Fracturing Parameters Optimization for Multistage Horizontal Well Fracturing Design in Ultra-low Permeability Reservoirs in Jidong Oilfield

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Abstract. The optimization of fracturing parameters can provide guidance for both design and construction of horizontal well fracturing. It is a multi-parameter optimization problem, key factors affect each other. For instance, fractures placing too tight may cause stress shadow effects and fracture interference within a stage, resulting in short half-length and uneven initiation and propagation. While too wide cluster spacing will lead to larger non-swept zone, thus affect stimulation results and decrease oil production. In this study, in order to improve the accuracy of horizontal well fracturing design, we performed an optimization process to a horizontal well –P2 in Jidong Oilfield. We first optimized staging spacing and perforation locations by using a new method - MSE, which use the value of mechanical specific energy of the lateral rocks around horizontal well as the index of rock hardness, and combined with log data and rock mechanical properties to determine final perforation locations. Then, by using reservoir numerical simulation software PreSL together with fracturing simulation software Stimplan, the geological model of X5 fault block and multi-stage fracturing model of horizontal well P2 in Jidong Oilfield were established, the cumulative production in 3 years was forecasted, parameters such as cluster spacing, pumping rate and so on were determined. Besides, the change of fracture morphology caused by different parameter were observed. Fracture length and width can be affected by stress shadow and fracture interference, the uneven initiation and short fracture half-length would cause problem in placing proppants. The results showed that at most 4 fractures can be developed uniformly within a stage, the recommended cluster interval is 13 m. The optimal pumping rate of this well is 12 m^3/min. Equidistant distribution of fractures can be more conducive to enhance ultimate recovery. After fracturing, the average daily oil production was 20t/d, which is 5 times higher than the average production of vertical wells in the same block. The simulation results can help to increase the success rate of the construction, and guiding the fracturing design of ultra-low permeability reservoirs in Jidong oilfield.

Keywords: Ultra-low permeability tight reservoir · Multi-stage fracturing · Horizontal wells · Cluster spacing optimization · Modeling · Stimplan

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1 Introduction

With the development of fracturing technology, the proportion of tight reservoir exploration is increasing year by year (Al-Ameri et al. 2018; Wigwe et al. 2019). However, due to the poor physical properties and strong heterogeneity of tight reservoirs, vertical well drilling followed by conventional hydraulic fracturing cannot effectively stimulate the reservoir (Oladoyin and Sajjad 2019). Multi -stage fracturing of horizontal well often serves as an important technique for the exploration of low permeability reservoir, it has a great advantage in increasing stimulated reservoir volume (SRV), especially in low permeability reservoir. Hydraulic fractures are crucial to the success of horizontal well recovery since they create pathways for hydrocarbon migration and communicate natural fractures within the reservoir, thus enhancing oil and gas recovery rates. Besides, stress shadow and fracture interference would hinder fracture propagation and even result in the failure of fracturing treatment.

The ultra-low permeability tight reservoirs in Jidong Oilfield have great development potential. However, technical and economical limitations often hinder the development of multi-stage fracturing of horizontal well in these tight reservoirs. In this study, we collected data of a horizontal well in Jidong oilfield, built geological models and carried out software simulation experiments, and selected the best design parameters for horizontal well fracturing.

2 Methodology

Fracturing design parameters are crucial to the success of fracturing filed treatment. In order to obtain the most suitable parameters, we performed an optimization process for a horizontal well in Jidong oilfield, and divided the optimization procedure into 3 steps. The first step is to optimize staging and perforation locations of horizontal well P2. Normally, staging design and perforation locations were obtained from stress profile and other petrophysical data, while in this case, a new method called MSE-G was used as a supplementary technique to improve the accuracy. It used the value of mechanical specific energy of the lateral rocks around a horizontal well as the index of rock hardness and gave a more comprehensive solution. Secondly, we calculated the cumulative production in three years under different fracture conductivity assumptions, and chose the more suitable fracture conductivity that can met both economic and production needs. In the third step, we optimized cluster spacing and fracture distribution pattern to avoid shadow stress effect and fracture interference, and adjusted fluid injection rate to ensure fracture initiate uniformly without any collapsing (Oladoyin and Sajjad 2019; Salah and Ibrahim 2018). The change of fracture geometry along with fracturing parameters such as fracture number within a stage, cluster interval, pumping rate were also observed. After hundreds of simulation experiments, the final optimal fracturing design was obtained, and the results provide valuable guidance of hydraulic fracturing design and operations in Jidong Oilfield.

