Fracturing Parameters Optimizing Simulation of Horizontal Well In WeiYuan Shale Gasfield

Mingguang Che1,2*, Meng Wang3, Bo Zeng3, Yi Song3, Wei Jiang4, Xiaofeng Zhang5, Kai Dong5

1 Department of Modern Mechanics of University of Science and Technology of China, Anhui Hefei, 230026
2 Research Institute of Petroleum Exploration and Development, PetroChina, Beijing, 100083, China
3 XiNan Oil and Gas field Co. Ltd, PetroChina, Chengdu, Sichuan, 610041, China
4 CNPC Chuanqing Drilling Engineering Company Limited, Sichuan Chengdu, 610031
5 CNPC Great Wall Drilling Engineering Company Limited, Beijing, 100101
*Corresponding author’s e-mail: chemg69@petrochina.com.cn

Abstract. Multistage fracturing and multi-clusters with long lateral fracturing were applied during developing the WeiYuan shale gas field, and the fracturing parameters were variable obviously for the fracturing lateral, perforating clusters, pumping rate, fracturing fluid volume and proppant quality. In this paper, the 3D geological model of a WeiYuan shale gas pad was used to simulate and optimize the fracturing parameters of the shale gas horizontal wells. The simulating results show that there is a reasonable matching relationship between different fracturing lateral length and the perforating clusters, and there is an optimal fluid volume and proppant quality. As the length of the fracturing lateral and the number of clusters increase, the spacing of horizontal wells need to be reduced reasonably. With the purpose of fracturing parameters optimization for WeiYuan shale gas horizontal wells, it is recommended to increase the number of perforation clusters, increase the treating rate, and use the reasonable fluid volume and proppant quality for different fracturing lateral. The research results of this paper have guiding significance for the optimization and treatment of fracturing shale gas horizontal well.

1. Introduction
China is the second country in the world to realize effective large-scale exploitation of shale gas. By 2020 the annual shale gas production in China has reached of 200×10⁸ m³ and the marine-facies shale gas in the Sichuan Basin has become the major contributor to growth of China’s natural gas production [1-5]. The WeiYuan shale gas field is one of China’s national demonstration areas for shale gas development, which presents the production capacity of 39×10⁸ m³ in 2020. The major reservoir of the WeiYuan shale play lies in the mid-lower part in the Silurian Longmaxi Formation [6-10], with TOC of 5.0%–6.5%; porosity of 6.0%–8.0%; gas content of 5.0-7.0 m³/t; Brittle mineral content of 70.0%–80.0%; favourable reservoir rock thickness of 1.0–7.0m; the horizontal stress difference of 7.7–18.7 MPa [11-13]. The WeiYuan shale gas oilfield is characterized by the rapid decrease in production rates and highly varied gas outputs among wells [14-17]. The horizontal well multi-stage fracturing is the key technology to improve the shale gas production. A sound combination of fracturing parameters has
proved to be significant for improving the single-well production capacity, optimizing the development index, and realizing efficient large-scale shale gas development.

This paper has analyzed the horizontal well multi-stage fracturing practice applied to the WeiYuan shale gas field and summarized the characteristics of the fracturing parameters. Then, based on two major parameters—the fracturing stage length and the perforation cluster numbers, the horizontal well multi-stage fracturing practices adopted in the WeiYuan shale gas play has been classified. A 3-D geological model for a WeiYuan platform has been established to optimize the parameters of various fracturing practices. Statistics of fracturing parameters and corresponding simulated optimization results were compared, based on which the recommendations on improving the fracturing parameters of horizontal wells in the WeiYuan shale gas play have been developed. The conclusions drawn in this paper can be informative and instructive to the future optimization of the fracturing treatment of shale gas horizontal wells.

