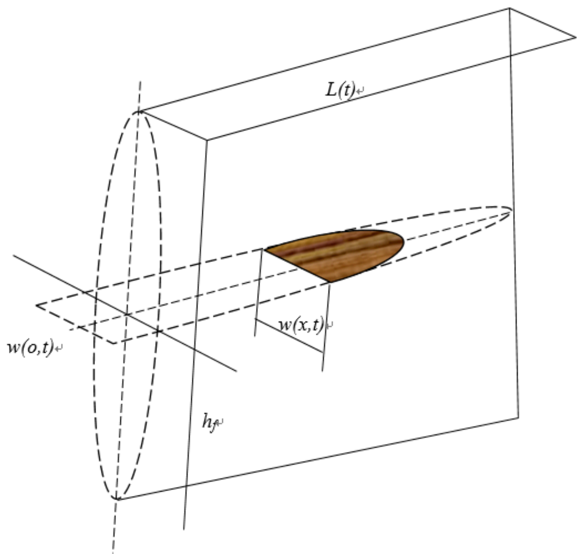

Fig. 2. Model of PKN Fracture

Net pressure is the excess pressure inside the fracture to keep the fracture open. It is also considered as the energy in the fracturing fluid available for propagating the fracture and for producing width. For each single crack, the pressure system at the fracture tip is

$$P_E = P_w - P_{pipe} - \Delta P_i \tag{5}$$

$$P_{net} = P_E - P_c - \sigma_\varepsilon \tag{6}$$

PKN model uses the vertical plane strain assumption and the continuity equation of the PKN fracture model is[18]

$$\frac{\partial q}{\partial x} + q_L + \frac{\partial A}{\partial t} = 0 \tag{7}$$

Net pressure determines the fracture width. For any given positive net pressure, there is a fracture width that will be generated by specific net pressure. The relationship between width and net pressure is[19,20,21]

$$\omega \propto \frac{P_{net} h_f \left(1-\nu^2\right)}{E} \tag{8}$$

Therefore, fracture width could be used to represent pressure. Formula (7) can be transformed to

$$\frac{E'}{128\mu h_f}\frac{\partial^2\omega^4}{\partial x^2}=\frac{8C_L}{\pi\sqrt{t-t_{\exp}(x)}}+\frac{\partial\omega}{\partial t} \tag{9}$$

where P_c is the closure pressure (MPa), σ_ξ is the induced stress (MPa), P_{net} is the net pressure in cracks (MPa), μ is the fluid viscosity (mPa•s), h_f is the fracture height (m), w is the fracture width (mm), E' is the Young's modulus (MPa), and v is Poisson's ratio.

3.3 Solution of Multi-Fracture Induced Stress Field

Fracture opening changed the initial earth stress field of the reservoir. According to linear elastic mechanics, the arbitrary point of induced stress around the single fracture was related to the fracture height and the distance. Figure 3 presents the rock triaxial stress tests, which demonstrated that the fracture geometry affected the properties of rock mechanics. The fracture height h and fracture spacing d could be used as dimensionless impact factors to characterize induced stress. The induced stress field might compress the circumferential stress; thus, the minimum principal stress σ_h of the neighbor fracture would increase. Warpinski studied the relationship of the impact factor φ for the single fracture-induced stress field. And the net pressure inside the fracture can be expressed as

$$\phi=1-\left(1+\left(\frac{h}{2d}\right)^2\right)^{-3/2} \tag{10}$$

$$P_{net}'=P_{net}\left(1+\phi\right) \tag{11}$$

Fig. 3. Rock Triaxial Stress Test

The stress superposition principle was used to deduce the analytical formula of the multi-fracture induced stress factor φ_ε. As shown in Figure 1, with the assumption that the presence of n clusters also implies the presence of n fractures, the induced stress influence of i crack over j can be expressed as

$$\phi_{ij}=1-\left(1+\left(\frac{h}{2d_{ij}}\right)^2\right)^{-3/2} \tag{12}$$

Thus, the induced stress influence of n cracks over j can be expressed as

$$\phi_{\varepsilon j}=\sum_{i=1}^{n}1-\left(1+\left(\frac{h}{2d_{ij}}\right)^2\right)^{-3/2} \tag{13}$$

