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Estimation of the Largest Russian Oil Field Development Efficiency Using the Combination of Hydrodynamic Modeling and Horizontal Well Production Logging Methods Using Markers

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Abstract

Increasing the pace of oil production to achieve profitability in projects has increased significantly with the transition to the active development of deposits with low-permeable reservoirs throughout the West Siberian oil and gas province. The key to increasing production rates for objects with degraded reservoir properties is to increase the technical and technological effectiveness of the applied solutions. The purpose of the article is to evaluate the project using data obtained by the new, innovative tracer-based methods and contemporary types of well completion in well testing to increase the drainage area, flow rate and improve the operational parameters of the pressure maintenance system.

Greater reservoir filtration areas in reservoirs with abnormally low permeability is achieved by using horizontal drilling and fracturing. Modern modeling tools allow for the consideration of uneven development of the horizontal shaft length. Conventional logging methods cannot provide detailed information during the operation of hydraulic fracturing stages, but marker-based methods present a proper production logging alternative, especially given their widespread development in recent years. Using the data of marker diagnostics, it is possible to adapt hydrodynamic models to specify the hydrocarbon production profiles.

The present article brings to your attention sector hydrodynamic model (HDM) calculations that take into account the uneven development of depleting reserves based on marker diagnostics data. A comparison was made with HDM under the assumption of a uniform inflow into horizontal well with MFrac. The model showed several levels of inflow variability obtained through statistical data on the marker production logging of 60 wells performed at various fields.

Introduction

In recent years, several horizontal wells were monitored using marker diagnostics methods that complement and, in some cases, replace conventional studies of horizontal well inflow profiles. These tools are lowered into the well using flexible tubing systems or tractors. The fundamental difference between marker technologies and traditional well logging methods is the ability to monitor well ports over a long period of time, thereby significantly reducing the required resources and costs while improving production safety. Due to the technical difficulties and high cost associated with downhole operations for building inflow profiles, an extremely small number of wells are actually investigated. For example, the highest number is the Salym field, where studies are conducted in 20-25% of horizontal wells. As a rule, this parameter is much lower for onshore reserves. Tracer-based or indicator methods of analysis have been recognized throughout the oil and gas industry for several decades; however, these methods have been used exclusively for cross-well studies for analyzing the filtration non-uniformity of the inter-well space. Conventional tracer-based technologies that use chemicals (uranin, rhodomin or eosin) or natural fluorophores for a variety of reasons do not allow for quantitative analysis and are limited by qualitative assessments. In recent years, a new generation of materials and technologies has appeared on the market, allowing users to realize and experience the potential of tracer-based technologies for increasing field development efficiency.

Solution of applied problems in the development of the largest Russian oil field using hydro-dynamic modeling based on marker production logging

The field is characterized by a complex structure of productive horizons with three layers of a particular interest; two of them being medium and low productive, one – anomalously low productive.

Field development is impossible without an active impact on its productive strata. One potential method to solve this problem is by the implementation of measures to intensify oil production. Multi-stage hydraulic fracturing (horizontal fracturing) in horizontal wells (HW) is one of the most effective methods for intensifying oil production from low-permeable formations and increasing the oil reserve's production.

This field has already accumulated considerable experience in multi-stage hydraulic fracturing. The analysis of multiple hydraulic fracturing performed at the field indicates the high efficiency of this type of production enhancement for the field. At the end of 2017, additional oil production by way of hydraulic fracturing accounted for more than 50% of the total oil production for the year. In this condition, hydraulic fracturing is not only a method for intensifying production, but also enhancing oil recovery. First, the multi-stage hydraulic fracturing system allows for connecting non-drained oil reserves in intermittent reservoir fields. Second, this type of impact enables the selection of an additional amount of oil from the low-permeable reservoir for an acceptable time of field operation.

A sector hydrodynamic model of the field was selected to demonstrate the effect of reducing the development efficiency in the absence of dynamic information on the qualitative and quantitative contribution of hydraulic fracturing to the total flow rate. The developed object is characterized by low a permeability of 0.2–0.3 mD, low effective oil-saturated thickness 10–15 m, the presence of a transition zone and an initial water-cut of 40–60%. The site is scheduled for drilling in 2019-2020 through the horizontal well with the length 1000 m and an 8-stage hydraulic fracturing. The hydraulic fracture half-length is assumed to be 100 m in the calculation, and the distance between the wells is 250 m.