2. Characteristics of the fracturing parameters in the WeiYuan shale gas field

2.1. The horizontal well fracturing technique in the WeiYuan shale gas play

Multi-stage fracturing has been carried out for more than 300 horizontal wells in the WeiYuan shale gas play since 2015. As shown in Figure 1, with respect to the fracturing lateral length and perforation cluster numbers, optimization of the horizontal well multi-stage fracturing technique can be divided into three stages. In 2015–2016, the average length of horizontal well fracturing stage is 70–80 m, associated with 3–4 perforation clusters in each stage. In 2017–2019, intensive fracturing has been mainly performed with more fracturing stages and some wells increase the perforation clusters. The average length of fracturing stage is reduced to 50–70 m, and each stage has 3–5 perforation clusters. In 2020 fracturing is mainly done in a manner involving multi-cluster perforating with narrowed cluster spacing (high fracture density) and extended fracture stage length. The fracturing stage length is restored to an average length of 70–80m, while the perforation clusters in each stage grow to 7–9.

2.2. Distribution characteristics of fracturing parameters

Figure 2 is the box-and-whisker plot of the horizontal well multi-stage fracturing parameters in the WeiYuan shale gas play. The parameters include the length of the fractured horizontal wellbore, fracturing stage length, cluster spacing, pumping rate, proppant intensity (the amount of proppant per
unit length of the fractured horizontal wellbore), and fluid intensity (the amount of fluids consumed per unit length of the fractured horizontal wellbore).

As shown in Figure 2a, the range of the fractured horizontal wellbore length is 502–2577 m with a lower quartile of 1389.8 m, an upper quartile 1654.8 m, and an average of 1530.7 m.

As shown in Figures 2b and 2c, the length of fracturing stage is 41.1–127.3 m, with a lower quartile of 62.7 m, an upper quartile of 72.9 m, and an average of 69.1 m. The cluster spacing is 8.54–48.57 m, with a lower quartile of 16.42 m, an upper quartile of 23.10 m, and an average of 20.23 m.

As shown by Figure 2d, the pumping rate is 10.2–16.6 m³/min, with a lower quartile of 13.0 m³/min, an upper quartile of 14.2 m³/min, and an average of 13.7 m³/min.

As shown in Figure 2e, the proppant intensity is 0.70–3.50 t/m, with a lower quartile of 1.46 t/m, an upper quartile of 1.95 t/m, and an average 1.73 t/m.

As shown in Figure 2f, the fluid intensity is 13.47–47.94 m³/m, with a lower quartile of 25.03 m³/m, an upper quartile of 29.20 m³/m, and an average of 27.19 m³/m.

Figure 2. The box-and-whisker plot of horizontal well multi-stage fracturing parameters in the WeiYuan shale gas play

3. Geological model for fracturing

On the basis of the data of the Wei-20XHXX platform, the Petrel software has been used to build the 3D geological model, including the structure, attribute, natural fracture and geo-mechanical models. Then, hydraulic fracturing simulation and production history matching have been carried out. The effects of the perforation cluster numbers, pumping rate, treatment scale, and the horizontal well spacing in cases of different fracturing stage lengths have been simulated and investigated.
3.1. Geological model parameters for the pad
The planar meshing is 15 m × 15 m for the WeiYuan 20XHXX platform. Structurally constrained by the base of the Longmaxi Formation, the model of each layer is built via correction of data of each layer. For the purpose of vertical refined layering, considering the thickness of various layers in the Longmaxi Formation, the vertical dimension of the mesh is set to be 1 m. The total number of meshes in the model has reached 8940810, with 9091192 grid nodes. The geological attributes of the Wei 20XHXX platform model are shown in Figure 3, including the reservoir rock properties such as TOC, porosity, total gas content, and brittle index, and the engineering properties such as the Young’s modulus, Poisson’s ratio, compressive strength, tensile strength, and internal friction angle.

3.2. Fracturing model correction
Based on the platform geological model and rock mechanical model, volumetric (stimulated reservoir volume-oriented) fracturing simulations were carried out to establish a high-precision non-structural-meshing numerical model. Then, the numerical model is corrected and calibrated into a static model via production history matching.

(1) Hydraulic fracturing simulation
A “zipper” fracturing simulation has been done in line with the actual fracturing operation sequence, based on the platform geo-mechanical model with adequate considerations for the impacts of stress shadowing between stages and wells on the fracture geometry. A strict quality control has been imposed over the fitting results of the pumping parameters—the fluid volume, proppant quantity, pumping pressure curve, and shut-in pressure drop, and the fracture length and height measured by micro seismic monitoring were used to constrain the simulated reservoir volume, so as to improve the prediction reliability of the fracture network morphology.