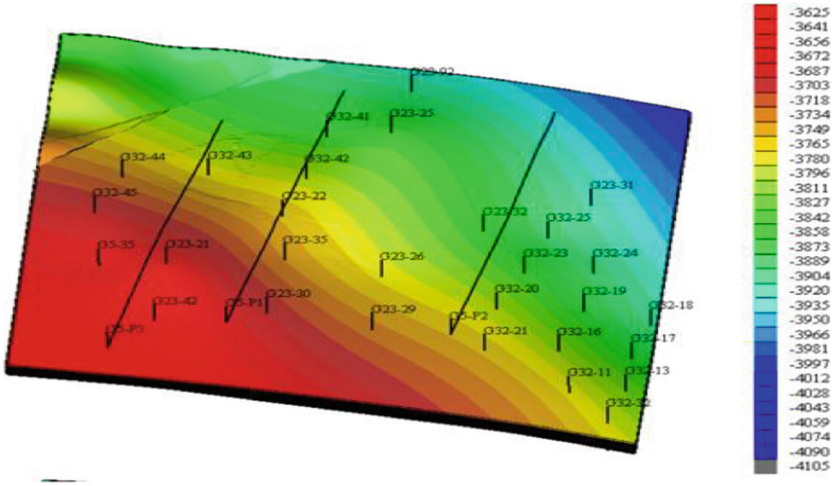


Fig. 1. Geological model of G5 block

3 Numerical Simulation

3.1 Geological Model

The key to a successful dynamic prediction and detailed reservoir description is to numerize the actual reservoir and built geological models. In this study, PreSL was used to build 3D geological model of G5 block. This software can easily deal with complex geological conditions and reflect geological characteristics, especially for strong heterogeneous low permeability reservoirs. 30 oil wells were inserted into this model including 3 horizontal wells and 27 vertical wells, as showing in Fig. 1.

3.2 Staging Optimization

Staging and perforation design often required logging data and lots of calculations to obtain parameters like Young's modulus, Poisson's ratio, brittleness index of reservoir rock etc. However, it is difficult to obtain comprehensive logging data for horizontal wells. A new method called "mechanical specific energy method", is adopted as a supplementary technique to optimize staging and perforation parameters in this study (see Fig. 2). In general, Mechanical Specific Energy (MSE) value defined as the amount of energy required to destroy a given volume of rock. It is put forth by Teale and is commonly used to optimize the drilling operation by analyzing drilling in real-time (Rashidi et al. 2010). However, since ideally the value of mechanical specific energy is equal to the compressive strength of the rock (Prajapati 2011), MSE value is also a tool that can provide qualitative analysis of rock type during drilling process. So in this case, we use it as a supplementary technique to optimize perforation locations and staging of horizontal well fracturing.

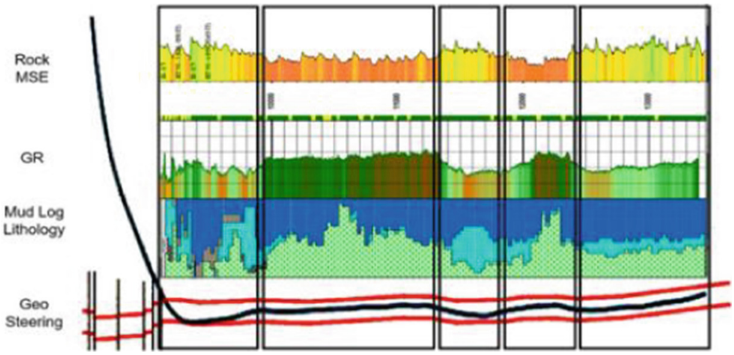


Fig. 2. MSE-G method diagram

The MSE value is calculated by the following formula:

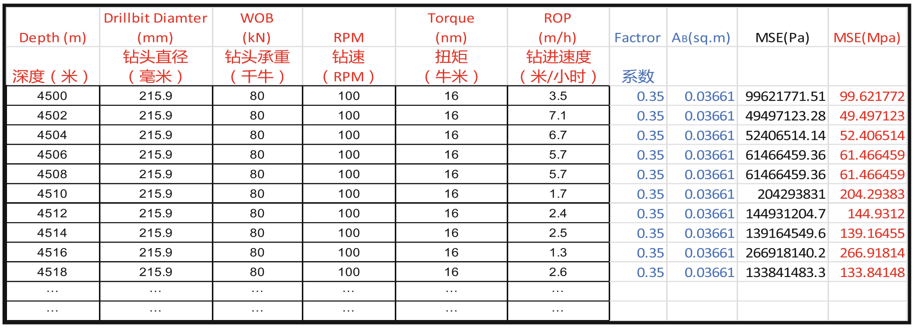
$$MSE = 0.35 * \frac{\text{WOB}}{\text{Ab}} + \frac{120 * \pi * \text{RPM} * \text{T}}{\text{Ab} * \text{ROP}} \tag{1}$$

In formula (1):
MSE = Energy Input, psi;
WOB = WOB (lbs);
AB = Bit Area, sq. inches;
RPM = Rotary speed;
T = Torque, ft-lbs;
ROP = Rate of Penetration, ft/hr;
Factor = 0.35 (Efficiency factor).