A critical factor for this study is the economic profitability of the development. In the optimal location of the wells, the yield index slightly exceeds 1, provided that all the fractures are operating. Therefore, in this case, the share of operating ports is an important factor that affects the profitability of the whole project. Is it then correct to base calculations on the assumption that 100% of the ports are operating?

The hydro-dynamic model was designed with a crosshole distance of 250 m. In real economic conditions, this option turned out to be unprofitable, but a high oil recovery factor is achieved through this method in the depletion mode, as this configuration ensures good contact of the wells with the formation on the site. Water flooding is not recommended in this case due to the risks of water breakthrough through the fractures and the low efficiency of water flooding in low-permeable clay reservoirs observed in the areas neighboring areas the field. With the flooding of low-permeable reservoirs, problems arise with the injectivity of injection wells, presumably associated with a complex of factors: migration and swelling of clay particles in the formation, contamination of the bottomhole zone with injected water, and loss of paraffins from the oil during cooling of the formation. Production scenarios depending on the number of working ports in the horizontal well and calculation of cumulative production based on these scenarios are presented in Figures 1 and 2 correspondingly.

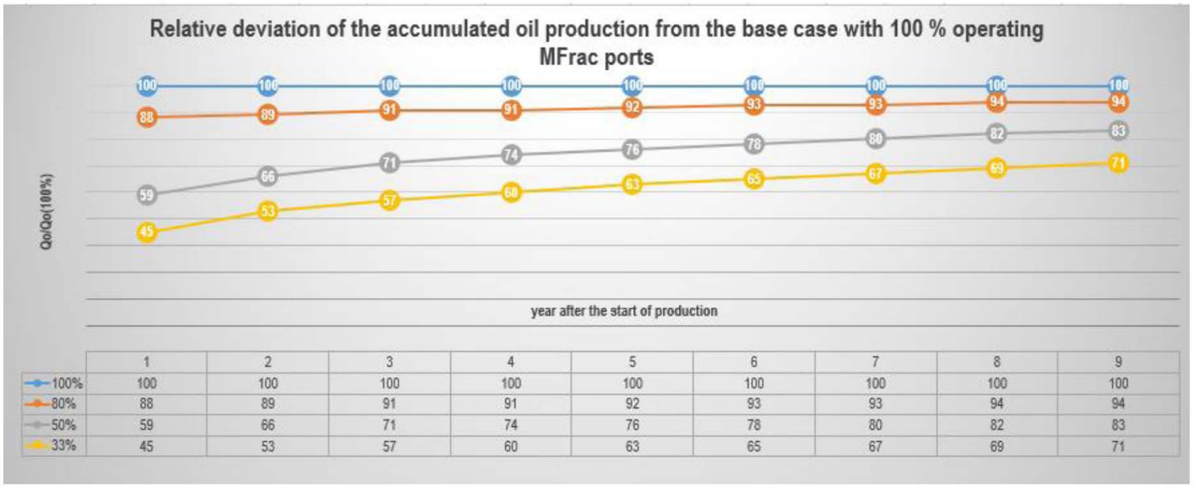

Figure 1—Production scenarios depending on the number of working ports in the horizontal well

