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Multistage Isolating Acid-fracturing in Naturally Fractured Deep Carbonate Horizontal Wells of Tarim Oilfield, West China

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Abstract: *The naturally fractured carbonate reservoir of Ta-zhong has been developed for over ten years due to new technologies. Since 2008, a program was undertaken to test openhole multistage acid-fracturing technology in the Ta-zhong gasfield to determine if deep fractured carbonate reservoir could be effectively developed by horizontal wells.*

This paper will introduce the challenges including the segregated completion through optimized design and individual acid-fracturing treatment through simulation, production history of stimulated horizontal wells and the comparisons with offset wells. Ta-zhong carbonate reservoir is buried from 5000m to 7000m TVD with low matrix permeability and porosity, the hydrocarbon is mainly stored in the interconnected natural fractures and vugs, so a novel segregated completion method was gradually formed during the development from the reservoir description.

To avoid circulation loss or blowout during drilling horizontal well, the horizontal interval was usually close to the top of reservoirs with natural fractures and vugs by control while drilling. The reservoirs and numbers of segments will be distinguished by 3D seismic, well course and stress direction, and then the distances between reservoirs and horizontal interval was calculated through horizontal well track superimposed on the seismic profile, each section divided by openhole packers need special acid-fracturing technique to get sufficient height or length to communicate the hydrocarbon reservoirs. Simulation work gives the results which pad and ground cross-linked acid multi-alternative injection fracturing is favorable for longer length, and pad acid-fracturing is favorable for higher height. The performances of frac fluid and ground cross-linked acid are also showed in the paper, the residual viscosity of gel fluid is greater than 150mPa•s in the conditions of 140 ℃ and 170s^{-1} shear rate, and ground cross-linked acid's is more than 200mPa•s in the conditions of 120℃ and 170s^{-1} shear rate.

Production comparisons showed that stimulated horizontal wells extended the production life of development wells and improved development effectiveness. Several years' production history analysis of TZ62 block highlighted that the average hydrocarbon rate of multistage acid-fracturing horizontal wells was several times the stimulated vertical offset wells.

1. OVERVIEW

Ta-zhong carbonate condensate gas reservoirs in the Central Tarim Basin are Paleozoic Ordovician reservoirs buried at the interval of 5000-7000 m and with a temperature range of 120-170℃, with H_2S content of 100-400000 PPm. Reservoir rocks are mainly limestone, followed by dolomitic limestone and dolomite. Matrix porosity and permeability are very low; average porosity is less than 5% and average permeability is less than 0.01×10^{-3} μm^2. These quasi-layered reservoirs are highly anisotropic with complicated fractures and dissolved pores and cavities.

These carbonate reservoirs were mainly developed with vertical wells through acid fracturing and proppant fracturing before 2008. Some pilot tests were made in 2008 on horizontal wells drilling to improve single-well production. During horizontal well drilling, several reservoir units, i.e. fractures and cavities, would be drilled in the horizontal section, which may lead to downhole problems such as blowout and circulation loss. Therefore, the horizontal section should be drilled as per the requirements of drilling design. As shown in Figure 1, large fractures and cavities should be kept out of the wellbore track; the track may be close to but would not penetrate those fractures and cavities. As a result, horizontal wells for carbonate reservoirs development in the Central Tarim Basin had low or no natural productivity and had to be stimulated through acid washing and acid fracturing for commercial recovery. A horizontal well may be completed with open hole or screen pipe. In the first half of 2008, the horizontal well was stimulated through large-scale integral acid fracturing for open-hole completion and selective ball acid-fracturing for screen pipe completion. The former is not target-oriented and could not address the problem of production decline in a short time and low final recovery because the horizontal section could not be treated completely. The latter could be used to solve the problem of near-wellbore damage but could not realize deep stimulation in each section due to the existence of communication outside the screen pipe. Consequently, open-hole segregated packer completion was introduced in the second half of 2008, so that petroleum production from carbonate reservoirs in the Central Tarim Basin was increased.