We noticed that the MSE value calculated for horizontal wells are not as accurate as vertical wells, so calibrations are needed. As GR log data can distinguish sandstone from shale and reflect the shale content near wellbore, we can use GR to calibrate the MSE value. The Gamma-ray calibrated value is called MSE-G, it can reflect the heterogeneity of reservoir near wellbore.

To optimize the staging design of well P2, we first input drilling data into the MSE calculation module in IUT software, then combined with GR log data and other rock mechanics parameters such as young's modulus and Poisson's ratio to rectify the results. The corrected calculation results are showing in Fig. 3. In general, the reservoir section with higher brittleness, lower Poisson's ratio considered to be engineering sweet spots. Reservoir rock with similar mechanical characteristics considered to be the same stage. The MSE-G value directly reflect engineering sweet spots, namely higher MSE-G value, better perforation location.

Figure 4 contains all the index we used for determine perforation locations, including Young's modulus, Poisson's ratio, brittleness index of reservoir rock and MSE-G values. It can be seen that the calculated MSE-G values are well correlated with other index of reservoir rock. In this figure, red section indicates higher MSE-G, namely engineering sweet spots. Blue dots represent initial perforation locations and red dots are corrected perforation locations. By optimizing perforation locations, the efficiency of fracturing can be improved.



Depth (m) 深度（米）	Drillbit Diamter (mm) 钻头直径（毫米）	WOB (kN) 钻头承重（千牛）	RPM 钻速（RPM）	Torque (nm) 扭矩（牛米）	ROP (m/h) 钻进速度（米/小时）	Factror 系数	AB(sq.m)	MSE(Pa)	MSE(Mpa)
4500	215.9	80	100	16	3.5	0.35	0.03661	99621771.51	99.621772
4502	215.9	80	100	16	7.1	0.35	0.03661	49497123.28	49.497123
4504	215.9	80	100	16	6.7	0.35	0.03661	52406514.14	52.406514
4506	215.9	80	100	16	5.7	0.35	0.03661	61466459.36	61.466459
4508	215.9	80	100	16	5.7	0.35	0.03661	61466459.36	61.466459
4510	215.9	80	100	16	1.7	0.35	0.03661	204293831	204.29383
4512	215.9	80	100	16	2.4	0.35	0.03661	144931204.7	144.9312
4514	215.9	80	100	16	2.5	0.35	0.03661	139164549.6	139.16455
4516	215.9	80	100	16	1.3	0.35	0.03661	266918140.2	266.91814
4518	215.9	80	100	16	2.6	0.35	0.03661	133841483.3	133.84148
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…	…	…	…	…	…				

