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Technology for Determining the Inflow from Near and Far Zones of Fractures During Hydraulic Fracturing by Chemical Tracers in a Production Well

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Abstract

The tracer-based production logging technology can be used to obtain the well production data continuously for several years without the need for risky well interventions and expensive equipment. The paper examines the case of placing polymer-coated tracers dopped proppant in a horizontal well with ten multi-stage frac intervals and using two different tracers dopped proppant codes for two frac ports (the first and the last ones) to identify the performance of the far and near zones of a hydraulic fracture.

Upon the completion of the hydraulic fracturing operations, the collected reservoir fluid samples were studied in the laboratory. Chemical tracers contained in the samples were detected by flow cytofluorometry using custom-tailored machine learning-based software. The studies helped identify the productivity of each frac port, calculate the contribution of each port in percentage points, and also evaluate the productivity of the near and far hydraulic fracture zones in the first and the last intervals.

The analysis provided data on the exact content of oil and water in the production profile for each frac interval. The results of tracer-based logging in the well in question revealed that the interval productivity is changing in the course of several months of surveillance. The most productive ports and those showing increasing oil flow rate were identified during quantitative analysis.

The use of tracer dopped proppant with different codes within one multi-stage frac interval enabled detecting a peak release of chemical tracers from the far fracture zone in the initial periods of well operation followed by a consistent smoothing of the far and near zones' production profiles. Laboratory analysis of reservoir fluid samples and hydraulic fracturing simulations proved the uniform distribution of proppant across the entire reservoir pay zone and laid the foundation for further research required to better understand the fracture geometry and reduce uncertainties in production optimization operations.

Introduction

The industrial consumption of hydrocarbons (HC) is constantly growing, so, to prevent the oil and gas shortage in the global market, the upstream sector has to respond by bringing unconventional oil and gas reserves into development. Intensively developed over the past century, today conventional hydrocarbon reserves show a declining trend in commercial hydrocarbon production.

Every year oil companies have to either increase their expenditures associated with prospecting and development of new oil and gas fields or shift to the development of hard-to-recover reserves.

As oil and gas production technologies develop and such methods as horizontal drilling and hydraulic fracturing evolve and find commercial application, the opportunity has emerged to focus on industrial cost-effective development of shale deposits that have a unique structure.

The "shale revolution", which began in the United States in the late 2010s and led to a surge in hydrocarbon production from hard-to-recover reserves, gave a great impetus to the improvement of the technologies enabling greater access to oil and natural gas in shale formations. [Bukov O. V. 2020.]

The Kondinskoye field is located in the floodplain of the Konda river in the Khanty-Mansi Autonomous Okrug (District) and belongs to the West Siberian oil and gas province, where the hard-to- recover reserves of the Ah deposits with an average permeability of 0.4 mD and a porosity of 16% are developed.

JSC NK Kondaneft, a company of the PJSC Rosneft Oil Company, is engaged in the development of the Kondinskoye, Zapadno-Erginsky, Chaprovsky, and Novoendyrsky license areas (Kondinsky group of fields) of the Khanty-Mansi Autonomous Okrug-Yugra. [*https://www.rosneft.ru/about/Glance/OperationalStructure/Dobicha_i_razrabotka/Zapadnaja_Sibir/Kondaneft*], total reserves (ABC1+C2) amount to 259 million tons of crude oil *[https://www.rosneft.ru/press/news/item/194683*], figure 1.

Figure 1—Map of the Kondinskoye field ***[https://neftegaz.ru/tech-library/mestorozhdeniya/522630-kondinskoe-mestorozhdenie/]***

The geographical location of the deposits and substantial pay zones are favorable factors enabling prompt commencement of the commercial development and production.

However, no field development operations were started since the 1970s. The development of the above-mentioned areas could not be initiated due to a complex geological structure, low porosity and permeability, as well as very little information available on the field, the lack of field maps, etc., along with a small number of exploration wells and a low flow rate, even taking into account large net pays (50-70 m) (Figure 2) [Kruchkova T. 2008.].

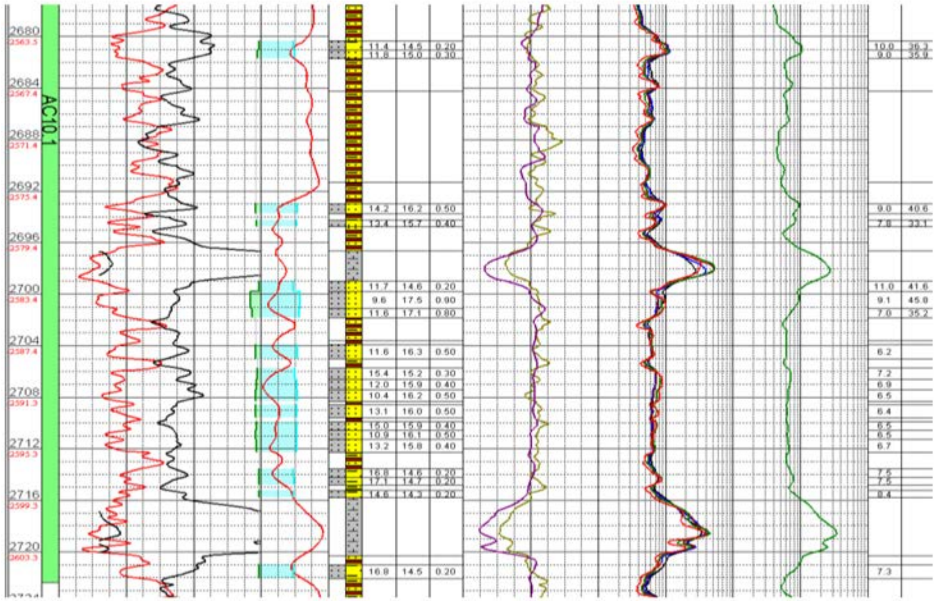


Figure 2—Interpretation of geophysical well logs for the Ah deposits

In the 2010s, an active implementation of such methods as horizontal drilling and multi-stage hydraulic fracturing (MSHF) in oilfield industry of Russia set the stage for the development of hard-to- recover reserves in the Ah deposits.

The multi-stage fracturing operations in this case were conducted for two purposes:

- To increase the well's performance by eliminating/bypassing the bottom-hole zone with reduced porosity and permeability (for example, due to drilling mud filtration), see figure 3.
- To enhance oil recovery by bringing reservoir intervals with poor performance as well as the zones with low permeability and high heterogeneity into development.

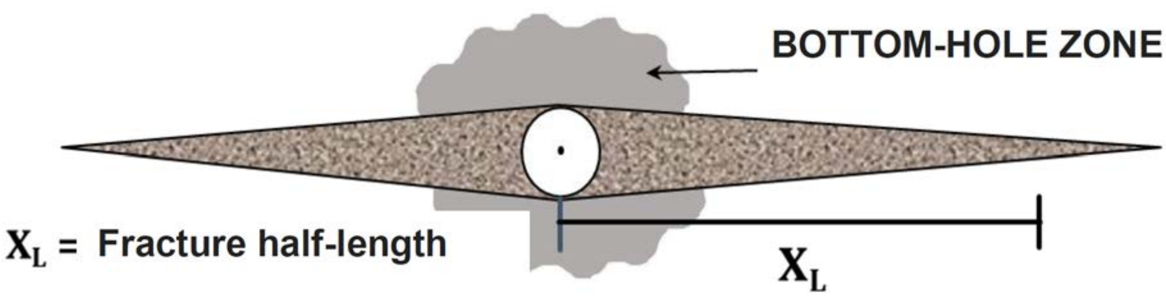


Figure 3—Bypassing the bottom-hole zone

Typical hydraulic fracturing operations performed to develop reserves with similar structure, geomechanical characteristics, and porosity and permeability include standard treatment operations with flow rates of ~ 5 m^3/min and injection of high-viscosity fluids with large-fraction proppants.