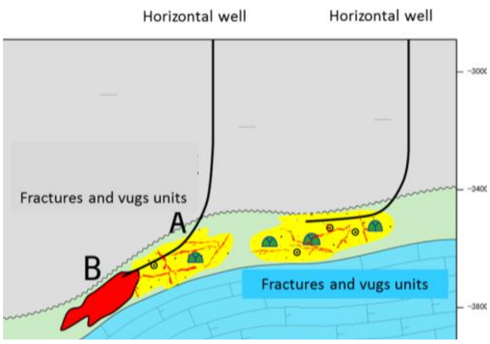


Figure 1: *Schematic horizontal wellbore track penetrating fractured-vuggy carbonate reservoirs*

2. MULTISTAGE HORIZONTAL WELL STIMULATION

Isolating completion tools

Depending on downhole tools, the completion tools with openhole packers can be divided into: (1) conventional packer + multiple hydraulic open-hole packers + multistage fracturing sliding sleeves, (2) expandable liner hanger + multiple oil-swell packers + multistage fracturing sliding sleeves, and (3) casing packer + multiple oil-swell packers + multistage ICV. In view of the advantages and disadvantages of these three segregated completion tools, horizontal well stimulation techniques for carbonate reservoirs development in the Central Tarim Basin, strategies of horizontal well drilling close to the top of reservoir, costs of completion and difficulties in well completion, the segregated completion with oil-swell packers + multistage fracturing sliding sleeves was selected, as shown in Figure 2.

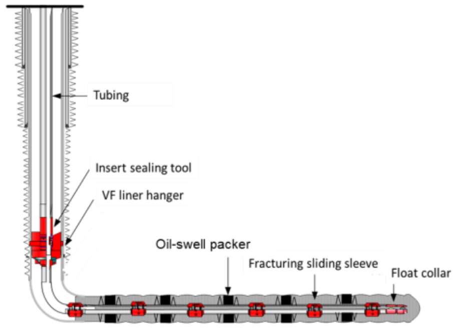


Figure 2: *Isolating completion tools composed of oil-swell packers + multistage fracturing sliding sleeves*

Isolating completion design for fractured carbonate reservoir

Number of Segments would be based on 3D seismic-based reservoir characterization, oil and gas shows and well-log information. Seismic data are important to the deployment of oil and gas wells and would be used to delineate structures and reservoir properties. For anisotropic fractured-vuggy carbonate reservoirs, 3D seismic data with high precision could be used to characterize reservoir geometry and distribution. In detail, 3D seismic profiles and attribute maps would be used firstly for reservoir characterization and initial segmentation, and then information of oil and gas shows and well logs would be integrated for the adjustment of segmentation. Finally, the scheme of segmentation and setting positions of tools would be determined.

For example, the zone of interest in Well TZ-A contains Ordovician carbonate rocks and total measured depth is 5843 m (vertical depth of 4846.22 m). Total horizontal displacement is 1172 m and total length of the horizontal interval is 933 m, as shown in Figure 3. Several fractured-vuggy units with NW-SE elliptical geometries were encountered. There were oil and gas shows in four intervals: 5093-5115 m with TG of 13.41%, 5440-5461 m with TG of 8.28%, 5537-5700 m with TG of 4.98%, and 5790-5843 m with TG of 70.47%. Well logging was terminated at 5720 m due to wellbore track complexities. Well logs are unavailable for the interval 113 m apart from bottom hole; therefore, reservoirs in this interval could not be interpreted with well logs.

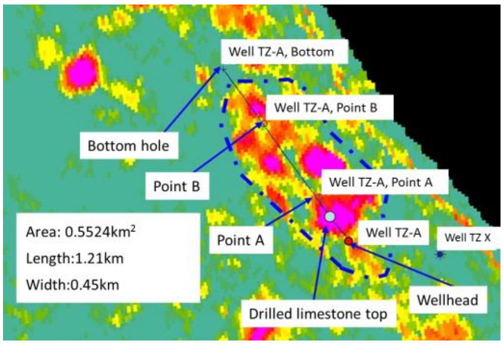
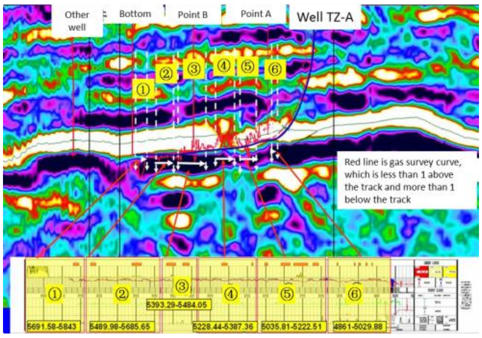


Figure 3: *reservoirs prediction of Well TZ-A*

As shown in Figure 4, deviated wellbore track is superimposed on a 3D seismic profile and attribute map. Initial segmentation was determined in accordance with independent reservoir unit and would then be modified as per information of oil and gas shows and well logs. Finally, the plan of 6-section stimulation was established. Setting positions of tools are shown in Figure 5.