Fig. 3. Calculation results of MSE value

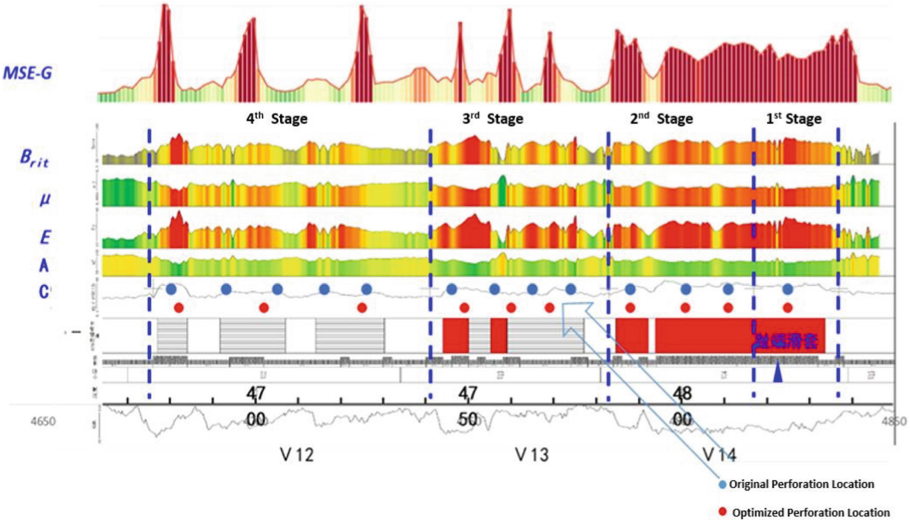


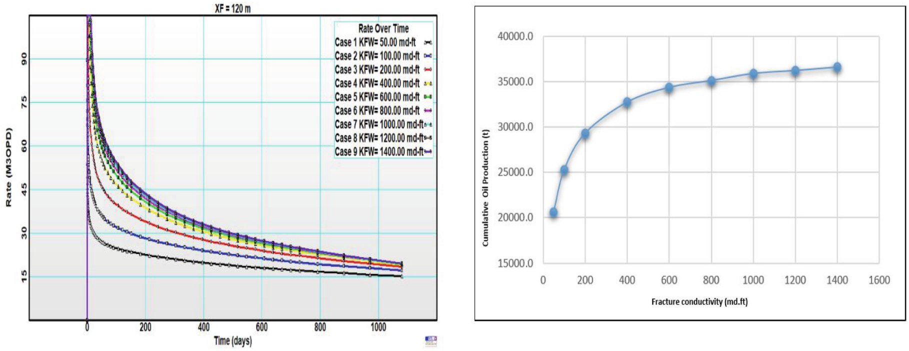
Fig. 4. Original perforation location VS Optimized perforation location

The fracturing design of all four stages were optimized, and parameters such as perforation locations, cluster and staging spacing of each stage were all simulated. In this paper, we only take the simulation results of the third stage as an example.

3.3 Fracture Conductivity Optimization

The impact of fracture conductivity on productivity extends to the front and middle stages of the whole production cycle. At the beginning, the impact was obvious, the higher the conductivity, the higher the cumulative productivity. However, when fracture conductivity reached a certain level, the impact on cumulative productivity slowed down, while the economic benefit of fracturing reduced sharply. Therefore, we need to find a fracture conductivity that can meet both economic and production requirements.

In this part, we first assumed the fracture length is 120 m (Xf = 120 m), production period is 3 years, and varied fracture conductivity from 50 to 1400 mD.ft to see how production rate and cumulative production changed with fracture conductivity. Figure 5(a) presents the oil recovery rate in 3 years under different fracture conductivity. We can conclude that when fracture conductivity is under 200 mD.ft, the higher the conductivity, the higher the oil production rate. However, when conductivity increased to 400–1500 mD.ft, the improvement of production is little, the oil production rate under 1500 md.ft is only slightly higher than the oil production rate under 400 md.ft, which is not economically friendly. Then we plotted the conductivity VS cumulative oil production curve, demonstrates in Fig. 5(b). At first, when fracture conductivity increased from 50 to 200 mD.ft, cumulative oil increased sharply. Then, when the conductivity reached 200 mD.ft (6 μm^2.cm), the increase of cumulative production slowed down significantly. After 600 mD.ft, the increasing rate of productivity curve turned flat, meaning there is barely no increasing. Taking economic factors into consideration, the suggested fracture conductivity of P2 is 200 mD.ft.



(a). Oil production rate over time **(b). Cumulative production VS Fracture conductivity**

Fig. 5. Cumulative production VS Fracture conductivity

3.4 Cluster Spacing Optimization

Cluster spacing is a critical parameter in fracturing design of multi-stage horizontal wells. Fractures placing too tight may cause stress shadow effects and fracture interference within a stage, resulting in short half-length and uneven initiation and propagation. Moreover, the stimulated volume between the fractures often overlapped, which reduced the efficiency of reservoir stimulation to some degree. However, cluster spacing too loose will lead to a larger non-swept zone and smaller drainage volume, thus affect stimulation results and decrease cumulative oil production. In this study, we analyzed how fracture morphology changed with design parameters and found a suitable cluster spacing for well P2.

Fracture Distribution Pattern. According to the results of literature research, distribution pattern can affect fracture initiation and may result in big differences in productivity.

In general, fracture distribution can be divided into three patterns (Fig. 6): equidistant distribution, sparse inside and dense outside (SIDO) pattern, sparse outside and dense inside (SODI) pattern. The proper fracture distribution pattern should be selected according to the characteristics of different reservoirs and the level of heterogeneity. Since the magnitude of principal stresses anisotropy changed because of fracturing, other fractures within this disturbed region are easy to deviate. Moreover, fractures with overlapping stress shadow zones will even result in collapse. Hence, reducing the stress shadow effect around induced fractures enables the opportunity of having optimized spacing between fractures with no deviation or collapse (Salah and Ibrahim 2018).