(2) Numerical simulation based on non-structural meshes
A high-precision non-structural-meshing numerical model has been established to characterize the morphology of the fracture network and fracture conductivity, based on the fitting results of hydraulic fractures. Compared with the structural meshing, the upside of the non-structural meshing is that a highly heterogeneous fracture system could be characterized precisely by small meshes; the permeability of fracture meshes can be calculated from the fracture conductivity distribution of hydraulic fractures; in the meantime, larger meshes are used to characterize the rock matrix, while the original meshes of the matrix are kept untouched. By doing so, the fracture features are elaborately described in the model and meanwhile the total required mesh number is reduced to improve the numerical simulation computation efficiency.

4. Optimization of fracturing parameters
A stepwise optimization has been done in line with the range of horizontal well fracturing parameters of the WeiYuan shale gas play. As shown in Figure 4, the fracturing stage length has been set to be 50 m, 60 m, 70 m, and 80 m respectively. Then in each fracturing stage length scenario, the perforation cluster numbers, pumping rate, fluid intensity, proppant intensity, and the horizontal well spacing have
been optimized in sequence. Finally the fracturing parameters fitting to the different fracturing stage lengths as well as the optimal horizontal well spacing have been determined.

![Diagram of step-by-step optimization of fracturing parameters]

**Figure 4.** The map of step-by-step optimization of fracturing parameters

### 4.1. Optimized fracturing parameters

The matching configurations between the fracturing parameters such as the perforation cluster numbers, proppant intensity, and fluid intensity, and the varied fracturing stage lengths have been obtained via simulation. Figure 5 presents the relationships between the accumulated production over 5 years per kilometer of reservoirs and the parameters (the perforation cluster numbers, pumping rate, fluid intensity, and proppant intensity). In the case of a 60-m long fracturing stage, the accumulated production tends to first grow and then decline, with increasing perforation clusters. Thus it is optimized to have 6-7 clusters per stage with cluster spacing of 8–10 m.

![Graphs showing accumulated production vs. parameters]

**Figure 5.** Accumulative gas production over 5 years per kilometre of reservoirs vs. perforation clusters, pumping rate, fluid intensity, and proppant intensity, in the case of the fracturing stage length of 60 m

Due to the effects of limited entry of multiple clusters and stress interference, with decreased cluster spacing and increased clusters, the reconstruction of the area near the horizontal well; yet, too many clusters often result in the excessively stimulated near-wellbore area, and degraded communication among propped fractures in the area far from the wellbore, which impact the accumulated well
production. Accumulated gas production can be greatly improved by increasing the pumping rate, which shall be optimized to be more than 16 m³/min. For brittle shale gas reservoirs, an increased pumping rate can result in a higher net pressure and create complex fractures. In the meantime, increasing the fluid efficiency helps to expand the stimulated reservoir volume (SRV). With the growth of fluid intensity, the accumulated production slowly climbs up. The optimized fluid intensity is approximately 30 m³/m. With the growing injected fluid volume, the stimulated shale volume increases. However, when the stimulated reservoir volume reaches a certain value, the fluid injection is balanced with the fluid filtration. Under such circumstances, it is difficult to further expand the SRV by increasing the injected fluid volume. In the case of increased proppant intensity, the accumulated production first rises and then reaches an equilibrium state. The proppant intensity is optimized to approximately 2.5 t/m.

Raising up the proppant intensity can lead to an expanded effective supported SRV, which in turn improves gas production. When the proppant intensity reaches a certain value, the fracture conductivity will meet the demand of shale gas flow. Afterwards, it is hard to considerably increase the accumulated production by further enhancing the proppant intensity.

