Application of horizontal well multi-cluster network fracturing in tight reservoir

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Abstract: GD14H, a horizontal well drilled in tight reservoir of Dagang Oilfield, reveals complex lithology, large burial depth, and poor physical properties. In order to improve its fracturing performance, a new technique of multi-cluster network fracturing was adopted based on a series of optimized multi-cluster perforation parameters and fracturing treatment parameters, and the 15-cluster fracturing was determined. Field test has demonstrated outstanding stimulation results. Moreover, the horizontal well fractures monitoring via the stable electric field/potential method shows that the measured results match well with the results of physical model for GD14H. The successful application of this technique in Dagang Oilfield implies a great breakthrough in the fracturing of tight oil horizontal wells in Dagang Oilfield, and lays a valuable foundation for stimulation of other similar tight oil and gas reservoirs.

1. Introduction
GD14H is a horizontal well drilled in the eastern part of Nanpi slope of Cangdong Sag. The target reservoir has the characterized with low-porosity and low-permeability which is porosity of 5.09–11.12% and permeability of 0.44×10^{-3} μm^2–4.84×10^{-3} μm^2. The reservoir needs to be fractured. Compared to conventional horizontal well staged fracturing, the horizontal well network fracturing technique can induce multiple fractures perpendicular to the primary fractures and communicate the natural fractures to create a complex fracture network system that the low-permeability tight reservoir can be more effectively stimulated[1-4].

This paper presents the multi-cluster network fracturing for GD14H depending on its reservoir characteristics. Specifically, according to the separate-cluster perforation and multi-cluster fracturing mode, multiple fractures are extended simultaneously by virtue of high displacement to increase the stimulated reservoir volume (SRV) and t create a complex fracture network.

2. Optimization of multi-cluster perforation parameters for horizontal well in tight reservoir

2.1 Cluster spacing
Optimization of perforation cluster spacing is one of the prerequisites to form multiple fractures. It can be achieved by virtue of inter-fracture interference caused by fracture extension and fracturing induced stress. For different cluster spacings, the fracture extension is shown in Figure 1(a), (b), (c) & (d), and the inter-fracture interference is shown in Figure 2(a), (b), (c) & (d).
In Figure 1, the extension of fractures in the clusters in the middle is limited when the cluster spacing is 20 m; the fractures in all clusters can extend evenly when the cluster spacing is more than 30 m. In Figure 2, the inter-fracture interference caused by induced stress is strong when the cluster spacing is less than 40 m, and it is weak when the cluster spacing is more than 40 m, thereby failing to reorient the fractures to create a complex fracture network. Comprehensively, it is determined that the cluster spacing between 30 m and 40 m is optimal.
2.2 Number of perforation clusters
A simulation was made by using the Meyer 3D fracturing software (Figure 3 and Figure 4). With the increase of the number of perforation clusters, the cumulative production and fracture net present value (NPV) increase, at a slower rate. When the number of perforation clusters is 15, the cumulative production and fracture NPV reach to peak. When the number of perforation clusters increases further, the cluster spacing reduces, and the extension of fractures in the middle is limited; meanwhile, the perforation costs increases and the cumulative production and fracture NPV decline rapidly. Based on the optimization of cumulative production and fracture NPV of GD14H, the optimal number of clusters is determined as 15.

![Figure 3. Cumulative production vs. number of clusters.](image)

![Figure 4. Fracture NPV vs. number of clusters.](image)

2.3 Perforation length in each cluster
According to the geological factors such as interval stress and presence of natural fractures, for GD14H, 6 perforation stages are designed. Depending on the optimal cluster spacing and number of perforation clusters, 2–3 clusters are designed for each stage according to the theory of uneven staging/clustering.