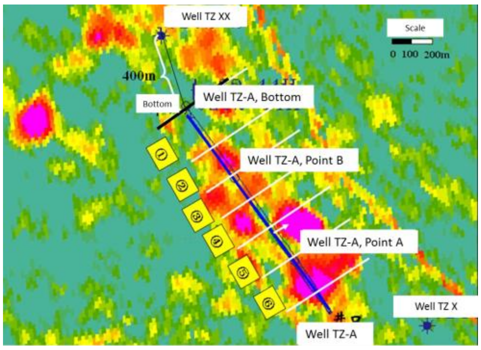


Figure 4: *Profile for segregated stimulation of Well TZ-A*

Figure 5: *Setting positions of tools for segregated stimulation of Well TZ-A*

The spatial distribution of wellbore track, in situ stress azimuth and fractured-vuggy units should be taken into account in well stimulations. In view of large buried depth and quasi-layered distribution of fractured-vuggy units, wellbore track could not be adjusted greatly during well drilling to avoid severe circulation loss. As a result, reservoir units and properties drilled and their offsets from wellbore track would be different and consequently techniques and intensity of stimulation would also be different. Besides, the maximum in situ stress azimuth has a great impact on stimulation design. The knowledge of spatial distribution of wellbore track, in situ stress azimuth and reservoir unit would facilitate the target-oriented design of segregated stimulation.

Figure 6 shows wellbore track of Well TZ-A superimposed on a 3D seismic profile. As per quantitative analysis, wellbore track is at the top of the reservoir; the maximum vertical distance to the top of limestone is 59 m and the minimum distance is 15 m. The maximum distance to the middle of the nearest reservoir is 45 m and the minimum distance is 33 m. Two reservoirs below are 164 m and 192 m respectively apart from wellbore track. As shown in Figure 5, section-2 and section-6 are just under the track, but other 4 sections are 50-100 m laterally apart from the track. Figure 7 shows the azimuth of wellbore track ranges in 320-330°, nearly perpendicular to the major principal stress in NE-SW direction, which would facilitate acid-fracturing to connect separate fractured-vuggy reservoir units and to increase discharge area and single-well productivity.

Depending on vertical and lateral distances between reservoirs and wellbore track, each section should be treated differently. In general, artificial fractures and reservoirs should be connected both in vertical and lateral directions.

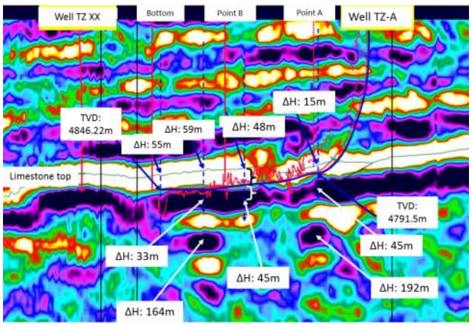


Figure 6: *Predicted distances between wellbore track of Well TZ-A and reservoirs*

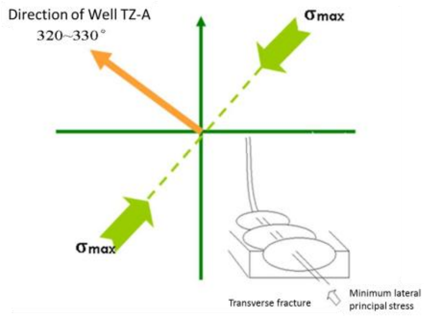


Figure 7: *Diagram of wellbore track, major principal stress and artificial fracture*

3. OPTIMUM DESIGN OF ACID-FRACTURING STIMULATION

Multistage acid-fracturing stimulation of horizontal wells for carbonate reservoirs development in the Central Tarim Basin is mainly to connect the fractured-vuggy reservoirs. Geophysical data would be used firstly to estimate vertical and lateral distances between wellbore and reservoirs, followed by the design of fractured length and height which should be sufficient to connect reservoirs. For this purpose, it is necessary to optimize acid fracturing design in addition to segmentation with open-hole packers, which includes (1) optimization of pad fluid volume, (2) optimization of acidizing fluid injection and conductivity of acid-corroded fractures, and (3) optimization of injecting rate. A large volume of pad fluid would generally be used in operation for the purpose of (1) fracturing, because near-wellbore leakoff may be compensated by pad fluid for a long open-hole section, and (2) fluid substitution, because pad fluid has a larger specific weight than hydrocarbon and could deposit at the bottom of reservoir to replace hydrocarbon.