Challenges of conventional production logging techniques

Usually a license holder does not have reliable analytical data on the actual structure of the reservoir fluid production profile in horizontal laterals. Conventional production logging requires well interventions, evacuation of artificial lift equipment, as well as costly coil tubing-based logging operations and thus are associated with technical difficulties and the risks of loosing tools and equipment getting stuck downhole.

Therefore, currently there is an unmet need for techniques that would enable calculating the optimal length of horizontal laterals and the number of frac stages as well as effectively facilitate development and production at fields where horizontal wells are drilled. In addition, the assessment of the reservoir pressure maintenance system's effectiveness appears to be challenging.

Production logging in horizontal wells using coiled tubing is fraught with difficulties due to the stratified fluid flow, the presence of a gas fraction in the fluid, recirculation zones and others, which hinders the estimation of the recorded parameters and often impairs the accuracy of measurements. In addition to the difficulty of a multiphase flow analysis, conventional production logging requires a number of standard measures to be taken when assessing the production such as well kills and RIH/POOH operations for special equipment eventually leading to well downtime and clogging of the formation bottom-hole zone, which in turn results in impaired hydraulic fracture conductivity in the near wellbore area and, consequently, worse performance of the fracture and the well in general. Given the low porosity and permeability of the rock, well interventions can cause a dramatic decrease in the well flow rate after the production logging operations.

Well logging techniques designed for production profiling after hydraulic fracturing and PVT analysis of the fluid can be grouped into three categories:

- Conventional production logging;
- Fiber optic sensors for online monitoring distributed along the entire wellbore (with additional software);
- Tracer-based production logging.

It is worth noting that tracer-based production logging techniques are becoming increasingly widespread in the global oil industry. These methods offer obvious advantages as they do not require well shutdown or well interventions during production logging and also provide the possibility to collect data on the selective water and oil production profile from each interval continuously for a long period of time.

Table 1 compares different production logging and profiling methods.

Table 1—Production logging methods

Production logging method	Conventional production logging using coiled tubing	Distributed fiber optic sensors for online monitoring	Proppant with tracers
Logging period	several hours	Up to several years (depending on the quality of the optical material)	Hydrophilic, oleophilic, and gas — up to 3—5 years (depending on the conditions)
Well intervention or change in the operating mode are required	Yes	Yes	No
Possibility of laboratory tests	Very rare	No	Yes
Number of logging operations per year	1—2	Continuous surveillance	6—12 (optional at request)
Necessity of the lab analysis	N/A	N/A	Yes
Multilateral or ERD wells	Limited	Yes	Yes
Applicable in cemented liners	Yes	No	Yes
Applicable for old/new wells	Yes	For new wells	Yes
Applicable in open holes	Yes (with restrictions)	No	Yes (with restrictions)
Evaluation of the quality of the bottom-hole zone treatment or	No	Acid treatment — Yes Hydraulic fracturing — limited	Yes
The results can be used to enhance the efficiency of field development	Yes	Yes	Yes

Production logging method	Conventional production logging using coiled tubing	Distributed fiber optic sensors for online monitoring	Proppant with tracers
Application specifics	Horizontal lateral is accessible; Risks of well interventions; Data reliability	Difficult RIH operations; Well workovers are required; Limited in application;	Limited use in case of high- viscosity oil Depends on the success of the hydraulic fracturing operation;

Well

Table 2 provides the geological and engineering data on well no. A at the Kondinskoye field, pad B, AS-10 formation where tracer dopped proppant was injected during multi-stage hydraulic fracturing.

Table 2—Geological and engineering data on well no. A

Item no.	Parameter	Value
General information		
1	Field	Kondinskoye
2	Well no.	A
3	Well pad no.	B
4	Type of well	producing horizontal well
5	Operation method	Artificial lift
Well data		
6	Number of producing wells	1
7	Net pay, m	15.5
8	Average permeability, mD	0.4
9	Porosity, %	15.6
10	Reservoir pressure, atm	230
11	Reservoir temperature, °C	83
12	Number of hydraulic fracture zones	10

Figure 4 shows the profile along the borehole of the well under study.

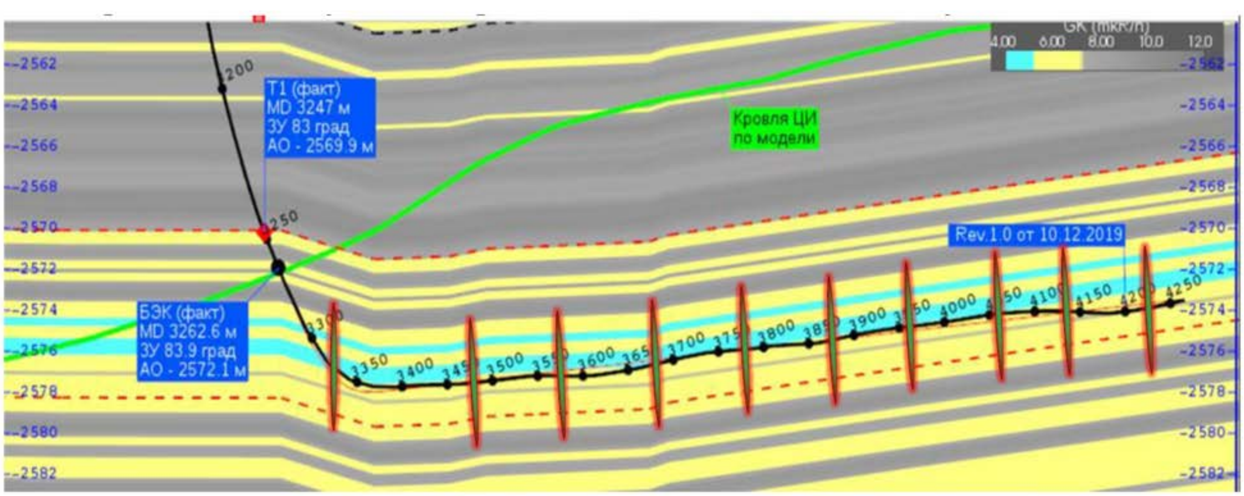


Figure 4—The borehole profile of well no. A

Hydraulic fracturing at the well no. A was performed in the period from 18 to 21 February 2020. The data on tracer dopped proppant injection is summarized in Table 2.

Multi-stage hydraulic fracturing operations were performed using a cross-linked gel with frac fluid pumped down at the rate of 3.6 m^3/min, a proppant mass of 50 to 120 tons per hydraulic fracturing operation, and a 16/20 proppant fraction. The following amounts of tracer dopped proppant were used for each treatment stage: 15 tons for the final treatment stages and 15 tons for the first and the last operations with the supply of proppant at the first stages. It is noteworthy that the dopped proppant used for the first and last hydraulic fracturing operations was a 20/40 fraction when injected at the first stage.

The proppant was injected at the first and the last stages for the operations 1 and 10 to assess the contribution of the far zone of the hydraulic fracture and to answer the question whether the hydraulic fracture has sufficient conductivity at low concentrations of the injected proppant.

It was agreed to conduct a target multi-stage fracturing operation, taking into account the geological characteristics summarized in Table 3. Figure 5 shows data on the consumption rate, concentration and injection of proppant.