The net pressure in crack j is

$$P_{net}'=P_{net}\left(1+\phi_{\varepsilon j}\right) \tag{14}$$

The induced stress impact of n fractures over the entire multi-crack stress field is

$$\phi_\varepsilon=\sum_{i=1}^{n}\sum_{j=1}^{n}1-\left(1+\left(\frac{h}{2d_{ij}}\right)^2\right)^{-3/2} \tag{15}$$

Formula (13) was used to obtain the net pressure which take induced stress into consideration. P_{net}' was substituted into Formula (6) to obtain the propagation pressure. Formulas (1), (4), (5), and (9) were combined to obtain the numerical equation of multi-fracture propagation. To solve this equation numerically, a dimensionless time t_D was proposed to obtain the width and length as a function of time. The t_D used in the solution is defined by

$$\mathrm{t}_D=\left[\frac{64C_L^{\,5}E'h_f}{\pi^3\mu q_i^2}\right]^{2/3}\mathrm{g\,t} \tag{16}$$

where C_L is the leak off coefficient, , μ is the fluid viscosity, h_f is the fracture height, E' is the Young's modulus, q_i is the slurry, and t is the time step.

The new model can be used to analyze the propagation of every single fracture to create a precise fracture design for each stage.

4. Result Analysis and Discussion

4.1 Induced Stress Field versus Cluster Spacing and Number of Clusters

Different cluster spacing and numbers of perforation clusters were set to study the effect of induced stress field on perforation and fracturing parameters. The induced stress impact factor was used to characterize the induced stress field. In Figures 4 and 5, the relationship among cluster spacing, perforation cluster number, and induced stress was investigated. The simulation results indicate the following. First, as the cluster spacing increases, Φ_ε exhibits a descending trend, and the interference among fractures becomes weak. Second, if the cluster spacing is fixed, Φ_ε positively correlates with the number of perforation clusters, and the interference among fractures becomes strong. Third, 20–30 m of each cluster interval is the best optimization after the simulation, and three perforation clusters are preferred.