Based on previous simulation results in this study, the suitable fracture number within a stage is 6. In this part, the 6 fractures were distributed in three ways, namely, equidistantly, inner sparse and outer dense, inner dense and outer sparse, and the productivity with different distribution patterns were investigated. The result is showing in Table 1.

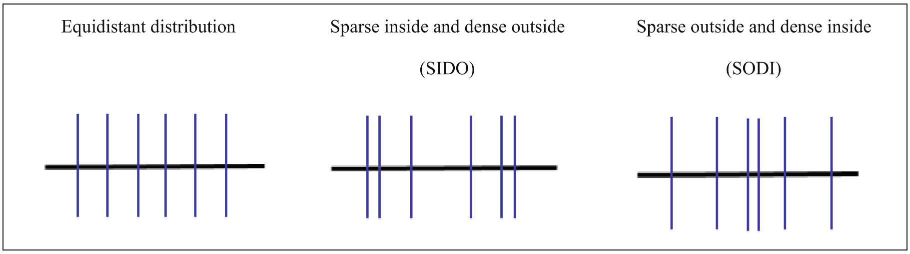
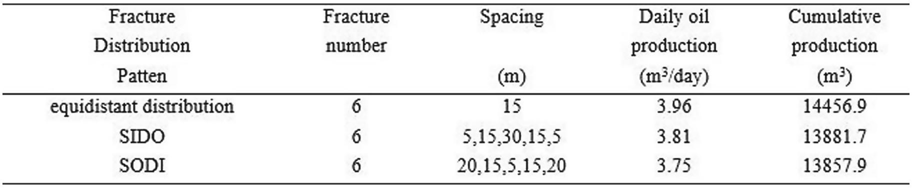


Fig. 6. Fracture distribution patterns

Table 1. Production VS Fracture distribution patterns



Fracture Distribution Patten	Fracture number	Spacing (m)	Daily oil production (m^3/day)	Cumulative production (m^3)
equidistant distribution	6	15	3.96	14456.9
SIDO	6	5,15,30,15,5	3.81	13881.7
SODI	6	20,15,5,15,20	3.75	13857.9

From Table 1, we can find that the highest cumulative oil production (14456.9 m^3) was achieved when fractures were distributed equidistantly. This can be explained by the followed reasons: The first reason is that fracture spacing too dense may result in a very high initial oil recovery rate, but fast oil withdrawal may also lead to a rapid decline of formation pressure, so the overall productivity was affected. Secondly, as production time increases, the impact of fracture interference in the densely fractured area will be strengthened, which also has a negative impact on production. As a result, in this case, depending on the reservoir characteristics in G5 block in Jidong oilfield, equidistant fracture distribution is the best pattern for productivity.

Fracture Morphology. Fracture morphology affected by many factors. To obtain optimum fracture lengths and widths, we evaluated the following parameters and their effects on fracture morphology:

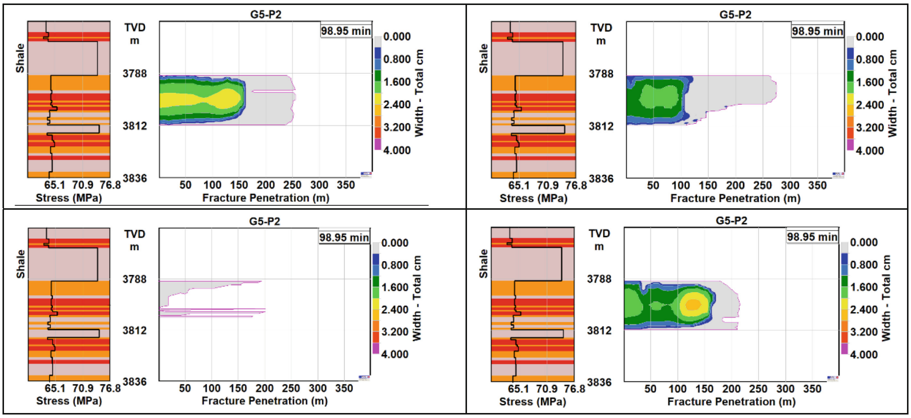
- Cluster spacing
- Perforation spacing
- Pumping Rates

In this part, we used the finite element method of Stimplan and took the third stage of P2 as an example. Finite element method in Stimplan can calculate stress shadow and simulate fracture interference, it is suitable for fracturing design of heterogeneous reservoirs with multiple thin layers (Yi et al. 2018). Case 1 focused on the morphology change caused by cluster spacing variation, Case 2 varied perforation length and Case 3 considered different pumping rates as a function of fracture lengths and widths.

