A new type of high density fracturing fluid system

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Abstract. Deep oil and gas reservoirs enjoy great opulence in resources, and yet the ultra-deep burial, high temperature, high pressure and natural fractures in reservoirs bring great difficulties to propped fracturing. Given the challenge of propped fracturing in deep reservoirs, a new cost saving and high density fracturing fluid system was developed, of which the performance was evaluated and formulation was optimized, and with this fracturing fluid system, wells that cannot be treated before, can now be effectively stimulated. The advanced fracturing fluid system has been applied to eight layers in five wells, which all proved to be successful and effective, with remarkable reservoir stimulation efficacy. The post-production in the formation testing grew twice of the pre-fracturing production, and two wells were seen gas production exceeding one million cubic meters. The advanced fracturing fluid system greatly expands the well depth range of exploration and development, and lays a solid technical foundation for implementation of propped fracturing in deep reservoirs.

1. Introduction

Deep oil and gas reservoirs, which hold positions of great importance with respect to all among resources, proven reserves and production capacity, are the main battlefields of exploration and development in recent years and for a long time in the future[1]-[6]. For the sake of safety, high-density drilling and completion fluids are usually used in drilling and completion of deep reservoirs, inevitably causing reservoir damage. Thus, reservoirs. regardless their physical properties being superior or inferior, generally need to be fractured and acidized to achieve industrial production and gain further insights into the reservoir[7]-[13]. On the basis of analyzing difficulties of deep reservoir stimulation, a set of high density fracturing fluid systems was developed by optimizing the fracturing fluid weighting agent and evaluating the performance of the system. The fracturing fluid system has been applied in a certain oil field in western China, of which the performance was excellent, and the deep reservoirs were stimulated effectively.

2. Characteristics of deep reservoirs and technical difficulties in propped fracturing

According to data collected from well logging, mud logging, geophysical prospecting and core samples of deep reservoirs, deep reservoirs mainly have the following characteristics:

(1) Deep burial depth of reservoirs. Wells are usually 5,000 m to 7,000 m deep, and by far the deepest well has surpassed 8,000 m.

(2) High reservoir temperatures. Reservoir temperatures generally exceed 140°C, and the currently highest well logging temperature exceeds 180°C.
(3) High formation pressures. The formation pressure is generally greater than 105MPa, and may reach a maximum of 150MPa.

(4) Low matrix porosity and permeability and presence of natural fractures. Natural fractures can be seen from core sample observation, resistivity logging and imaging logging.

(5) Large reservoir thickness. The effective reservoir thickness span is often more than 100m, with no considerable stress barrier.

Reservoir characteristics mentioned above have resulted in great difficulties in hydraulic fracturing of deep reservoirs, which are mainly embodied as:

(1) High treatment pressures. The deep-buried reservoirs with the corresponding high formation pressures lead to a very high treatment pressure, and sometimes it is too high to carry out the treatment, because the resultant wellhead pressure exceeds the equipment pressure limit.

(2) High formation temperatures propose overwhelmingly demanding requirements upon thermal and shear resistance of fracturing fluids.

(3) High sand-plugging risks. The deep oil and gas reservoir is highly naturally-fractured and thus is seen with excess leak-off of fracturing fluids. Under joint effects of this combined with high treatment pressures and limited pump rates, propped fracturing in deep oil and gas reservoirs is prone to screen-out or even sand-plugging.

3. Development of high density fracturing fluid system and performance evaluation

Theoretically speaking, the surface treatment pressure is determined by the bottomhole pressure, friction resistance along the wellbore and hydrostatic pressure, namely:

\[ P_e = P_b + P_f - P_h \]  (Equation-1)

In the Equation-1:

- \( P_e \) — surface treatment pressure /MPa;
- \( P_b \) — bottomhole pressure /MPa;
- \( P_f \) — friction resistance /MPa;
- \( P_h \) — hydrostatic pressure/MPa.

