Analysis of the Use of the First Large-Volume Hydraulic Fracturing with Injection of Over 100 Tons Propping Agent at the Russian Fields

A V Sarancha¹, E I Inyakina¹
¹Tyumen Industrial University, 38, Volodarskogo street, Tyumen, 625000, Russian Federation

E-mail: 89044914477@mail.ru

Abstract. Hydraulic fracturing (HFT) is a technological process aimed at the productivity increasing of oil and gas wells by creating a highly permeable fracture diverging in diversely directions from the well or multiple fractures, which in turn will be filled with granular material – propping agent. For more than 25 years, hydraulic fracturing has been widely used in Western Siberia, as a very effective means of intensifying the fluid flow to the downhole of production wells. Analyzing the experience of oil fields development in the Khanty-Mansi Autonomous Okrug, where over 25 thousand treatments have already been carried out hydraulic fracturing technology has proved to be the most effective and has gained the greatest distribution among the other geological and technical operations. This paper will provide for analysis of the first large-volume hydraulic fracturing with injection of over 100 tons of propping agent in Russia, which was carried out at four wells at the Yaraynerskoye field.

1. Introduction

Theoretical representations describing the hydraulic fracturing process as a method of the inflow stimulation were performed by J. B. Clark in 1948. Later in 1957, M. K. Hubbert and D. G. Willis theoretically described the mechanism of cracking in producing reservoirs. Further, the mechanism of crack formation during the hydraulic fracturing was more thoroughly studied by G. I. Barenblatt, Yu. N. Vasiliev, A. T. Gorbunov, Yu. V. Zheltov, Yu. P. Zheltov, A. F. Zazovsky, G. K. Maksimovich, V. N. Nikolaevsky, S. A. Khristianovich, W. G. Beauder, H. B. Carroll, J. Desroches, M. Economides, C. Fairhurst, C. R. Fast, B. Haimson, S. A. Holditch, G. C. Howard, J. Groenenboom, L. R. Kern, C. T. Luiskutty, D. N. Meehan, B. R. Meyer, R. Oligney, I. D. Palmer, T. K. Perkins, J. R. Rice, N. B. Rubin, P. P. Scott, L. Weijers and many other authors.

The evolution of use of the hydraulic fracturing at the Western Siberia fields can be divided into 6 stages.

1 Stage (1989 – 1995) – hydraulic fracturing technology is used as a means of restoring the natural productivity of wells, worsened during drilling and production. That is, small cracks were created, which task was to overcome the contaminated area in the downhole area of the well;

2 stage (1995 – 1999) – during this period, there is a slight increase in the volume of the injected propping agent, which, in addition to restoring productivity, also allows the involvement of medium and low productivity reservoirs into the development;

3 stage (1999 – 2003) – larger propping fractions with an increase in its concentration are used,
creating high-conductivity cracks, which allow to engage areas with low formation reservoir properties and high discontinuity in the low-productive parts of the facility. The first operations with propping agent injection of over 100 tons are conducted;

4 stage (2003 – 2007) – hydraulic fracturing gains the systems approach, taking into account the layout of the production and injection funds. Operations with increased proppant concentrations up to 1800 kg/m³ and the injection of the large high-strength fractions 10/14 are carried out;

5 stage (2007 – 2010) – in addition to conducting the hydraulic fracturing using technologies of previous periods, operations with phase permeability modifiers are carried out;

6 stage (2010 – 2020) – hydraulic fracturing was carried out in almost all wells at the most productive areas, in some of them operations were even performed four times. In this regard, hydraulic fracturing starts to be carried out in the marginal areas with impaired reservoir properties, also using forced fluid sampling.

This is the history of the development of hydraulic fracturing technology at the Western Siberia fields. It is also worth noting that, despite the development of the method and the improvement of equipment, oil flow rate decreases with the transition from the earlier periods of hydraulic fracturing use to the later ones, which is due to both a decrease in the well fund suitable for the hydraulic fracturing, an increase in the number of repeated hydraulic fracturing as well as watering facilities and reserves.