The wellbore track of a horizontal well usually passing through the top of reservoirs would be connected with reservoirs through fractures with high fractured height. Fractured height is related to Young's modulus, net pressure, liquid viscosity and rate, the latter two of which could be controlled in operation. Using high viscosity and injecting rate would generate fractures with large height, as shown in Figure 8.

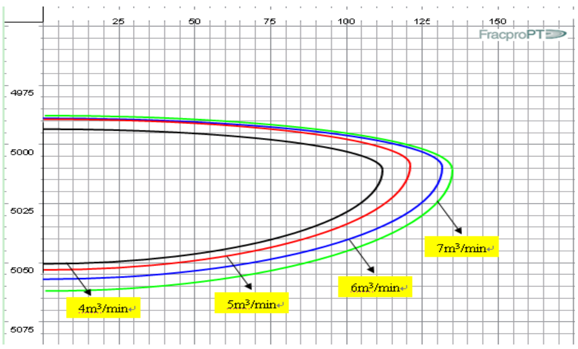


Figure 8: *Fracture profile with different rate for a high viscosity fracturing fluid (differential stress of 5 MPa)*

As for fracture height and length, simulations show that multiple injections of fracturing fluid + cross-linked acid + gelled acid may generate "narrow and long" fractures and high viscosity pad fluid + multiple injections of cross-linked acid + gelled acid may generate "wide and short" fractures.

4. FRACTURING FLUID AND ACIDIZING FLUID

Fracturing fluid should have high viscosity. Guar gum concentration should usually be 0.45% and fracturing fluid viscosity should be larger than 150 mPa▪s in the conditions of 140℃, 170s^{-1} and continuous shearing 60 minutes. Cross-linked acid is high temperature resistant and has high viscosity; its rheological curve is shown in Figure 9. The viscosity of cross-linked acid is larger than 200 mPa▪s in the conditions of 120℃, 170s^{-1} and continuous shearing 60 minutes. Gelled acid generally with the viscosity of 30-50 mPa▪s should be used together with cross-linked acid.

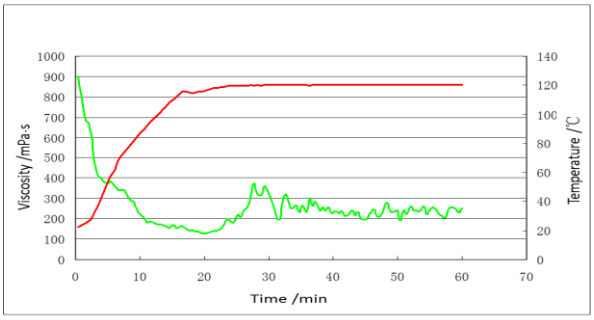


Figure 9: *Rheological curve of cross-linked acid*

5. FIELD APPLICATION

The horizontal section in Well TZ-A is 933 m and is divided into 6 segments with the workflow mentioned above. Parameters concerned are listed in Table 1. A large quantity of pad fluid, accounting for 58.01-67.28%, was injected into each segment. The injecting rate was 5.8-7.1 m^3/min. The operation curves are shown in Figure 10, which shows apparent pressure response to the opening of sliding sleeve in each segment separated by packers. At the later stage of operation for each segment, acid fluid was injected with smaller displacement, so as to generate acid-corroded fractures with high conductivity. Over 60 segments in sixteen horizontal wells have been treated using this workflow in Ta-zhong fractured-vuggy carbonate reservoir.