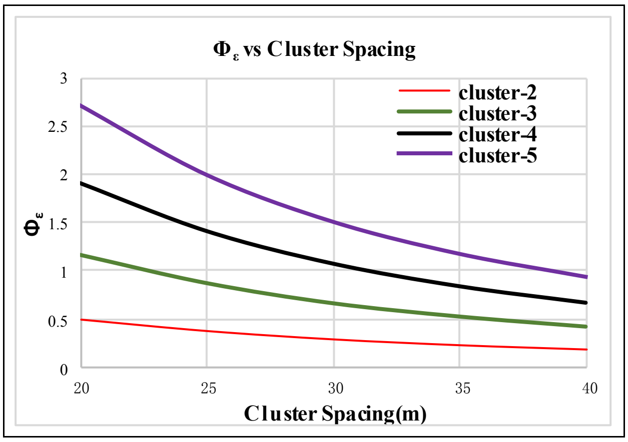

Fig. 4. Plate of Φ_ε vs. Cluster Spacing

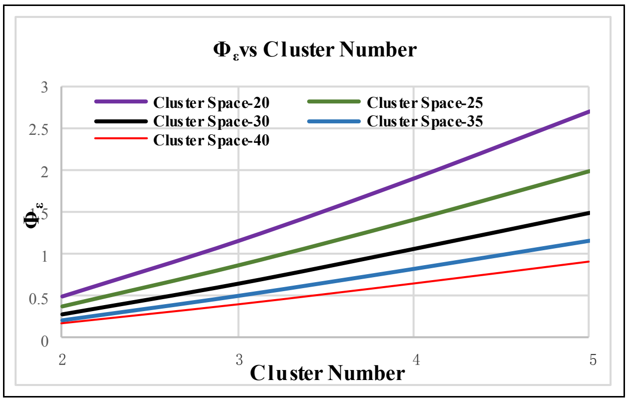

Fig. 5. Plate of Φ_ε vs. Number of Clusters

4.2 Net Pressure versus Cluster Spacing

The condition of the reservoir was given, and the net pressure with different crack numbers and cluster spacing was simulated. Simulation results can be seen in Figure 6 and 7. Three patterns can be observed throughout the simulation. First, external fracture suffers from the extra pressure coming from the initiation of the previous fracture. Thus, an increase in the minimum horizontal principal stress increases the net pressure and thus the operation surface pressure. This requires higher horsepower of frac pumps and also increases the operation risk. At the same time, if the interference among fractures is strong enough, the compression strain applied on the minimum principal stress makes little difference between maximum and minimum horizontal principle stress, this condition probably causes complex fracture propagation. Second, the larger the number of fractures, the higher the net pressure in fractures. The total net pressure could be increased by 77.7% if five fractures are opened instead of three. Third, the net pressure negatively correlates with cluster spacing. This also demonstrates that it is one of the efficient way to weaken the influence of induced stress by increasing the spacing among fractures.

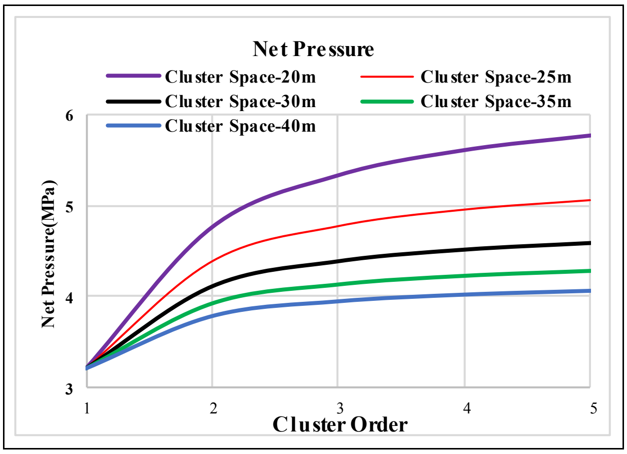

Fig. 6. Plate of Net Pressure in Each Single Fracture

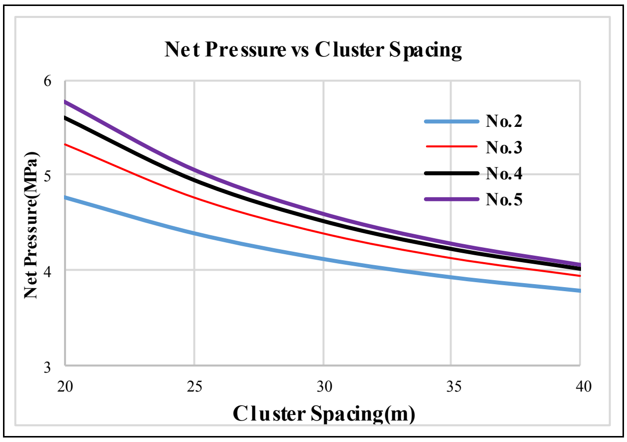

Fig. 7. Plate of Net Pressure vs. Cluster Spacing

4.3 Perforation and Fracturing Parameter

If the reservoir condition is consistent and the engineering condition is at the same level, the ideal fracturing makes every fracture accept the same volume of fluids and the same mass of sands to stimulate each fracture evenly in multi-cluster fracturing. However, based on the discussion mentioned above, each fracture has a different net pressure because of the stress interference effect, leading to an unequal absorption amount of sand and fluids. Figure 8 and 9 respectively exhibit the schematic diagram of fracture propagation under ideal and real condition. The fracture pressure can be balanced by changing the perforation friction. After setting the last opened fracture (the fracture with the highest net pressure) as the baseline, the other orders of the cluster's perforation parameters were similarly adjusted. Figures 10 and 11 show the following results: 1) Increasing the perforation holes can reduce the flow resistance. This will lead to the lower surface pressure. Hence, perforation holes positively correlate with cluster spacing, which also infers that the stress interference can be weakened by increasing the number of perforation holes; 2) perforation holes could also be increased for high slurry treatments. For those high flow rate operations, increasing the perf holes is a good way to obtain better production.