2. Results and discussion

Since 2000, at many oil fields with low-permeability facilities, large-volume hydraulic fracturing with propping agent injection of over 100 tons is beginning to be used. In this case, the Priobskoye oil field plays a special role, where since 1992 over 6 thousand operations have been carried out, more than 200 of which with over 100 tons propping agent injection.

In Since 2000, at many oil fields with low-permeability facilities, large-volume hydraulic fracturing with propping agent injection of over 100 tons is beginning to be used. In this case, the Priobskoye oil field plays a special role, where since 1992 over 6 thousand operations have been carried out, more than 200 of which with over 100 tons propping agent injection.

By itself, the large-volume hydraulic fracturing is the development and improvement of a conventional hydraulic fracturing. During this operation, more rupture fluid and propping agent volume are used. There are cases at the same Priobskoye field, when the volume of propping agent injected through the well into the reservoir exceeded 500 tons.

A large-volume hydraulic fracturing can significantly increase the wells productivity, since a large system of branched fractures is created in the reservoir, thereby increasing the filtration connection of the well with remote areas in the reservoir, sometimes even at a distance of over one hundred meters. The implementation of the large-volume hydraulic fracturing is possible in several ways, for example, using high-viscosity working fluids and foam systems. The large-volume fracturing is also carried out on gas-saturated low-permeability reservoirs. The Yarainerskoye field is the first field in Russia where the large-volume hydraulic fracturing was performed.

At the Yarainerkoye field, the Achimov sequence is one of the main facilities in terms of size and distribution area. The wells that opened the Achimov deposits are located unevenly along the dome of the reservoir. They were introduced into development at different times and worked on exhaustion.

The Achimov layer is Lower Cretaceous, represented by a characteristic alteration of sandstones, siltstones, mudstones and clay interlayers. The reservoir is low permeable and has the high saturation pressure of 260 bar with the reservoir pressure of 270 bar. It is saturated with low-viscosity oil of 0.24 cP. Wells operate with the high gas factor of the facility – 400 m³/m³. The layer is a layered system with fragmentation up to 11 interlayers. In some wells, the layers thickness reaches up to 4 – 5 meters. There are also powerful clay bratticings, which in turn also reach thicknesses up to 2 – 4 meters. All this indicates a high non-uniformity of the facility.

Four wells: No. 303, 5228, 5230 and 5222 were treated by hydraulic fracturing with the propping agent injection of 100 tons.
Starting production rates of the wells were from 10 to 58 tons per day before hydraulic fracturing, while at more successful wells No. 303 and 5230 they were 44 m³/day and 58 m³/day, respectively. The production rates of less successful wells No. 5228 and 5222 were 10 m³/day and 17 m³/day. The first massive hydraulic fracturing was carried out at the well No. 303 in September 2000. Before the hydraulic fracturing, the well has been operated for five months. During this period there was a decrease in flow rates from 44 m³/day to 19 m³/day, at the same time, the depression on the reservoir increased to 212 bar. Other wells, No. 5228, 5222 and 5230 ones, have not been used for a long time before hydraulic fracturing, for about one to two months.

Downhole pressure in wells subjected to hydraulic fracturing varied in the range of 40 - 90 bar before treatment, which is much lower than the saturation pressure. Operation below the saturation pressure resulted in the release of gas from the oil. The formation of a multiphase flow in the downhole area of the reservoir ultimately led to the decrease in well productivity.

Since the reservoir is a layered system consisting of several interlayers, it seems that not all of them were connected to work when start-up the wells. High skin effects in individual interlayers are also possible. Since it is known that there are no underlying aquifers in the lower part of the reservoir, the oil company decided to intensify the wells with conducting the hydraulic fracturing. Based on the fact that the reservoir is a powerful system up to 40 meters thick, massive hydraulic fracturing operations were carried out with propping agent injection of about 100 tons.

The first massive hydraulic fracturing at the Yarainerskoye field was carried out in well No. 303 in September 2000. In the next month after the hydraulic fracturing, the well operated with a flow rate of 115 m³/day with a water cut of 18%.