Table 3—Plan of the multi-stage hydraulic fracturing operations

Stages no.	Consumption rates, m^3/min	Vfluid, m^3	Mprop, t	16/20	16/20 (with tracers)	20/40 (with tracers)	Tracer dopped proppant injection concentration kg/m^3
1,10	3.4	320	100	70	15	15	100—600, 900
2,4—9	3.4	212	70	55	15	–	150—200
3	3.4	160	50	35	15	–	350—450

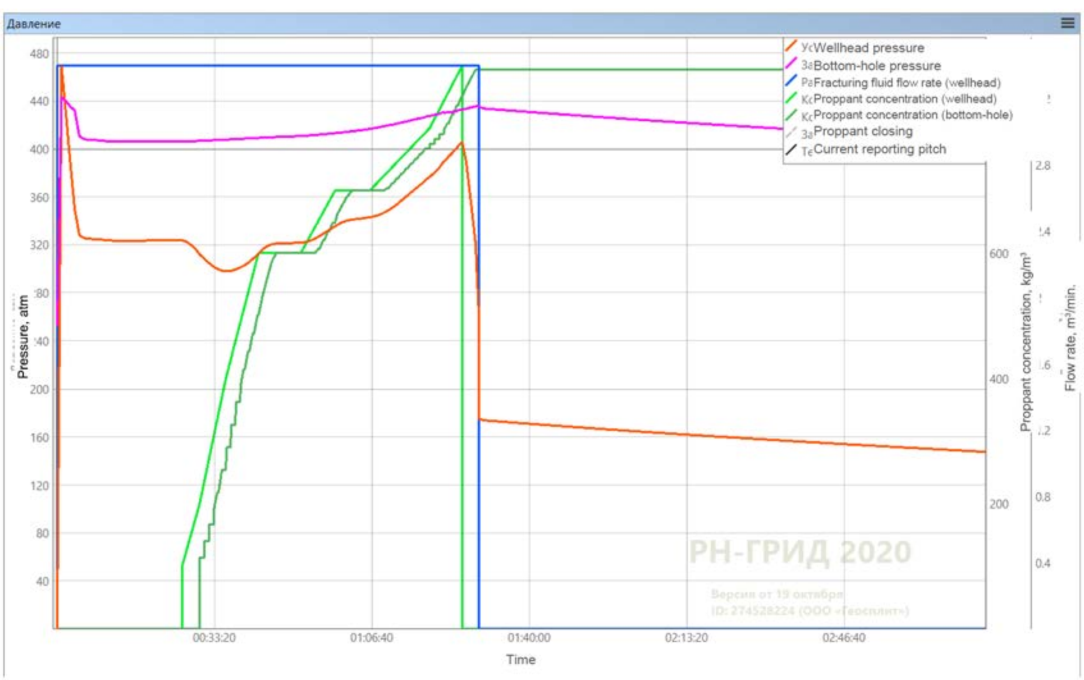


Figure 5—Hydraulic fracturing treatment plan for stages 1 and 10

Figures 6A. and 6B. show the proppant distribution for the frac stages 1 and 10. According to the simulation results, the 20/40 tracer dopped proppant fraction is observed at the periphery of the hydraulic fracture.

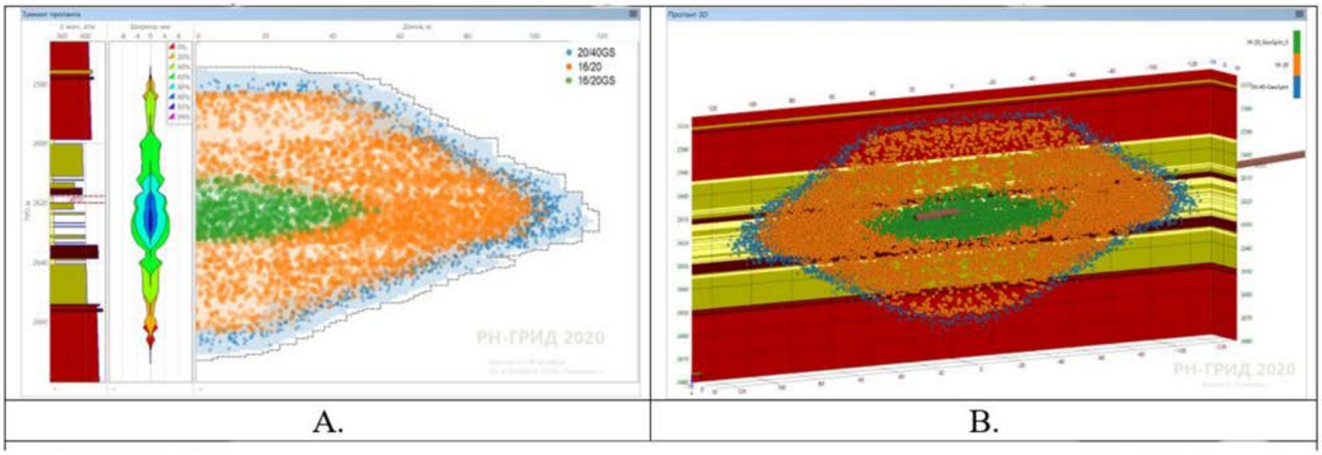


Figure 6—2D (A) and 3D (B) views of the proppant distribution for the frac stages 1 and 10

The tracer dopped proppant injected at the last stage is distributed across the entire bottom-hole zone, thereby ensuring the reliability of the recorded data provided by the chemical tracers that come from the entire hydraulic fracture interval together with the extracted fluid.

Figures 7 and 8 show the distribution of a total quantity of proppant (50—70 tons) for the remaining stages. Just like in stages 1 and 10, the proppant injection at the last stage leads to the overlap of the bottom-hole zone.