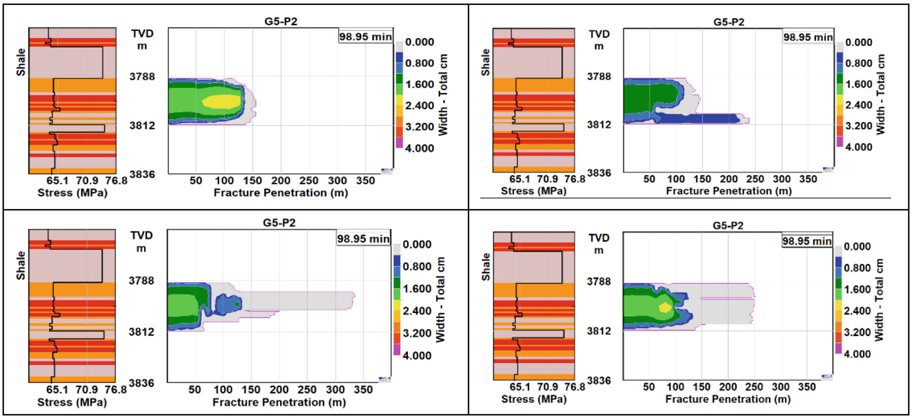
Cluster Spacing. In case 1, we simulated the effects of cluster spacing on fracture morphology. Firstly we set the distance between each cluster to be 10 m, and the simulation results are showing in Fig. 7(a). It is obvious that the width of the third fracture is around 0 cm, which is hardly initiated, this might because of stress shadow. Besides, the tips of all 4 fractures are very narrow with widths ranging from 0 to 0.4 cm, proppants could barely placed and fracture conductivity cannot be ensured. Figure 7(b) demonstrates the simulation results of 15 m cluster spacing. It can be seen that the fractures grew simultaneously at first until the third fracture was overshadowed by the 2nd and 4th fracture and then collapsed. This might be due to fracture interference. As a result, except from the first fracture, all fractures propagated unevenly. Then we adjusted the cluster spacing to 13 m, and the simulation results are showing in Fig. 7(c). The widths of the 1st, 3rd, 4th fracture ranged from 3.2–4.0 cm, which are wide enough to place proppants. So the suitable cluster spacing for this case was determined to be 13 m. However, the 2nd fracture is still narrow with a width of 0.7 cm. So the next target is to adjust perforation lengths and make sure that all 4 fractures are initiated uniformly.

Perforation Spacing. In order to further optimize the fracture morphology under the condition of 13 m cluster distance, perforation lengths were adjusted to 1 m, 1.2 m, 1 m, 1 m respectively (Fig. 8a). From simulation results, 4 fractures grew simultaneously and propagated far enough to achieve good fracture conductivity.

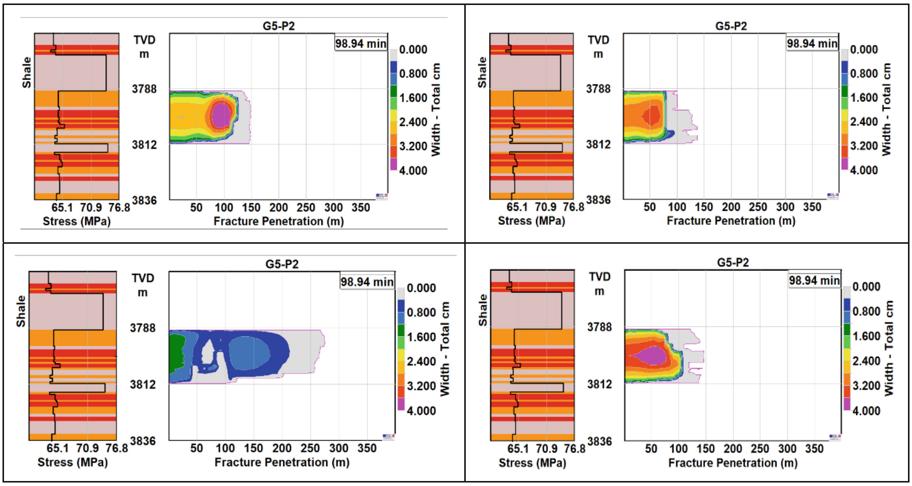
Pumping Rates. Based on the data collected from field treatments in this block, the pumping rates of 8 m^3/min, 12 m^3/min, 16 m^3/min were simulated and fracture lengths were observed. Table 2 demonstrates the simulation results. When the pumping rate was 8 m^3/min, the lengths of the 4 fractures are 60 m, 80 m, 50 m, and 70 m respectively. Although all that 4 fractures grew wide enough, lengths could not meet requirements. When the pumping rate was 16 m^3/min, the fractures are long enough but opened narrowly with the widths ranged from 0.8 to 1.6 cm, which will cause problems in placing proppants and even increase construction risks. When the pumping rate was 12 m^3/min, all 4 fractures grew simultaneously and propagated far and wide enough to achieve good