Table 1: *Operation parameters for Well TZ-A*

NO.	Fluid volume m^3	Acid volume m^3	Percentage of fracturing fluid %	Injecting rate m^3/min	Pressure MPa
1	246.9	120.1	67.28	1.1-5.8	0.6-78.4
2	318.9	230.8	58.01	2.0-6.9	12.0-91.8
3	199.1	120.0	62.39	2.0-7.0	12.3-79.5
4	230.1	120.1	65.71	2.0-7.1	6.8 - 84.1
5	249.1	150.3	62.37	2.0-7.0	6.2 - 81.1
6	325.3	230.8	58.50	2.0-6.8	15.0-86.1

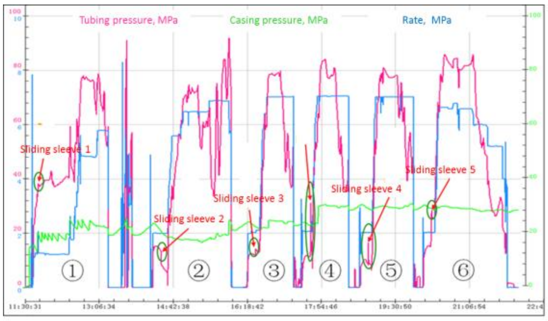
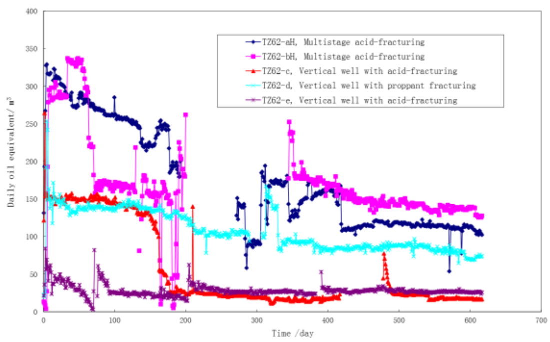


Figure 10: *Multistage acid fracturing curves for Well TZ-A*

6. HORIZONTAL WELL PRODUCTION

As a key technique for fractured-vuggy carbonate reservoirs development in the Central Tarim Basin, multistage acid fracturing with openhole packer in horizontal well has made a good score. Two horizontal wells drilled in Block TZ62 have yielded more daily oil equivalent than 3 vertical wells after segregated acid fracturing. Figure 11 compares daily oil equivalent of horizontal and vertical wells. Figure 12 compares cumulative oil equivalent of horizontal and vertical wells in a same period. As per production testing curves, the horizontal well has yielded daily oil equivalent which is 2.49 times of the vertical well on the average and yielded cumulative oil equivalent which is 1.66 times of the vertical well.



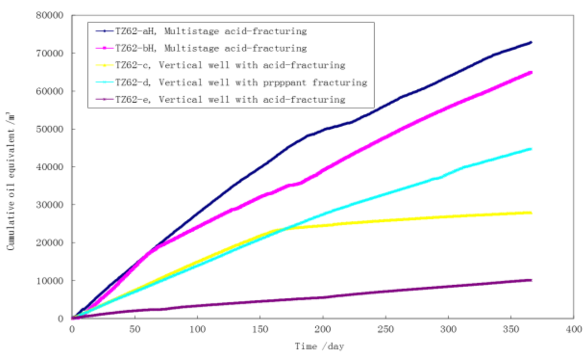


Figure 11: *Single-well daily oil equivalent of horizontal and vertical wells*

Figure 12: *Cumulative oil equivalent of horizontal and vertical wells*

7. CONCLUSIONS

To address the problem of horizontal well segmentation for the development of carbonate reservoirs rich in fractures and caverns, the paper presents a novel method based on 3D seismic-based reservoir characterization, oil and gas shows and well logs.

The distribution of wellbore track, in situ stress azimuth and fractured-vuggy units should be taken into account in well stimulations.

Geophysical data would be used to estimate vertical and lateral distances between wellbore and reservoirs and fracture length and height should be appropriate to connect the fractured-vuggy reservoirs.

A large volume of pad fluid and high injecting rate are commonly used in the process of acid fracturing, so as to lower reservoir temperature and to connect fractures and caverns. Acid would be injected with smaller displacement at the later stage to improve conductivity of acid-corroded fractures.

Horizontal well is superior to vertical well in petroleum production. According to production testing curves for Block TZ62, average daily oil equivalent and cumulative oil equivalent of horizontal well are 2.49 and 1.66 times of vertical well, respectively.

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