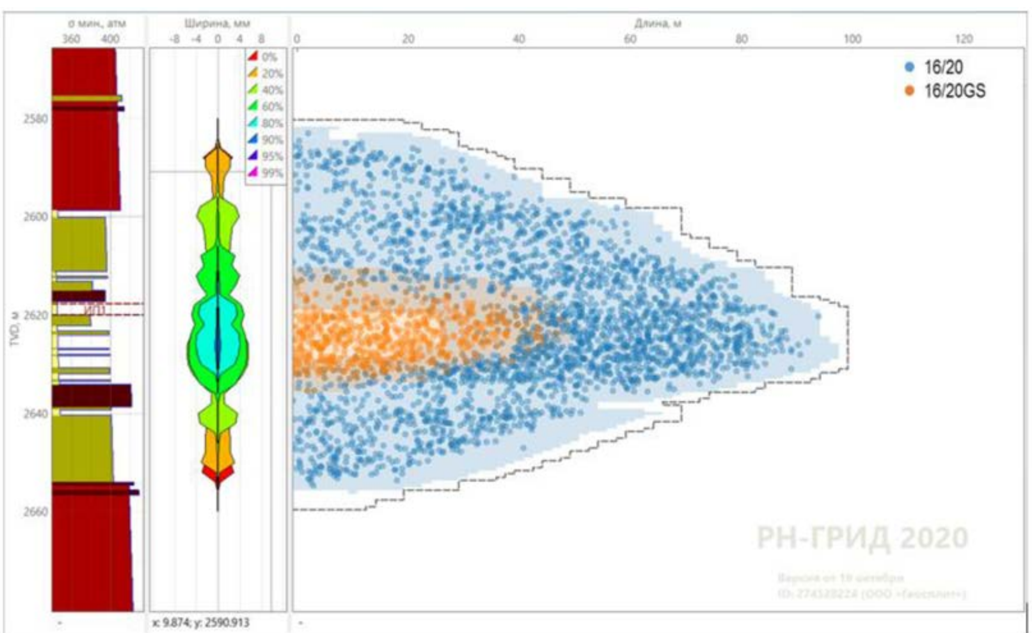


Figure 7—Proppant distribution for the frac stages 2 and 3—9

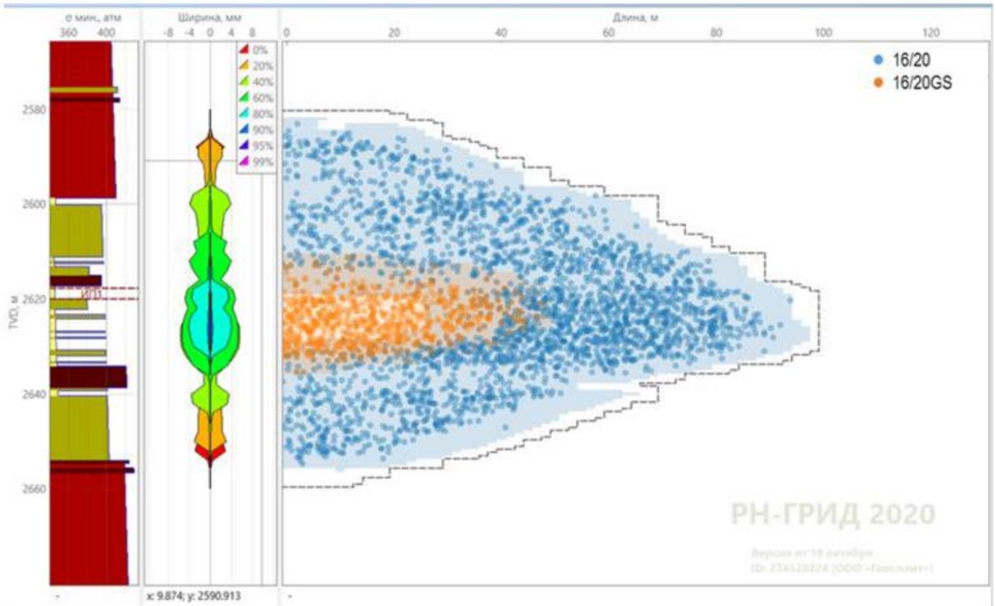


Figure 8—Proppant distribution for the frac stage 3

All hydraulic fracturing operations were performed normally, without any significant difficulties. The planned proppant quantity was injected into the frac stages. There was no breakthrough into upper and lower layers. Figure 9 shows 3D visualization of hydraulic fractures.

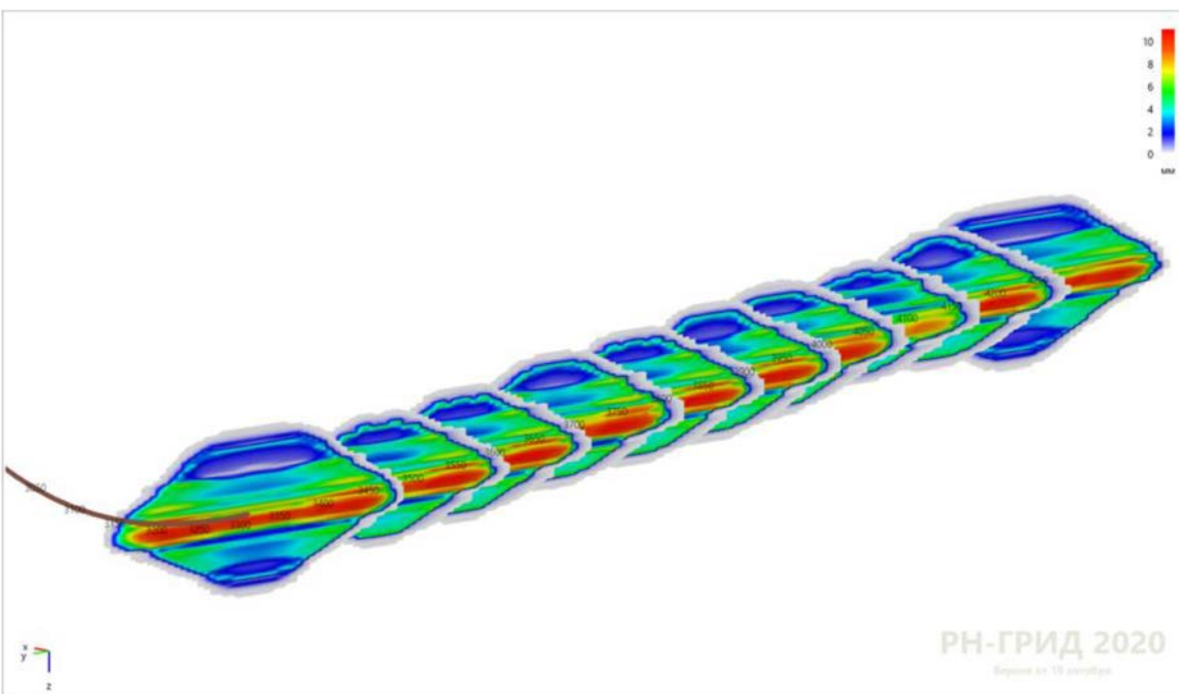


Figure 9—Hydraulic fracture geometry based on the result of actual treatment

Figure 10 shows the numerical design parameters of hydraulic fractures. It is noted that the fractures 1 and 10 are the longest and the highest ones with hydraulic fractures weighing 100 tons. The shortest and the lowest one is fracture 3 since the smallest quantity of proppant was injected there.