A feature of the operation of this well before and after the hydraulic fracturing is that its start-up after development gave an average inflow of 30 m³/day with a depression on the reservoir of about 220 bar. And after the hydraulic fracturing, the starting flow rate was 115 m³/day, while the depression on the reservoir decreased sharply to 80 bar.

Well productivity is defined as
\[ \eta = \frac{q}{\Delta P} \]
where \( \eta \) – productivity, \( q \) – flow rate, \( \Delta P \) – depression on the reservoir, which is defined as \( \Delta P = P_r - P_d \),
where \( P_r \) – reservoir pressure and \( P_d \) – downhole pressure.

Well productivity before the hydraulic fracturing amounted:
\[ \eta_{before h} = \frac{30}{(270-50)} = 0.13 \text{ (m³/day)/bar}. \]
And after the conducting of the hydraulic fracturing, the productivity increased to \( \eta_{after h} = \frac{115}{(270-195)} = 1.53 \text{ (m³/day)/bar} \), that is, increased by 11 times. Downhole pressure after the hydraulic fracturing has become equal to \( P_d = 195 \text{ bar} \).

Given a previous depression, this well could operate with a flow rate of:
\[ q = \eta_{after h} \times \Delta P = 1.53 \times 220 = 336 \text{ m³/day}. \]
That is, when installing a pump with the higher power, for example, with a capacity of 300 m³/day, it would be possible to obtain a starting flow rate up to 300 m³/day.

In the mentioned example, four specific periods of well operation are clearly distinguished. The first period from the moment the well was started up after the hydraulic fracturing in October 2000 to May 2001 is characterized by a decrease in the flow rate to 70 m³/day. During the second period, which lasted 9 months until February 2002, the well operated relatively persistent with a productivity of 60–70 m³/day. The downhole pressure over two periods decreased from 195 bar to 95 bar. In the third period, which lasted until November 2002, there was a decrease in the flow rate to 33 m³/day, and in the behavior of the downhole pressure there was a cessation of the decline and stabilization in the range of 80 – 90 bar. During all three periods of the well operation, the inflow production contained water, which percentage remained unchanged and amounted 10–25%. Most likely, water entered the annulus from the underlying horizons, although it is possible that a crack could also reveal water bearings. In the last, fourth period, the oil flow rate continues to decline at the same rate as in the previous period: monthly production rate decreased by an average of 3 m³/day. Also during this
period there is an increase in water cut, as in June 2003 it amounted 65% for a flow rate of 14 m³/day. Over the next two months, the well did not operate, most likely it was stopped for overhaul. During the repair with the well-killing fluid, the downhole area and a crack could be clogged, which is confirmed by the fact that after the well was started again, the production of the well amounted 95% water. As the percentage of water in the well production increases, a decrease in depression is observed and in the final state, the water percentage has reached 99%, the depression on the reservoir has already reached 90 at.

Do not forget that the well is operated much lower than the saturation pressure. Until recently, this phenomenon was not given enough attention in the design of the hydraulic fracturing. It was believed that when carrying out the hydraulic fracturing on low-permeability reservoirs, there was no need to create wide and, therefore, highly conductive cracks. But recent conducted studies in this area, both by oil companies and proppant and propping agent manufacturers, have shown that even the slight presence of any of the phases, whether water or gas in oil and vice versa, leads to a significant decrease in the conductivity of the crack injected with the propping agent. Therefore, it is most likely that the conductivity of the fracture during two years of operation decreased so much that it could not deliver the amount of fluid that the pump required. As a result the cement stone is destroyed with a high depression on the reservoir (up to 190 bar) and underlying water bearing horizons are included, which is confirmed by the increase in the downhole pressure in the fourth period and the fact that in the future the well begins to operate only by extracting fluid from the water-saturated horizon.