For GD14H, the stress difference is calculated, and the perforation length in each cluster is optimized (Table 1). According to the perforation friction formula, the chart for selecting multi-cluster perforation parameters is established (Figure 5).

| S/N of stage | Number of clusters | Depth /m | GR /API | GR difference /API | Stress difference /MPa |
|--------------|--------------------|----------|---------|-------------------|-----------------------|
| 1            | 3                  | 4744     | 100     | 0                 | 0                     |
|              |                    | 4712     | 104     | 4                 | 0.44                  |
|              |                    | 4684     | 100     | 0                 | 0                     |
|              |                    | 4623     | 99      | 0                 | 0                     |
| 2            | 2                  | 4593     | 105     | 6                 | 0.66                  |
|              |                    | 4529     | 105     | 3                 | 0.33                  |
|              |                    | 4499     | 102     | 0                 | 0                     |
|              |                    | 4454.7   | 110     | 1                 | 0.11                  |
| 3            | 2                  | 4415.7   | 109     | 0                 | 0                     |
|              |                    | 4378     | 110     | 1                 | 0.11                  |
| 4            | 3                  | 4343.5   | 100     | 0                 | 0                     |
|              |                    | 4320.5   | 106     | 6                 | 0.66                  |
|              |                    | 4258     | 106     | 7                 | 1.21                  |
| 5            | 2                  | 4232.2   | 99      | 0                 | 0.55                  |
| 6            | 3                  | 4202     | 100     | 1                 | 0                     |
As shown in Table 1 and Figure 5, given the displacement of 8.0 m^3/min, for 2 clusters/stage, the max stress difference is 0.66 MPa, and the perforation friction is 1 MPa if the perforation length in each stage is 1 m, which is greater than the stress difference, indicating that multiple fractures can be created; for 3 clusters/stage, the max stress difference is 1.21 MPa, and the perforation friction is 1.4 MPa if the perforation length in each stage is 0.7 m, which is greater than the stress difference, indicating that multiple fractures can be created.

3. Optimization of fracturing parameters for horizontal well in tight reservoir

3.1 Displacement
It is suggested to utilize a large fracturing displacement if the fracturing pressure allows. Table 2 provides the calculated fracturing pressure under different displacements.

| Displacement /m^3·min^{-1} | Casing friction /MPa | Hydrostatic pressure /MPa | Perforation friction /MPa | Near-wellbore friction /MPa | Pump pressure /MPa |
|---------------------------|----------------------|---------------------------|--------------------------|--------------------------|------------------|
| 7                         | 16.77                | 39.73                     | 2.3                      | 1.9                      | 59.91            |
| 8                         | 21.12                | 39.73                     | 3.1                      | 2.1                      | 65.26            |
| 9                         | 26.82                | 39.73                     | 3.9                      | 2.4                      | 72.06            |

For GD14H, 5-1/2” casing is adopted in fracturing. Its rated burst resistance is 85.2 MPa and maximum shut-in pressure not greater than (1) the rated working pressure of well control device or (2) 80% of the casing burst resistance (or casing test pressure for old wells), whichever is lower. According to the technical indicators (refer to the technical manual provided), the main valve below the Christmas tree is closed before fracturing, while the working pressure of the Christmas tree and high-pressure pipeline is limited to 68 MPa. As shown in Table 2, the optimal displacement is 8 m^3/min.

3.2 Fracture network parameters
The artificial fracture network affects the contacted area between wellbore and reservoir, and it is an important factor for the productivity of low-permeability tight reservoir. The key parameters that can characterize the fracture network include: primary fracture length (a), fracture network width (b), secondary fracture spacing (s), primary fracture conductivity (d), and secondary fracture conductivity (e). An optimal combination of parameters is obtained by the L16 (4^5) orthogonal test method. Table 3 shows the factor levels, Table 4 shows the fracture network parameter combination scheme and simulation results, and Table 5 shows the range analysis for fracture network parameter combination schemes.
| Factor level | a/m | b/m | s/m | d/μm²·cm | e/μm²·cm |
|--------------|-----|-----|-----|-----------|-----------|
| 1            | 80  | 40  | 10  | 10        | 1         |
| 2            | 95  | 50  | 15  | 15        | 2         |
| 3            | 110 | 60  | 20  | 20        | 3         |
| 4            | 125 | 70  | 25  | 25        | 4         |

Table 4. Fracture network parameter combination scheme and simulation results.