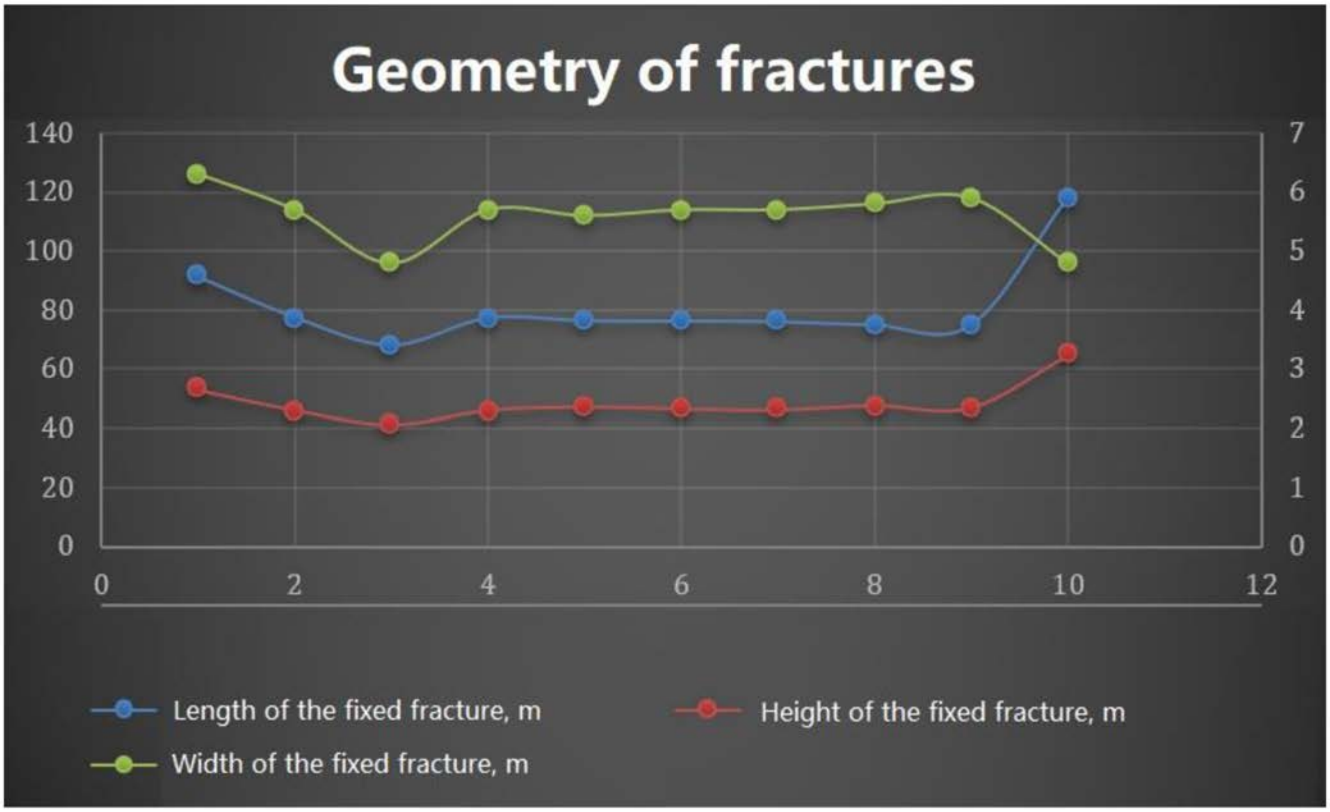


Figure 10—Numerical characteristics of the hydraulic fractures' geometry

Description of the tracer-based production logging technology used in wells with long horizontal laterals penetrating formations with hard-to-recover reserves.

The tracer-based production logging technology used in horizontal wells involves the use of quantum chemical tracers that are high-precision indicators of the reservoir fluid flow [Anopov A., Dulkarnaev M., Guryanov A., Malyavko E., Ovchinnikov K. 2018.]. This technology assumes placing high-precision reservoir fluid tracers into conductive hydraulic fractures (with a half-length up to 600m). Once the multi-stage fracturing is completed and the well is brought into production, reservoir fluid samples are taken at the wellhead and analyzed for the quantitative distribution of each tracer code to reflect how the oil and water flow rates are distributed across the intervals.

Chemical tracers are polymer microspheres made of quantum dots (Figure 11). Various combinations of quantum dots form a tracer code.

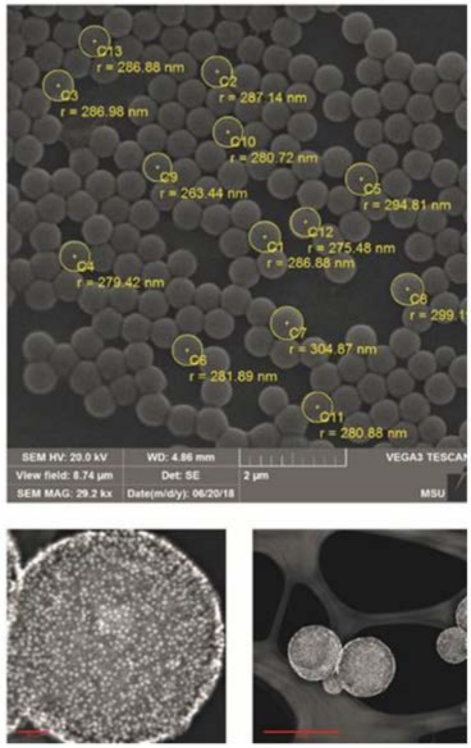


Figure 11—A photo of chemical tracers in the scanning election microscope

Figure 12. A grain of the tracer dopped polymer-coated proppant with quantum chemical tracersSilica-alumina ceramic proppantQuantum tracer dopped polymer- proppantIn tracer-based production logging, tracers are placed in a polymer coating of proppant that is injected into the reservoir during multi-stage hydraulic fracturing [Guryanov A. V., Katashov A. Yu., Ovchinnikov K. N. 2017.]. Figure 12 shows a tracers dopped proppant grain that contains tracers in its polymer coating.

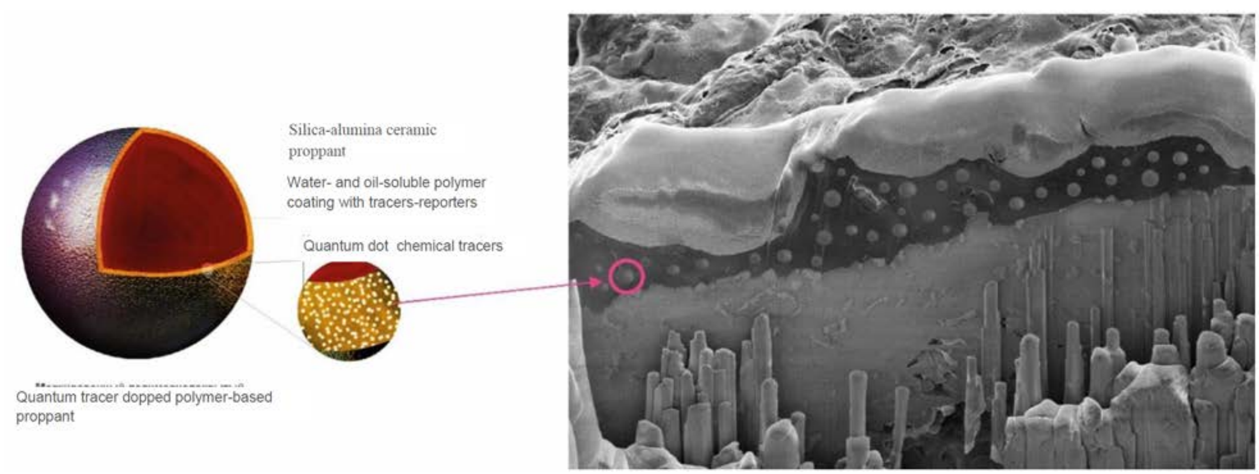


Figure 12—A grain of the tracer dopped polymer-coated proppant with quantum chemical tracers

Proppant with a certain code is pump down into each stage during multi-stage hydraulic fracturing as the last proppant pack to ensure maximum contact when contacting the reservoir fluid coming from the reservoir into the well (Figure 13).

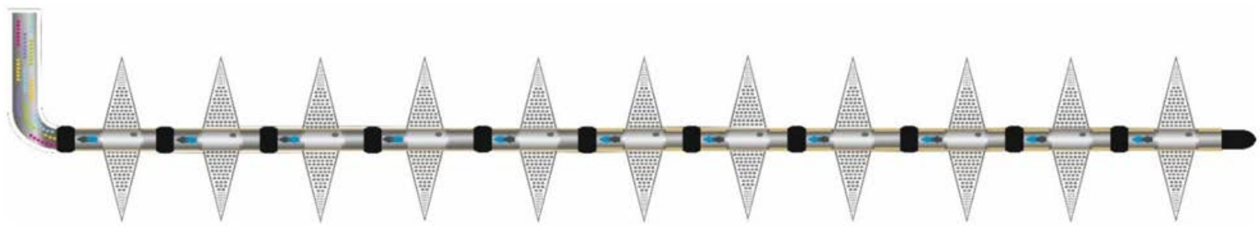


Figure 13—MSHF design with injection of tracer dopped proppant as the last proppant pack

Tracer dopped proppant may have three types of polymer coating: oleophilic, i.e. absorbing oil, and hydrophilic, i.e. absorbing water.

As per the plan, 15 tons of tracer dopped proppant are injected into each frac stage, which is a uniform 50:50 mixture of hydrophilic (targeting the water phase) and oleophilic (targeting the oil phase) proppant.