The second hydraulic fracturing was carried out at the well No. 5228 in April 2001. The first two months after the hydraulic fracturing, the well operates with a flow rate of 65–75 m³/day. Although the conducted operation at this well repaid expenditures of hydraulic fracturing, it cannot be called successful. During a year after the hydraulic fracturing, the well worked with an average flow rate of 37 m³/day, and in the next 2.5 years, its production rate amounted to about 4 – 7 m³/day. During the first two years the water cut was not high, but then in the period from August 2003 to December 2004, it increased from 21 to 51%.

The bulk of oil was produced during the first year of operation after the hydraulic fracturing and amounted 9689 tons. During the second and third years, a total of 1,633 tons of oil was produced. It can be concluded that the well No. 5228 takes the least place for oil produced in the first, second and third years of operation after the hydraulic fracturing.

A feature of the well operation after the hydraulic fracturing is that after an increase in the flow rate due to the hydraulic fracturing to 65–70 m³/day, it began to decrease sharply. Downhole pressure also decreased more intensively. Compared with the previous example (well No. 303), in the mentioned well for eight months of operation, the downhole pressure decreased by 77 bar and amounted to 88 bar, while as in the well No. 303 the pressure decreased by 60 bar and amounted to 125 bar for this period.

Exactly one year after the well hydraulic fracturing, the production rate decreased sharply and amounted to 2–3 m³/day. So the well had been operated for another two years, i.e. was in the unprofitable category. A sharp drop in production may be due to the fact that at the end of March 2002 the well was shut down. Studies were carried out and the pressure recovery curve was recorded. At the end of May 2002, the well was put into operation, however, its starting production rate was 2.5 m³/day, and before stopping, the production rate was 40 m³/day. Due to the lack of information on other operations were carried out at the well during its shutdown, it is not possible to analyze what such low flow rates are associated with after starting the well.

The pump was probably replaced by a less powerful one. By July 2003, the pressure in the well had dropped to 60 bar and subsequently there was an increase in the water cut.

The third well, where massive hydraulic fracturing was performed, was the well No. 5230. Before the hydraulic fracturing, the well was put into operation in March 2001 with an oil flow rate of 58 m³/day. In the next two months, the flow rate drops to 37 m³/day. High depression on the reservoir
was noted – about 200 bar. After the conducted hydraulic fracturing, the flow rate of the wells was 75 m$^3$/day. Well productivity has increased by 4 times.

$$N = \eta_{\text{after}} / \eta_{\text{before}} = (q_{\text{after}} / \Delta P_{\text{after}}) / (q_{\text{before}} / \Delta P_{\text{before}}) = 4.2,$$

where $N$ – the increase in productivity.

In the first 10 months after the hydraulic fracturing, the well operates with an increased flow rate: the maximum oil flow rate reached 105 m$^3$/day. A pump with a capacity of 100 m$^3$/day provided for the fluid production during this period in the range of 75 – 110 m$^3$/day.

Downhole pressure in the first two months after the hydraulic fracturing slightly increased from 178 to 198 bar. After that a slow decline begins. In March 2004 it amounted to 60 bar. The water cut of the well is low, during three years of operation after the hydraulic fracturing its maximum value was 30%, which was the first month of operation after the hydraulic fracturing. According to the results of monitoring the well operation for three years, its 44801 tons accumulated oil can be called the most successful of the 4 wells subjected to massive hydraulic fracturing at the Yarainerskoe oil field.

Well No. 5222 was the least one of a series of treated, massive hydraulic fracturing at the Yarainerskoye field. After the development, it operated with a low flow rate of 17 m$^3$/day. In August 2001, the hydraulic fracturing was performed on it, after which the well was put into operation with a flow rate of 80 m$^3$/day, the depression decreased from 180 to 50 bar. The productivity increased by 16 times.

$$N = \eta_{\text{after}} / \eta_{\text{before}} = (q_{\text{after}} / \Delta P_{\text{after}}) / (q_{\text{before}} / \Delta P_{\text{before}}) = 16,$$

where $N$ is increase in productivity.