| Scheme | a/m | b/m | s/m | d/μm²·cm | e/μm²·cm | Cumulative production additions /t |
|--------|-----|-----|-----|----------|----------|-----------------------------------|
| 1      | 80  | 40  | 10  | 10       | 1        | 2150                              |
| 2      | 80  | 50  | 15  | 15       | 2        | 2993                              |
| 3      | 80  | 60  | 20  | 20       | 3        | 3572                              |
| 4      | 80  | 70  | 25  | 25       | 4        | 4131                              |
| 5      | 95  | 40  | 15  | 20       | 4        | 3982                              |
| 6      | 95  | 50  | 10  | 25       | 3        | 4444                              |
| 7      | 95  | 60  | 25  | 10       | 2        | 2361                              |
| 8      | 95  | 70  | 20  | 15       | 1        | 2892                              |
| 9      | 110 | 40  | 20  | 25       | 2        | 4199                              |
| 10     | 110 | 50  | 25  | 20       | 1        | 3564                              |
| 11     | 110 | 60  | 15  | 15       | 4        | 3630                              |
| 12     | 110 | 70  | 15  | 10       | 3        | 3942                              |
| 13     | 125 | 40  | 25  | 15       | 3        | 3302                              |
| 14     | 125 | 50  | 20  | 10       | 4        | 2811                              |
| 15     | 125 | 60  | 15  | 25       | 1        | 4172                              |
| 16     | 125 | 70  | 10  | 20       | 2        | 3945                              |

Table 5. Range analysis for fracture network parameter combination schemes.

| Scheme | a/m   | b/m   | s/m   | d/μm²·cm | e/μm²·cm |
|--------|-------|-------|-------|----------|----------|
| Mean value 1 | 3211.500 | 3408.250 | 3542.250 | 2816.000 | 3194.500 |
| Mean value 2 | 3419.750 | 3453.000 | 3772.250 | 3204.250 | 3374.500 |
| Mean value 3 | 3833.750 | 3433.750 | 3368.500 | 3765.750 | 3815.000 |
| Mean value 4 | 3557.600 | 3727.500 | 3399.500 | 4236.500 | 3638.500 |

According to the simulation results in Tables 3 and 4, the mean value and range (R) for each factor level are calculated (Table 5). The higher the R is, the greater the effect of this factor on the results is. Consequently, based on the R value, the factors can be ranked as follows: primary fracture conductivity (d) > primary fracture length (a) > secondary fracture conductivity (e) > secondary fracture spacing (s) > fracture network width (b). The level with the highest mean value is considered as the optimal level of the factor. Thus, the combination of the optimal levels of 5 factors constitutes the optimal fracture network parameter combination scheme, that is, primary fracture conductivity of 25 μm²·cm + primary fracture length of 110 m + secondary fracture conductivity of 3 μm²·cm + secondary fracture spacing of 15 μm + fracture network width of 25 m. Therefore, the optimal fracture network parameter combination scheme is a3+b4+s2+d4+e3.
secondary fracture spacing of 15 m + fracture network width of 70 m, which can help effectively stimulate the reservoir.

4. Field application
By adopting the multi-cluster network fracturing, GD14H is fractured with 15 clusters. During the fracturing operation, all technical indicators reached the designed requirements. Totally, 4527.89 m$^3$ fracturing fluid and 274.09 m$^3$ proppant was pumped, with the maximum displacement of 8.0 m$^3$/min. The fracture monitoring based on stable electric field reveals that multiple fractures are induced, which contribute to the stimulation. The measured results are consistent with the designed fracturing parameters. Producing with 4 mm chock after fracturing, GD14H realized the daily oil production rate of 8.0 m$^3$/min and the daily liquid production rate of 81 m$^3$, which are 4.7 times of the post-frac production of offset vertical well. By November 2016, the cumulative production of oil and liquid reached 6000 t and 8,148 m$^3$, respectively.

5. Conclusions
(1) Horizontal well multi-cluster network fracturing is an effective technique to stimulate the deep and tight reservoirs via horizontal well by stages. It can help effectively develop the low-permeability tight reservoirs.

(2) Selection of cluster spacing, number of clusters, perforation length, and fracturing parameters is crucial to guarantee the successful application of horizontal well multi-cluster network fracturing technique. Field application demonstrates that the multi-cluster fracture network fracturing technique contributes to GD14H with an oil production rate 4.7 times of that of offset vertical well.

(3) The fracture monitoring based on stable electric field reveals that multiple fractures are induced, which contribute to the stimulation. The measured results are consistent with the designed fracturing parameters.

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