In the subsequent long period of well operation, the chemical tracers are gradually washed out by water or oil and are carried by the reservoir fluid to the wellhead. Chemical tracers are released into both the HC and water phases of the reservoir fluid.

Upon completing the MSHF operations and bringing the well into production, fluid samples are taken from the wellhead on a regular basis and are further sent to the laboratory for analysis. Water and hydrocarbon phases are separated in the lab during the first stage, i.e. sample preparation, and then each phase is analyzed separately using analytics equipment and software package. During the analysis, a small diameter fluid flow is formed (Figure 14), in which the tracers are lined up in a row and are irradiated with a laser as they flow, which helps identify tracers of each code individually based on the scattered light signal, direct and lateral. Thus, the analysis of the total volume of delivered samples enables identifying the contribution of each port by phase (water and oil) in the total flow rate.

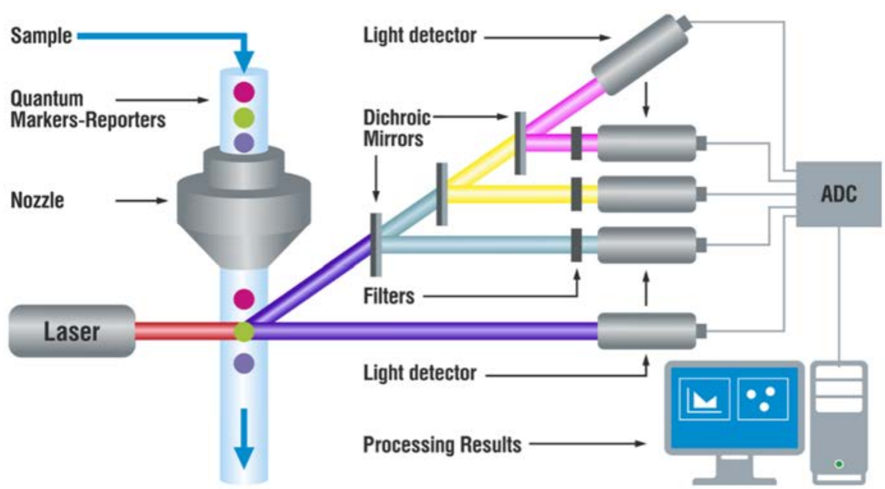


Figure 14—Analytical hardware and software complex for flow cytometry

Machine learning methods, in which learning occurs as a result of analyzing solutions for many similar problems, are among the key elements of the technology. Production logging in horizontal wells involves processing of large amounts of data. For example, the data on the identification of each tracer is a 15-dimensional point cloud, so manual calculations would be very time-consuming. For this reason, tracer-based logging technology is supported by custom-tailored machine learning-based intelligent software using the Random Forest algorithm.

The basic underlying principle can be described as follows: initially, the neural network is trained using reference samples of chemical tracers to build a "decision tree", wherein parameters are sorted at each level (for example, whether the particle emits green light). A huge number of such trees with various structures is created. As a result, a tracer with a specific code passes through this tree and gets into a strictly predetermined "basket". Trained algorithms "know" which "basket" each specific code should get into. Then a mixture of many tracers passes through the entire tree and is sorted, i.e. the algorithm counts the exact number of each tracer code in the mixture (Figure 15).

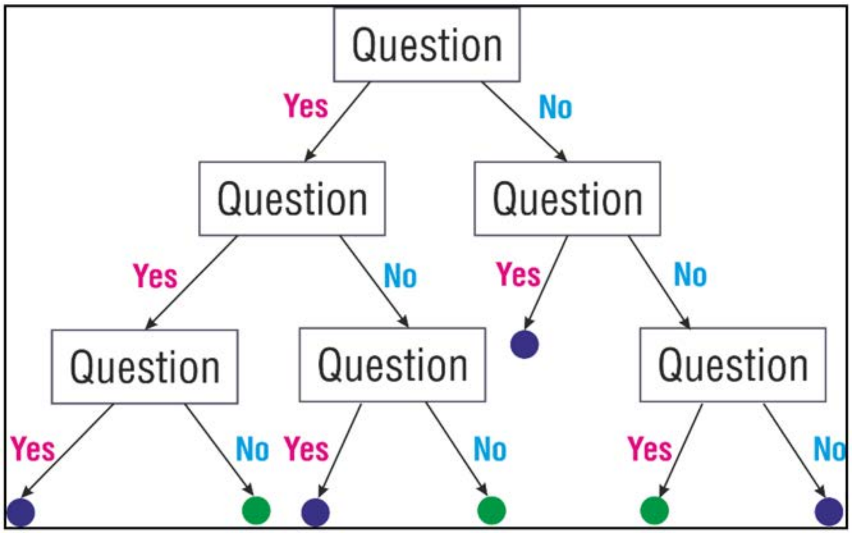


Figure 15—Machine learning and decision tree building algorithm

In general, machine learning algorithms enable processing large data sets with a given accuracy within a short time frame, while avoiding human errors. Thus, this algorithm is a highly accurate and fast method for analyzing incoming samples.

Information about the tracer-based production logging based on the result of the multi-stage hydraulic fracturing

Upon the hydraulic fracturing operation five samples were selected in the period from March to July 2020. A photo of the reservoir fluid samples is shown in Figure 16.

Figure 16—A photo of reservoir fluid samples delivered to the research laboratory

Figure 17 shows the periods when reservoir fluid samples were taken for analysis in the laboratory.

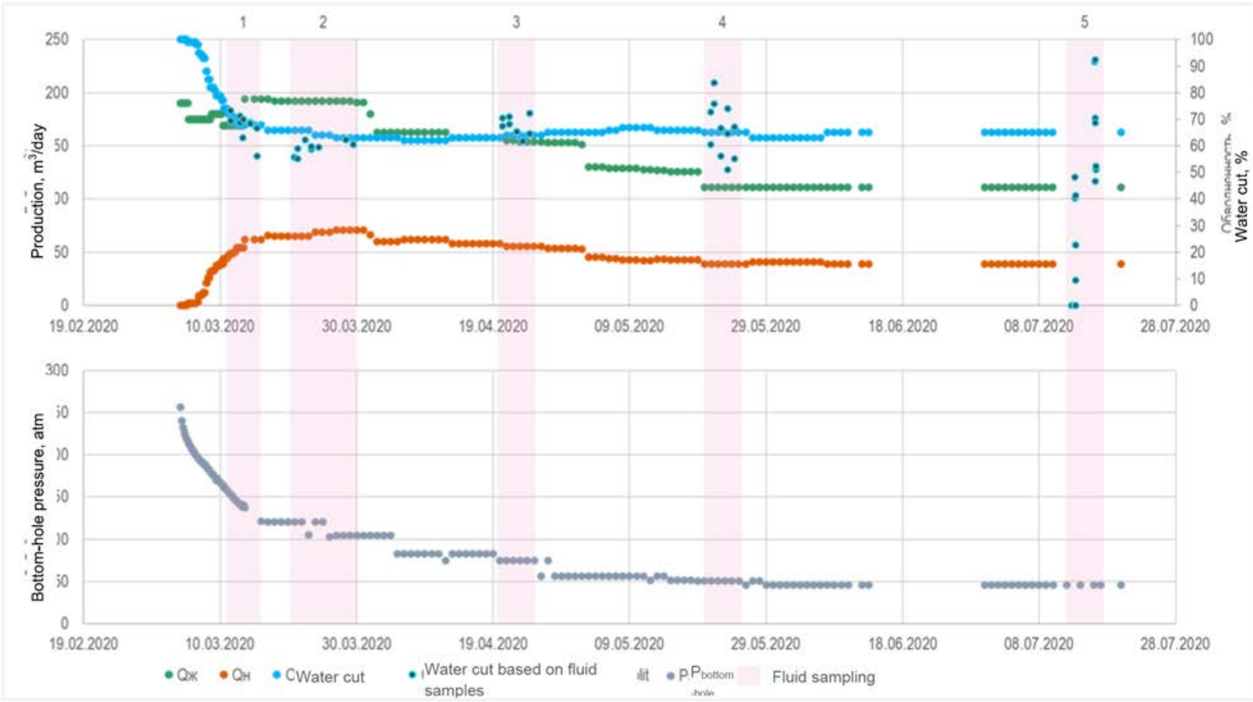
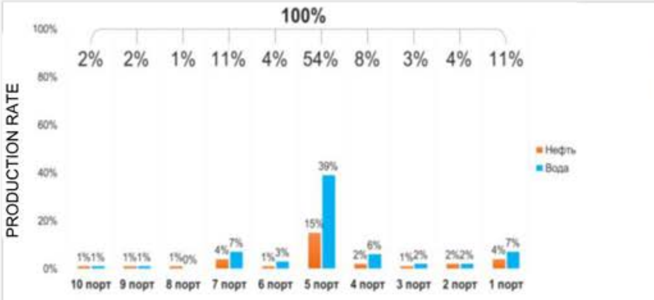