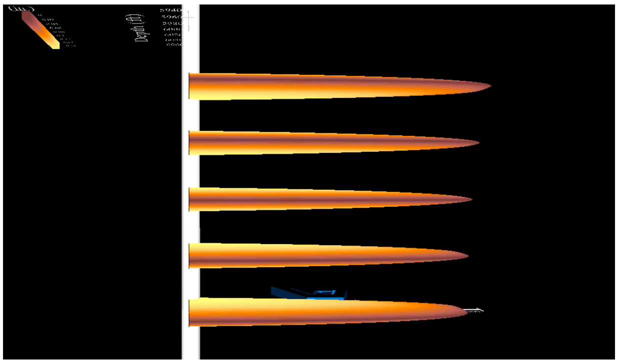

Fig. 8. Ideal Fracture Propagation

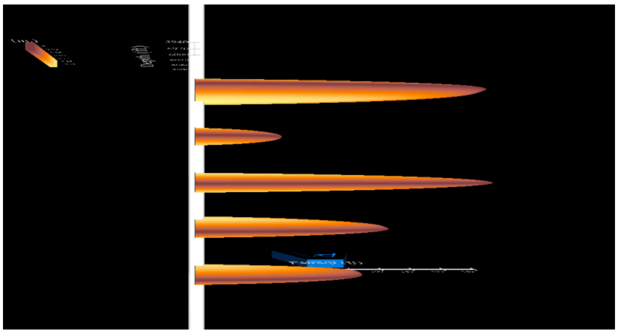

Fig. 9. Real Fracture Propagation

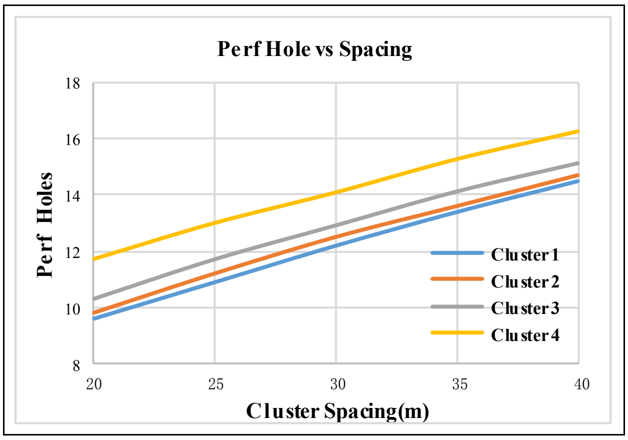

Fig. 10. Plate of Number of Perf Holes vs. Spacing

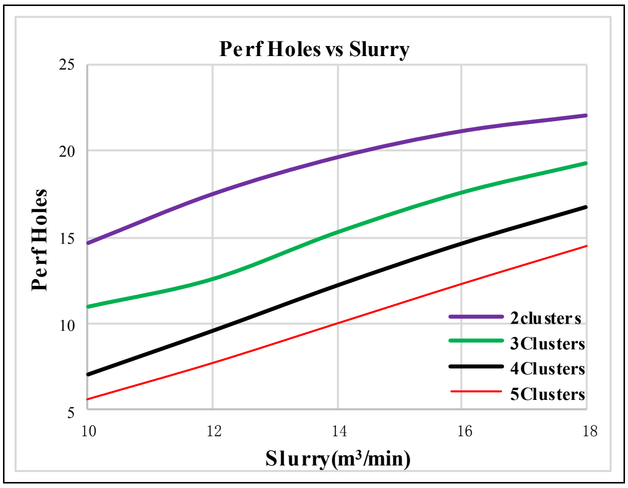

Fig. 11. Plate of Number of Perf Holes vs. Slurry

4.4. Case History

With Well B as an example, the length of the horizontal interval was 1100 m, the effective permeability of the reservoir was 0.001 mD, the porosity was 4%, the pore pressure was 34.5 MPa, the Young's modulus was 30690 MPa, the Poisson's ratio was 0.25, the maximum principal stress was 53.8 MPa, and the minimum horizontal principal stress was 49.3 MPa. On the basis of previous experience on adjacent wells, the fracturing of 10 intervals of large-scale fracturing was performed for Well B in a certain block. The perforation design and fracturing parameters of this well were optimized using the modified model and research findings in the present study. Through simulation calculation, three cluster perforations per stage were fractured with a cluster spacing of 25 m. The amount of fracturing fluids injected into each stage was 3533 m^3, and 167 t of sand was added. The numbers of perforations for cluster 1, 2, and 3 at each stage were 16, 17, and 24, respectively.