a. Cluster spacing =10m

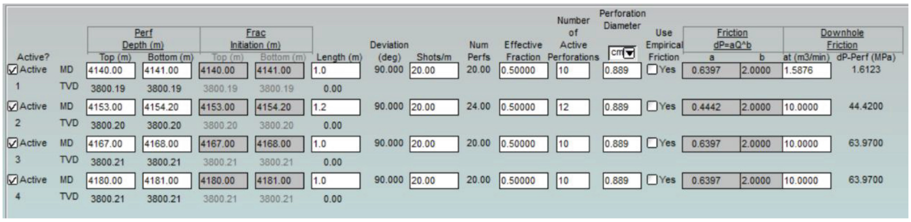


b. Cluster spacing =15m



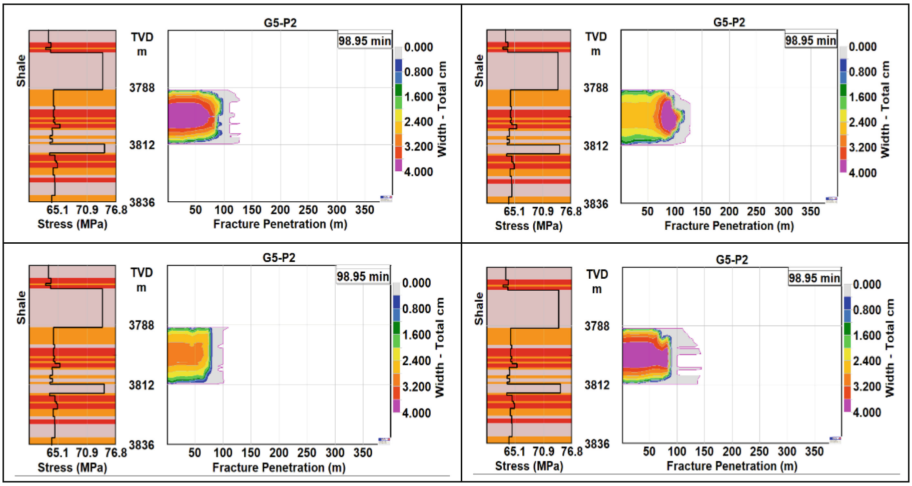
c. Cluster spacing =13m

Fig. 7. Fracture morphology under different cluster spacing (a.b.c)



Active?		Perf Depth (m) Top (m)	Perf Depth (m) Bottom (m)	Frac Initiation (m) Top (m)	Frac Initiation (m) Bottom (m)	Length (m)	Deviation (deg)	Shots/m	Num Perfs	Effective Fraction	Number of Active Perforations	Perforation Diameter cm	Use Empirical Friction	Friction dP=aQ^b a	Friction dP=aQ^b b	Downhole Friction at (m3/min)	Downhole Friction dP-Perf (MPa)
☑Active	MD	4140.00	4141.00	4140.00	4141.00	1.0	90.000	20.00	20.00	0.50000	10	0.889	☐Yes	0.6397	2.0000	1.5876	1.6123
1	TVD	3800.19	3800.19	3800.19	3800.19	0.00											
☑Active	MD	4153.00	4154.20	4153.00	4154.20	1.2	90.000	20.00	24.00	0.50000	12	0.889	☐Yes	0.4442	2.0000	10.0000	44.4200
2	TVD	3800.20	3800.20	3800.20	3800.20	0.00											
☑Active	MD	4167.00	4168.00	4167.00	4168.00	1.0	90.000	20.00	20.00	0.50000	10	0.889	☐Yes	0.6397	2.0000	10.0000	63.9700
3	TVD	3800.21	3800.21	3800.21	3800.21	0.00											
☑Active	MD	4180.00	4181.00	4180.00	4181.00	1.0	90.000	20.00	20.00	0.50000	10	0.889	☐Yes	0.6397	2.0000	10.0000	63.9700
4	TVD	3800.21	3800.21	3800.21	3800.21	0.00											

a. Perforation lengths settings



b. Fracture morphology with perforation lengths=1m,1.2m,1m,1m

Fig. 8. Fracture morphology after adjust perforation lengths (a, b)

fracture conductivity. As a result, 12 m^3/min was determined to be the final optimized pumping rate.