Figure 17—Well A operation record for the period from March to July 2020

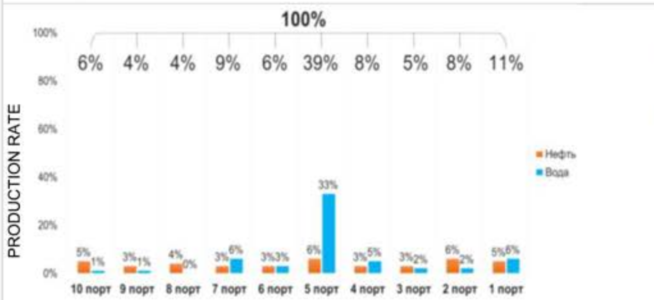
The analysis of the production data on well no. A at Kondinskoye field (Figure 18) revealed the following:

1. Bottom hole pressure decreased by 205.4 atm during the five months of the logging;
2. The water cut of the reservoir fluid decreased from 100% to 63% in the first month as a result of fracturing fluid flowback, and then stabilized at 65%;
3. The fluid flow rate for the first month increased from 169 to 192 m3/day and then decreased to 111 m3/day by the time of the fourth sampling period.

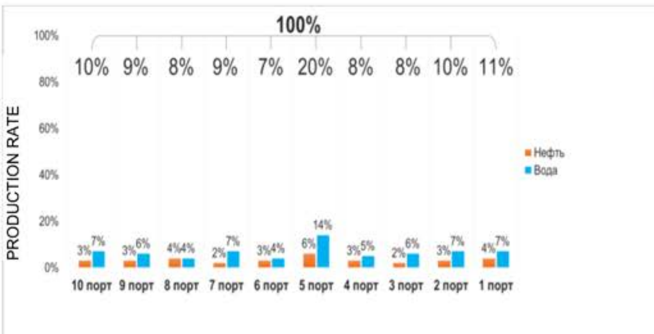
Figure 18 below shows the dynamics of the well's producing intervals for the entire logging period.



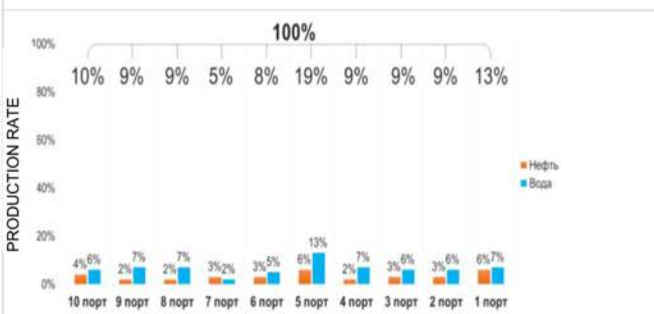
Sampling: March 11—15, 2020
Water cut: 68%
Fluid flow rate: 171.9 m³/day



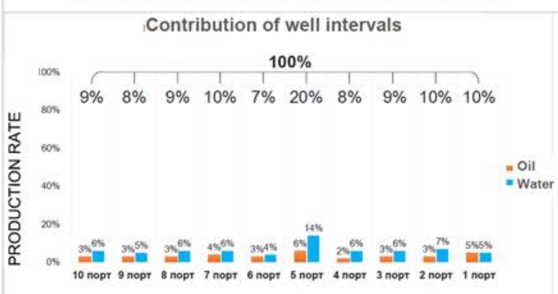
Sampling: March 20—29, 2020
Water cut: 59%
Fluid flow rate: 192 m³/day



Sampling: April 20—24, 2020
Water cut: 67%
Fluid flow rate: 155 m³/day



Sampling: May 20—24, 2020
Water cut: 66%
Fluid flow rate: 111 m³/day



Sampling: July 12—16, 2020
Water cut: 65%
Fluid flow rate: 111 m³/day

Figure 18—Dynamics of MSHF ports' production from March 11 to July 16, 2020

The analysis showed that production in port 5 significantly prevailed in comparison with other ports. According to frac report the proppant spill in the interval of the port 5 was detected during the RIH/POOH operations resulting in the release of an excessive amount of chemical tracers due to the flows from the ports 1—4 and the tracers coming from the 5th port. As the boreholes' bottom zone was cleaned later, the contribution of port 5 decreased by 34% and, as a result, the production profile smoothed. The well under study has a non-uniform production profile in the first period of sampling due to the well's transition to steady-state operation, and staring from the second period of sampling, uniform and constant production has been observed in each multi-stage frac interval.

In addition, there is a good correlation between the borehole trajectory and the production profile. Thus, as shown in Figure 18, all fractures are evenly distributed across the reservoir, which is confirmed by the results of tracer-based monitoring both qualitatively and quantitatively.

Water content in the reservoir fluid remains stable during the entire logging period, ranging from 62 to 66% after the well's transition to steady-state operation.

Figure 19 shows a graph of cumulative oil production by ports. As is clear from the graph, the largest contribution comes from the central part of the horizontal lateral (**port 5**), where cumulative production for the entire well operation period (from the start-up to July 20, 2020) slightly exceeded 5,000 m³.

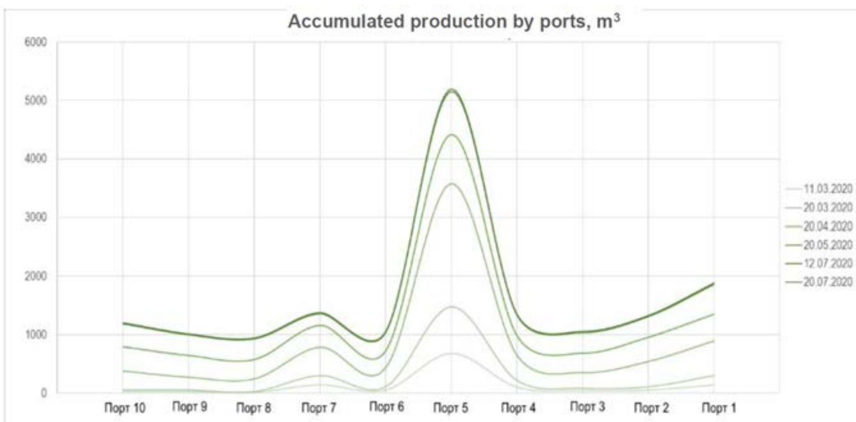


Figure 19—Cumulative fluid production for each port of well no. A

Figures 20 and 21 show the comparative dynamics of the contributions of near and far zones for frac ports 1 and 10, respectively. See Figure 22 for the boundaries of the proppant distribution areas in the hydraulic fracture.