It can be seen from Equation-1 that increasing the density of fracturing fluids can raise up the hydrostatic pressure and thus is an effective way to reduce the surface treatment pressure. Most of the high density fracturing fluid systems abroad are weighed with sodium bromide, but its high cost limits the large-scale application in China. An inorganic salt that is very soluble in water has been selected after a series of laboratory experiments, and the weighted fracturing fluid based on this agent has a density up to 1.30g/cm³, accompanied by good high-temperature and shear resistance. Compared with the sodium bromide-weighted fracturing fluid of the same density, the developed fracturing fluid system can save nearly 3000 Yuan per cubic meter from the cost of the weighting agent, and thus greatly reduce the expense of reservoir stimulation. Meanwhile, it is able to effectively reduce the wellhead treatment pressure and thus facilitate highly-efficient stimulation of deep oil and gas reservoirs and improve production capacity of wells.

3.1. Base fluid property

The bottomhole temperature of deep reservoirs is high (about 150°C in oilfields of western China). In order to ensure the temperature resistance of gel, the consumption of thickening agents is relatively large in the case of a high-density fracturing fluid system (thickening agent concentrations at 0.4%–0.45%). In the meantime, the endothermic dissolution of inorganic salts during the field preparation process will lead to a decrease in the fracturing fluid temperature, which in turn causes growth of the viscosity of base fluids. The viscosity of base fluids of the high density fracturing fluid system with different guar gum concentrations is shown in Table 1. It can be seen that viscosity of the
The viscosity of base fluids of the high density fracturing fluid system:

| Formula                          | Density g/cm³ | Viscosity mPa.s | Density g/cm³ | Viscosity mPa.s | Density g/cm³ | Viscosity mPa.s |
|----------------------------------|---------------|----------------|---------------|----------------|---------------|----------------|
| 40% weighting agent + 0.45% guar gum | 1.30          | 99             | 1.30          | 93             | 1.29          | 84             |
| 40% weighting agent + 0.40% guar gum | 1.30          | 81             | 1.30          | 76.5           | 1.29          | 69             |

3.2. Delayed cross-linking

For deep reservoirs, high pipe string friction is usually anticipated, because of the long treatment tool strings for deep wells. A pH modifier is added into the high-density fracturing fluid system so that the cross-linking time of fracturing fluids can be delayed, and the friction of strings and wellhead treatment pressure can be reduced during field operation. Table 2 shows the cross-linking time corresponding to different dosages of pH modifiers. It can be indicated that the lower the pH value is, the longer the cross-linking time is.

| pH modifiers (%) | Base fluid pH | Crosslinking time corresponding to different cross-linking ratios: 100:0.45 | Crosslinking time corresponding to different cross-linking ratios: 100:0.3 |
|------------------|---------------|-----------------------------------------------------------------------------|-----------------------------------------------------------------------------|
| 0.2              | 8             | Not cross-linking                                                            | Not cross-linking                                                            |
| 0.25             | 9.5           | 3min-4.5min                                                                 | 3min-4.7min                                                                 |
| 0.3              | 10.5          | 1min-1.5min                                                                 | 1min-2min                                                                   |

3.3. Thermal and shear resistance

Rheological properties of the high density fracturing fluid system under the condition of 160°C and 170s⁻¹ are shown in Figure 1. The viscosity of the high density fracturing fluid gel is more than 100 mPa.s after being sheared for two hours, which indicates that the system has good thermal tolerance and meets the needs of effective fracture generation and sand carrying in deep reservoir stimulation. Meanwhile, from the rheological curve, it is shown that the initial viscosity of gel is relatively low, which is conducive to reduce the friction resistance of fracturing fluids through fractures.
3.4. Gel breaking
The high density fracturing fluid of super guar gum has good rheological properties, which is inevitably accompanied by challenges in gel breaking. The test results show that only when the dosage of the gel breaker is more than 0.03%, the gel can be completely hydrated and broken so as to reduce damage to reservoirs and propped fractures. In view of the required high viscosity of the fracturing fluid during operation, the dosage of the encapsulated gel breaker should be increased in an appropriate manner, so that the rheological property of the fracturing fluid can be prevented from being affected by addition of the exposed sulfuric acid breaker.