Table 2. Fracture morphology under different pumping rate

Spacing (m)	Pumping Rate (m^3/min)	Fracture Length (m)	Fracture Width (m)	Fracture Propagation
13	12	100/130/90/95	4/3/3/3.8	Propagate uniformly
13	8	60/80/50/70	2.4/2/1.6/2.5	Fracture length too short
13	16	120/130/100/90	0.8/1.0/1.6/1.6	Fracture width too narrow

4 Field Application

The selected horizontal horizontal well P2 for this study is located in Jidong oilfield, China. It is drilled and completed with a horizontal length of 448 m. The buried depth of the reservoir is around 3700–4000 m with a temperature of 120 °C. The reservoir is highly heterogeneous with target zone varies from 7.4 m to 39.8 m in thickness. The reservoir porosity is 6%, permeability is 297 × 10^{-3}md and initial water saturation is 12.6%.

Figure 9 demonstrates the fracturing construction curve of the third stage of well P2. In this stage, 2550 m^3 fracturing fluid (including 1340 m^3 slick-water and 320 m^3 guar gum water-base fracturing fluid) and 105 m^3 proppants were injected into the reservoir with pumping rate varied from 8–12 m^3/min. The whole process went smoothly, average construction pressure was 60 MPa, and maximum sand concentration was 525 kg/m^3. After fracturing, the average daily oil production was 21.2 t/d, which is 5 times higher than adjacent wells. The success of this treatment implies the optimization process can provide strong technical support for reservoir reconstruction in ultra-low permeability heterogeneous reservoirs in Jidong oilfield.

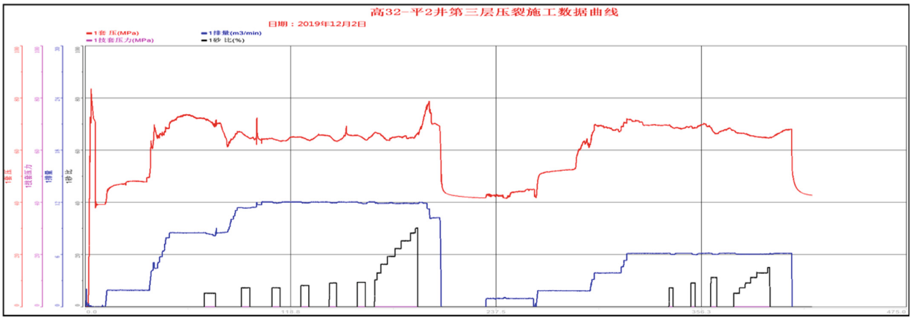


Fig. 9. Operation curve of the third stage of P2

5 Discussion

This study provides a comprehensive way of parameters optimization for multistage horizontal well fracturing in ultra-low permeability reservoirs in Jidong oilfield. The results can be concluded as followed:

(1) MSE-G method has proven to be an effective method of staging design and the determination of perforation locations, especially when logging data are hard to acquire.
(2) Fracture conductivity need to meet both economic and production requirements. By estimating the cumulative oil production in 3 years and plotting conductivity VS production plot, the point where the increasing rate of cumulative production tends to be flat is considered to be the most suitable conductivity. For P2, the suitable conductivity is 200 mD·ft.
(3) Fracture distribution can have a significant influence on cumulative production. Distribution patterns including equidistant distribution, sparse inside and dense outside (SIDO), sparse outside and dense inside (SODI). Fracture spacing too dense

may resulted in a very high initial oil recovery rate, and lead to a rapid decline of formation pressure as well as the productivity. In this case, equidistant distribution can reduce stress shadow effect and enable fractures initiate uniformly with no deviation or collapse.

(4) Fracture propagate long and wide enough can ensure the conductivity and sand concentration, and reduce construction risk. The most suitable fracture morphology is achieved by changing cluster spacing, perforation lengths and pumping rate.

Through the close combination of reservoir numerical model and single well fracturing models, the accuracy of simulation results increased a lot and can help guiding the horizontal well fracturing design of the ultra-low permeability reservoirs in Jidong oilfield.

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