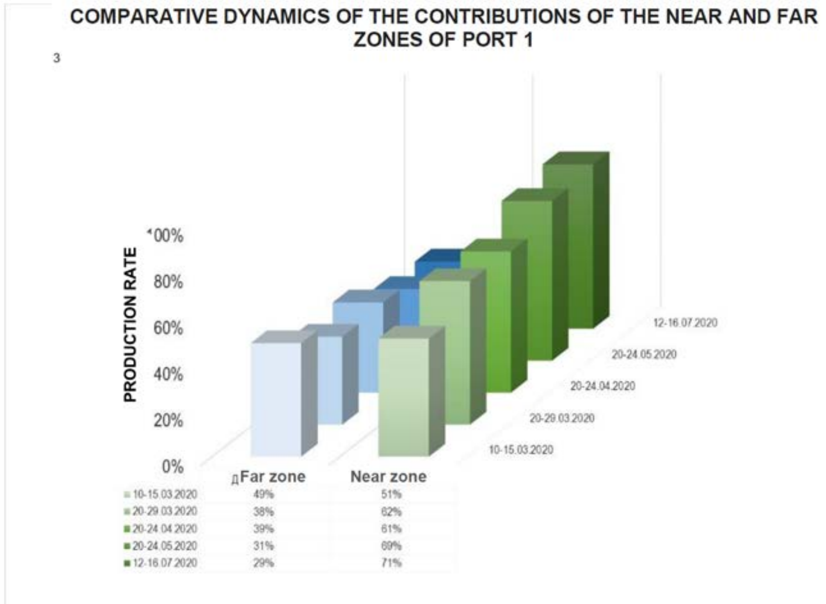


Figure 20—Comparative dynamics of the contributions of the near and far zones for port 1 from March 11 to July 17, 2020

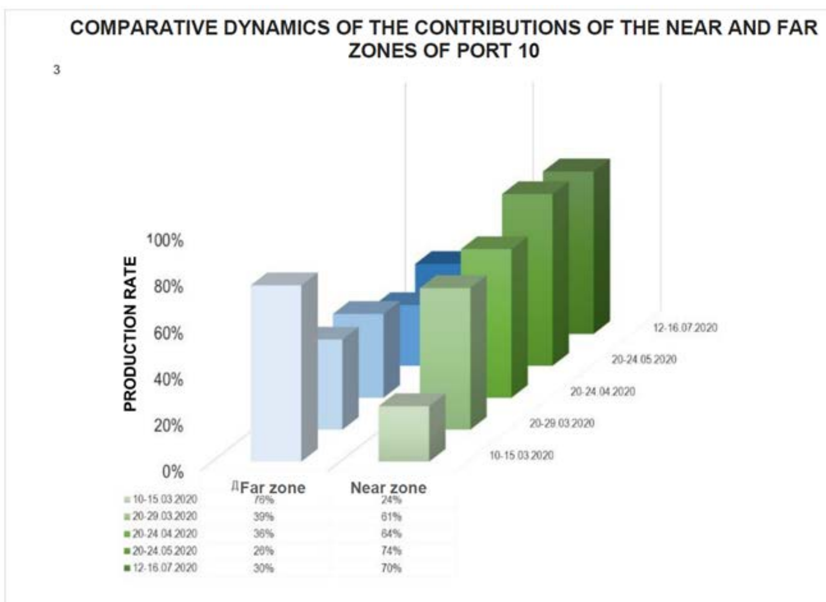


Figure 21—Comparative dynamics of the contributions of the near and far zones for port 10 from March 11 to July 17, 2020

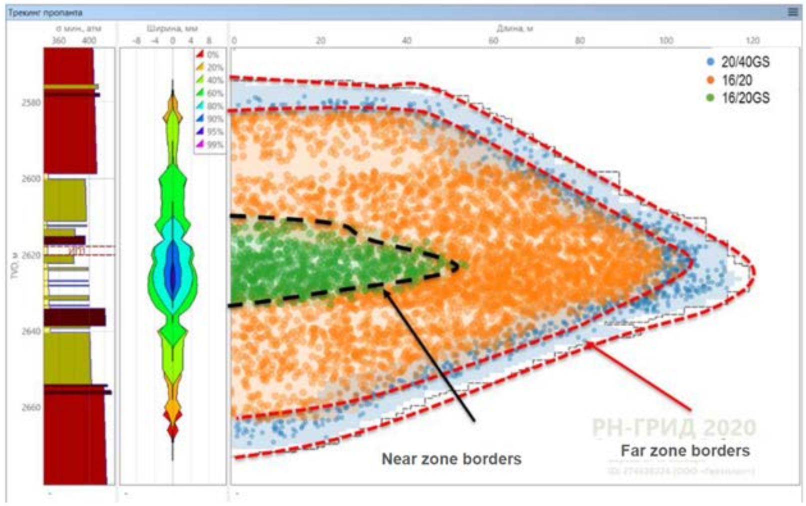


Figure 22—Comparative dynamics of the contributions of the near and far zones for port 10 from March 11 to July 17, 2020

As seen in Figure 20, the contribution of the near zone of port 1 to the entire well production increased by 20% during the logging period. In addition, Figure 21 shows that the performance of the near zone of port 10 improved a lot (the contribution increased by 46 %).

Production profiling in the near and far zones in fractures 1 and 10 reveals that the contribution of the near zones is growing over time compared to the far zones. The production in the far zone prevailed in the first period of sampling, perhaps as a consequence of the mechanical destruction of some proppant during hydraulic fracturing. However, during the second period of sampling, redistribution within the production profile occurred with the near zones becoming the major contributors in both port 1 and port 10, which is evidenced by the analyses of the subsequent reservoir fluid samples.

Thus, it is safe to say that the proppant in the far zone covers most of the treated formation and contributes to the production of the hydraulic fracture.

Conclusions

Application of tracers dopped proppant is the alternative to traditional production logging methods. In contrast to conventional PLT for horizontal wells, the technology of tracer-based production logging did not require any special means of conveying tools and was not associated with the risks of equipment getting stuck downhole or ambiguity in the interpretation of the results obtained.

Tracers dopped proppant was used in production profile surveillance at the well A of the Kondinskoye field with continuously for five months. Based on the results obtained, the dynamics of performance of the producing frac ports was evaluated. It has been revealed that the production is uniformly distributed across the ports of each well, which indicates the uniform distribution of the proppant in the hydraulic fractures for each stage.

In addition to the above, the performance of the far and near zones was analyzed during a long period of time yielding the results that can be further used for optimizing the MSHF design to create hydraulic fractures with a greater half-length and thus improve the well's production after hydraulic fracturing.

However, there is a risk of mechanical destruction of some part of tracers dopped proppant during its injection into the far fracture zone. Therefore, data analysis of different fracture zones performance should be considered not earlier than one month of well production.

The technology has several advantages, but its successful application is concerned with a range of factors:

- application of resin-coated proppant at the last stage of injection or overdisplacement the tracers dopped proppant by approximately 5 tons of a regular proppant type to minimize risks of proppant fallout;
- formation fluid sampling should be conducted under supervision of specialists implementing this certain technology.

Due to lack of statistical data of current study in the PJSC Rosneft Oil Company, it is recommended to proceed with this technology application in several other wells considering the recommendations made. Assessing the reserve recovery based on the accumulated average daily production data for all ports may become a promising trend of applying the results of this work.

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