3.5. Leak-off and damage properties
The static leak-off performance of the high density fracturing fluid system was measured under a pressure difference of 3.5 MPa, using the high-temperature and high-pressure static leak-off apparatus manufactured by Baroid, the US. The static initial leak-off was $6.19 \times 10^{-3}$ m$^3$/m$^2$, the leak-off rate was $1.09 \times 10^{-4}$ m/min, and the leak-off coefficient $C_{III}$ was $6.53 \times 10^{-4}$ m/min$^{0.5}$.

The core sample of the target layer was used in the experiment and the flooding experimental device was heated to 160°C. 2% KCl solution was first injected till the pressure was stable, then the high density fracturing fluid was injected and the device temperature was kept constant for four hours, after which 2% KCl solution was injected till the pressure was stable again. Test results in Figure2 show that the high density fracturing fluid does not cause damage to the core sample.
3.6. Corrosion to strings
During the process of injection of high density fracturing fluids, thanks to the short period of time and the cooling effects of injection, the corrosion induced by salts is not serious. However, it may take a long time for fluids after gel breaking to flow back, and meanwhile the wellbore temperature can be restored at this time. Therefore, the corrosion to downhole tools caused by salts has to be considered. A corrosion test was carried out in which N80 steel was soaked in fracturing fluids at 160°C. The average corrosion rate of the N80 steel sheet soaked for six hours was 3.36g/m².h.

4. Field application
This system has been used for eight layers in five wells of a deep reservoir in western China, and the specific treatment parameters are shown in Table 3. The reservoir stimulation has been seen with tremendous success. Under the similar drawdown pressure, the post-fracturing production testing presented production rates all over twice of those before fracturing and the daily gas production of Wells D3 and D4 exceeds one million cubic meters. In the aspect of treatment pressures, specifically in Well D1, the pump rate was 3.3-4.5m³/min, the treatment pressure was high up to 115-136MPa, and the operation with the treatment pressure over 120MPa lasts for 120min. The propped hydraulic fracturing was successfully completed in this well, and the daily gas production increased from 230,000 m³ to 440,000 m³.

Table 3. Parameters of propped fracturing in wells that have been treated.

| Well | Well section m | Pump rate m³/min | Treatment pressure MPa | Sand concentration kg/m³ | Sand volume m³ |
|------|----------------|------------------|------------------------|--------------------------|---------------|
| K1   | 6703-6742      | 3.5-4.2          | 108.0-115.0            | 50-320                   | 18.0          |
| D1   | 6930-6988      | 3.3-4.5          | 115.0-136.0            | 70-290                   | 15.4          |
| D2   | 5425-5479      | 3.7-4.3          | 93.0-102.0             | 75-290                   | 34.1          |
| D2   | 5315-5392      | 4.2-4.5          | 79.0-88.8              | 130-420                  | 42.8          |
| D3   | 5541-5593      | 4.9-5.3          | 80.6-99.3              | 110-460                  | 55.0          |
| D4   | 4947.5-4977    | 3.9-4.2          | 91.0-105.0             | 130-490                  | 41.8          |
| D4   | 4845-4876.5    | 4.0-4.6          | 83.0-98.2              | 150-340                  | 30.4          |
| D4   | 4766.5-4796    | 4.0-4.6          | 78.5-93.7              | 150-400                  | 39.1          |
5. Conclusions
High temperatures, high pressures and presence of natural fractures in deep oil and gas reservoirs result in limited pump rates of propped fracturing, excess leak-off of fracturing fluids, high difficulties in effective fracture creation, and accordingly extreme challenges for the propped fracturing treatment. In view of the difficulty of propped fracturing in deep reservoirs, a new cost saving and high density fracturing fluid system has been developed and evaluated, which can effectively stimulate reservoirs that cannot be reached before. The field application demonstrates great production stimulation performance, which therefore allows for large-scale economic exploitation of massive previously hard-to-recover reserves. The develop fracturing fluid system substantially expands the well depth range of the exploration and development, and realizes a great leap from the previous situation in which 5,000-m wells were hard to be treated to the current situation in which 7000-meter wells can also be stimulated, which lay a solid technical foundation for the large-scale economic development of deep oil and gas reservoirs.

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