The horizontal well spacing affects the ultimate recovery of shale gas. Small spacing between horizontal wells can lead to low recovery, due to resultant proneness to frac hit, strong inter-well interference, and decreased effective SRV. Moreover, too large spacing between horizontal wells can result in the limited affected range of pressure waves and thus low production degrees of inter-well reserves and a serious waste of resources. Figure 6 illustrates the predicted reservoir pressure distribution over 20 years of production, in cases of different horizontal well spacing. The fracturing stage length is 60 m and the perforation cluster numbers, pumping rate, fluid intensity, and proppant intensity are all set as the values optimized by simulation. When the horizontal well spacing is 320 m, the area between two adjacent wells that is not affected by the inter-well pressure redistribution at the end of production is relatively small, with the high recovered degrees. Accordingly, the optimal horizontal well spacing is 320 m.

The perforation cluster number, pumping rate, fluid intensity, proppant intensity, and horizontal well spacing in cases of the fracturing stage lengths of 50 m, 60 m, 70 m, and 80 m respectively, are optimized via simulation. As shown in Table 1, a reasonable match exists between the perforation cluster numbers and different fracturing stage lengths, associated with the optimal fluid and proppant intensities. With the increase of the fracturing stage length and perforation clusters, the horizontal well spacing shall be properly narrowed.
Four insights can be concluded from the above simulation results: ① A reasonable matching exists between the fracturing stage length and perforation cluster numbers and shall be identified, and with the increased fracturing stage length, the optimal perforation cluster numbers also grows. ② Enhanced pumping rate is in favour of improvement of complexity of the fracture network and accumulated gas production. ③ Different fracturing stage lengths correspond to varied optimal fluid and proppant intensities, which climb up with the extended fracturing stage length. ④ The horizontal well spacing shall be properly decreased, with the increases in the fracturing stage length and perforation clusters.

4.2. Compare between the Optimization Results and the Practical Case
Well Wei-20XHXX-b treated by fracturing is taken as the example to compare the ultimate recovery led by the actual fracturing design and the simulated ones with respect to the different fracturing stage length and corresponding optimal perforation cluster numbers, pumping rate, fluid intensity, and proppant intensity. The actual and simulation fracturing parameters as well as the corresponding predicted ultimate recovery are summarized in Table 2. The predicted ultimate recover based on the actual fracturing parameters is lower than those resulting from the optimized fracturing parameters for different fracturing stage lengths. The comparison shows that the optimal fracturing design for this well features the fracturing stage length of 70 m, 10 perforation clusters for each stage, a treatment pumping rate of 16 m³/min, fluid intensity of 32 m³/m, and proppant intensity of 2.6 t/m. Compared with the actual treatment design, the optimized design can improve the recovery by 51.8%.

Table 2. Compare between the actual treatment design and the optimized solutions for Well Wei-20XHXX-b

| Parameters                  | Actual  | Optimization |
|-----------------------------|---------|--------------|
| Fracturing stage length, m  | 63.7    | 50 60 70 80  |
| Stages                      | 23      | 29 24 21 18  |
| Perf clusters, Num.         | 3       | 4 6 10 13    |
| Pumping rate, m³/min        | 12.5    | 16.0 16.0 16.0 |
| Fluid intensity, m³/m       | 26.4    | 27.0 30.0 32.0 |
| Proppant intensity, t/m     | 1.7     | 2.0 2.4 2.6 3.0 |
| Ultimate recovery 10⁶m³    | 0.56    | 0.65 0.76 0.85 0.86 |
| Recovery increment, %       | /       | 16.1 35.7 51.8 53.6 |

5. Conclusions
During development of the WeiYuan shale gas play, the applied fracturing technique evolves the multistage fracturing with 3-4 cluster perforations and the long-fracturing-stage with 7-9 cluster perforations. The fracturing stage length and perforation cluster number significantly.

Simulation indicates that there is a sound matching between the different fracturing stage lengths and perforation cluster number, associated with the optimal fluid and proppant injection intensities. With the increase of the fracturing stage length and perforation clusters, the horizontal well spacing shall be properly narrowed.

Regarding optimization of horizontal well fracturing parameters in the WeiYuan shale gas play, it is recommended to increase perforation clusters by narrowing the cluster spacing, improve the pumping rate, and adopt the optimal fluid and proppant injection intensities identified by simulation for different fracturing stage lengths.

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