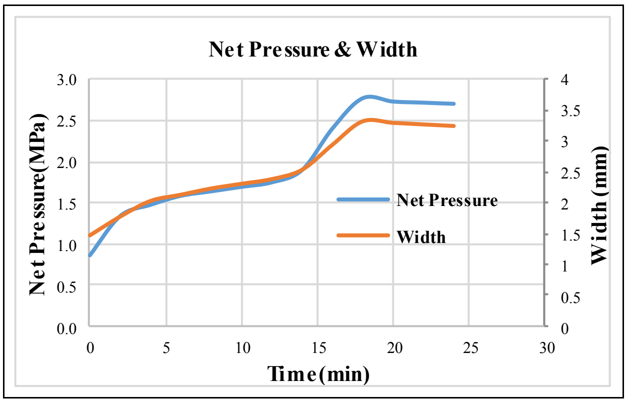

Fig. 12. Actual Net Pressure Simulation

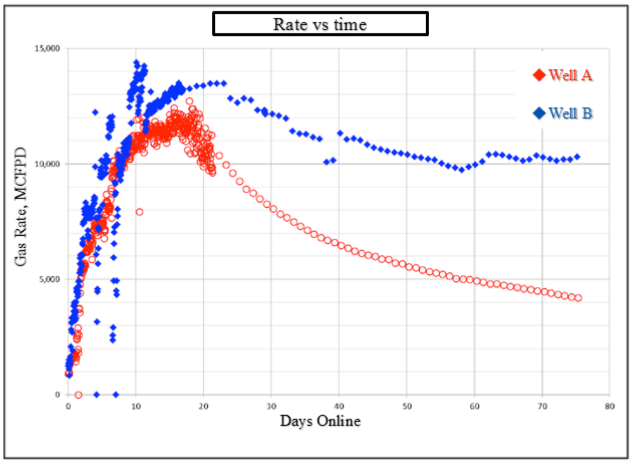

Fig. 13. Production Data of Well A and Well B

As shown in Figure 12, the actual maximum net pressure after fracturing was 2.8 MPa and the maximum width of the fracture was 3.3 mm after the simulation by using the data collected on the field. The maximum net pressure calculated by the model was 2.92 MPa. The calculated result demonstrated that this model had a good match with the field monitoring data. Furthermore, in Figure 13, the production data showed that the production of well B increased by 30% compared with the adjacent well A. Table 1 presented the comparison of operation parameters between well B and adjacent well A. The amount of fracturing liquid was reduced by 1000 m^3, the amount of proppants was reduced by 100 t, the number of perforation holes decreased by 150, and the total cost decreased by 10%. Figure 14 showed the treating pressure response of well B. Phase ① was the pressure test, phase ② was pad stage, phase ③ and ④ were slurry stages and phase ⑤ was flushing stage. During the whole operation, all stages went through smoothly and there was no abnormal pressure spike which demonstrated this optimal design was safe and reliable.