For five months of the well operation after the hydraulic fracturing, the oil production rate decreased to 22 m$^3$/day, i.e. almost by four times. During the same time, the depression on the reservoir increased by three times. Then the flow rate remained relatively constant for 18 months at 18–40 m$^3$/day, after which it still decreased and over the next year the well operated with a flow rate of 6–15 m$^3$/day.

A feature of the operation of the mentioned well is that for the entire three-year period of its operation, it operated with a large flow rate for water in relation to the flow rate for oil. That is, the water productivity has not changed, regardless of the depression on the reservoir, which increased by almost four times over the year after the hydraulic fracturing – from 53 to 198. This means that the underlying water-saturated horizon is the pressure one and does not depend on depression on the oil reservoir. Water most likely enters the well through the annulus in accordance with the performance of the pumps used.

In all four wells there is a decrease in downhole pressure. But the rate of the decline is different. It should be noted that in proportion to the decrease in the downhole pressure, a decrease in production rates is also noted. Essentially, the dynamics of the well operation is entirely determined by the reservoir energy, i.e. reservoir pressures in the drainage areas of the well. Obviously, the longer the downhole pressure reduction process is, the greater the drainage are per respective wells.

After calculating the reserves for each well and taking into account that the oil recovery factor for the Achimov deposits was taken equal to 0.25, it was found out that the wells were far from the planned recoverable reserves, but were already substantially flooded: thus, well No. 303 worked out 22% of the recoverable reserves, and its water cut reached 99%; well No. 5228 worked out 8% of the recoverable reserves, and its water cut reached 51%; well No. 5230 worked out 27% of recoverable reserves, and its water cut reached 23%; well No. 5222 worked out 8% of the recoverable reserves, and its water cut reached 81%.

As can be seen, only well No. 5230 still has the potential to achieve the forecasted oil production. Three out of four wells were ineffective from the standpoint of achieving the planned oil recovery factor.

The main reasons for the watering of wells with the hydraulic fracturing at the Yarainerskoye field is that when creating fractures with a large propping agent injection, water is supplied from the underlying water reservoirs. At the same time, overflows are associated both with the destruction of
the cement stone, and with the aerial extent of a crack in the cap of a water-pressure reservoir. The active water manifestation in production occurs after a significant decrease in the dynamic level and the creation of a deep depression on the reservoir. The fact that, with similar depressions on the reservoir, large volumes of water from the underlying objects do not enter the well when they are put into operation before the hydraulic fracturing, and after hydraulic fracturing, water begins to flow more intensively, this is evidence that the hydraulic fracturing with the propping agent injection of up to one hundred tons contributed to this.

The reserve for the use of the hydraulic fracturing at the Yarainerskoye field is more precise planning of operations, for example, with regulation of the development of the fracture with the preliminary proppant filling of the lower part of the reservoir.

It is necessary to carry out the insulation work for well rehabilitation. But first the water sources have to be measured carefully. It is also necessary to increase the pressure in the reservoir by the organization of the controlled injection.

3. Conclusion

This Thus, the first experience with the large-volume hydraulic fracturing showed:

- When water is present in the well production, it is necessary to determine the sources of its supply, and if there are annular cross-flows from water bearing horizons, the massive hydraulic fracturing cannot be performed without repair and insulation works.

- Wells are operated with the downhole pressures much lower than the saturation pressure, which leads to the formation of a two-phase flow and a decrease in the phase permeability. The conductivity of the crack and near the cracked space during two years of the operation is significantly reduced due to occurred blockages.

- The use of the massive hydraulic fracturing is not suitable for fields with a dense grid of wells. The distance between the wells should be at least 800 – 1000 meters.

- Only technically corrected wells are suitable for the massive hydraulic fracturing. The condition of the cement stone in the annulus should be in the good condition.

According to the mentioned wells, it can be finally concluded, that for a full analysis of the effectiveness of the hydraulic fracturing, there is not enough knowledge about the skin effect before and after the process, information on which can be obtained as a result of hydrodynamic studies with a recording of the pressure recovery curve.

4. References

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