Table.1. Comparison of Operation Parameters of Well B and Well A

Comparison Parameter	Well A	Well B
Number of Fracturing Interval	10 stages, three clusters per stage	10 stages, three clusters per stage
Interval Spacing (m)	51	50
Type of Fracturing Fluid	Hydrochloric acid + slick water	Hydrochloric acid + slick water
Type of Propping Agent	100-mesh sand, 40/70 Ottawa sand and pre-coated sand	100-mesh sand, 40/70 Ottawa sand and pre-coated sand
Total Amount of Liquid (m^3)	36222	35334
Total Quantity of Sand (t)	1711	1677
Displacement (m^3/min)	16	15
Number of Perforations per Cluster	24, 24, 24	16, 17, 24

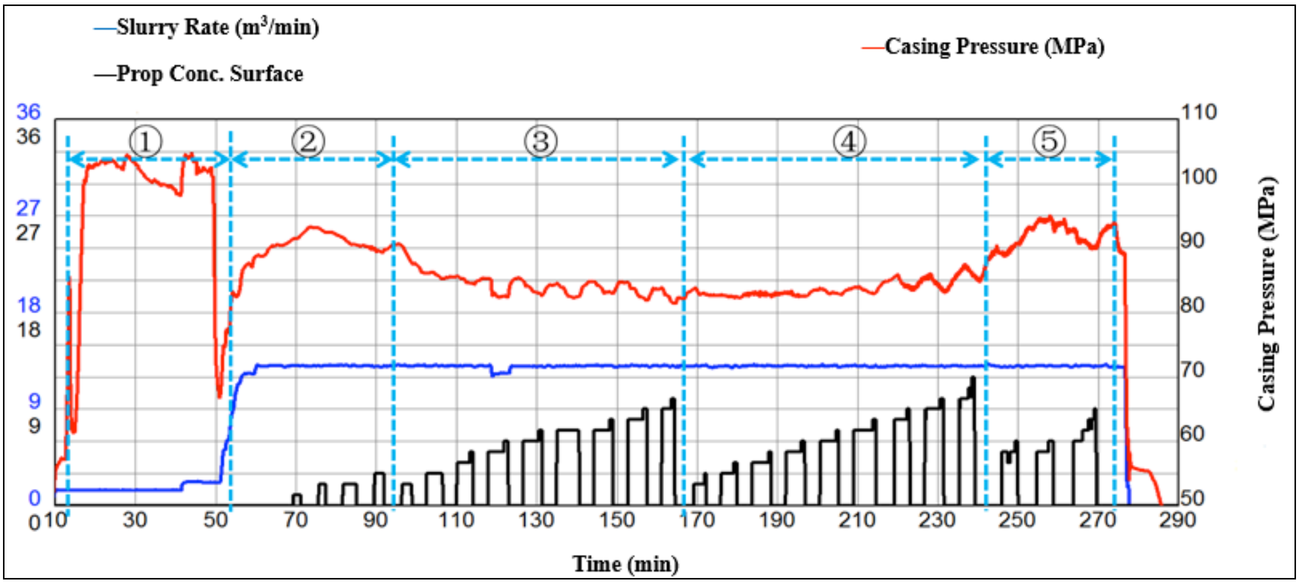

Fig. 14. Field Treating Pressure of Well B

5. Conclusion

In this study, a modified fracturing model specific to shale gas reservoir was proposed to optimize the fracturing design. The interference among fractures was considered, and the developed model was combined with the multi-fracture induced stress model and the PKN fracturing model. The effects of the model were evaluated by numerical simulations and field application. The following are the study's main conclusions. First, as the cluster spacing increases, interference among fractures becomes relatively small. Similarly, the number of clusters positively correlates with induced stress. An interval space of 20–30 m and three perforation clusters are preferred for the optimal design. Second, the net pressure is increased by the interference stress. Third, fracturing and perforation parameters should be optimized to ensure uniform and complete stimulation through the new model. The results of this study may be used to guide volume fracturing stimulation for shale gas. However, some aspects of the new model were not considered and require further study.

(1)Propagation through natural fractures: The communication between hydraulic fractures and natural fractures could result in a complex stress field and significantly affect fluid leakage and fracture extension.

(2)Three-dimensional fracturing model: The PKN fracture model discussed in this study was a 2D model that assumes that the fracture height is specified. This limitation can be remedied by the use of the planar 3D model.

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