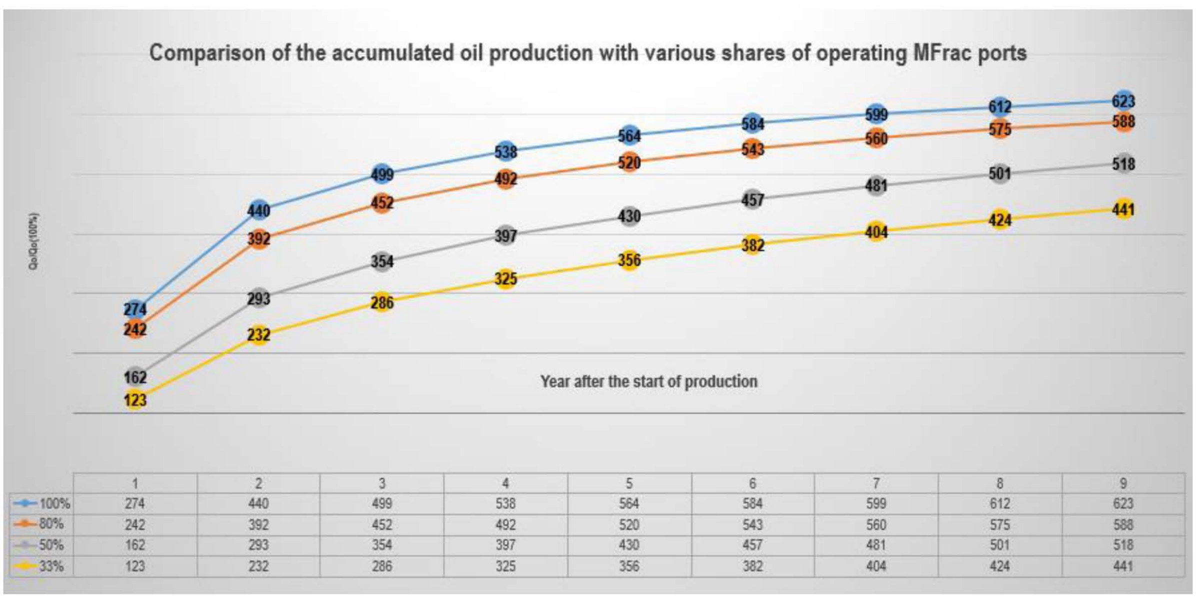

Figure 2—Calculation of cumulative production based on scenarios

Hydrodynamic Modeling

Reservoir modeling is a powerful, effective reservoir management method. It allows for understanding the geology and predicting its behavior under different development scenarios. Prediction of reservoir behavior can be used to solve problems related to planning, operation and diagnostics at all stages of field development. Static and dynamic models are distinguished among digital reservoir models. In static models, parameters and properties do not change over time; geological models are referred to this type of model. In comparison, a dynamic model's properties depend on time, and hydrodynamic (filtration) models are among them.

The main purpose of the field geological model is to establish a basis for further fluid flow modeling. Uncertainty in geological model construction remains at all stages of the field monitoring. Direct information on the formation structure and properties can only be obtained by analyzing well data such as analysis of the core. However, such studies only cover a very small part of the reservoir. Before starting the construction of any model, the collection and preparation of initial data, including the analysis of their quality, should be conducted. To build a dynamic model, the following initial data of the well test are required: field geophysical studies and multiple formation tests to obtain information on permeability, the presence of barriers, hydrodynamic connectedness of sand bodies, fluid type, reservoir pressure, the release of working intervals, and the position of oil-water and gas-oil contacts. An important factor is the development record that indicates the formation behavior, pressure change, material balance, production profile, water content and gas factor. Fluid samples are undoubtedly important for obtaining PVT data.

Due to the depletion of readily available reserves in oil production, the current focus is increasingly shifting to unconventional energy resources: shale gas or oil, high-viscosity oil or natural bitumen deposits. At the same time, today there is a considerable reserve for maintaining and increasing production at the developed areas and even in wells that have already been drilled, which does not require significant changes in the development technology.

With the advent of new horizontal drilling technologies and multiple hydraulic fracturing, new, impeding challenges have emerged. Related to development control, a horizontal well is a complex object to study. Even in the classical conditions of a vertical well, the possibilities of conventional well logging are limited by a number of factors. During conventional PLT logging attempts in horizontal wells, several new problems are added to the noted problems. Low multi-phase inflow is not sufficient to overcome the sensitivity threshold of the turbines of mechanical flow meters. Multiple cases of damage or blocking of the impellers have been recorded during the inspection of the production logging tool on the surface after a downhole operation. In case of incomplete removal and accumulation of heavy phase in the trunk, the methods for assessing the liquid composition do not reflect the distribution of the components in the inflow but rather reflect their current content in the column. With a complex structure of multiphase flow, the indicators of the methods depend on the position of the sensors in the barrel, the slope of the barrel, etc. A layer-by-layer flow of phases with different speeds is observed. In the bends of a non-uniform well profile, stagnant water zones or gas plugs are formed. When lowering the non-cemented filter into the barrel, part of the flow moves through the annular space and does not affect the sensor indicators. The influx can occur with the same probability along the entire length of the trunk, complicating the differentiation of working intervals and so on. The main disadvantage of conventional logging is that is only allows data to be obtained within a brief time slot of several hours during the downhole operation. This does not allow for monitoring the intervals dynamics or hydraulic fracturing stages, and also does not allow for an evaluation of the influence of many factors, including the change in depression and ESP operating mode, water breakthroughs from the formation pressure maintenance system and fractures in the bottom hole area.

In addition to obtaining a profitable flow rate, one of the major tasks is to increase the oil recovery rate, which is not always possible even with the application of multi-stage hydraulic fracturing. Several horizontal well studies with MFrac using conventional logging tools and coiled tubing indicate an uneven inflow along the well length or in the hydraulic fracturing ports. This has a very detrimental effect on the oil recovery rate, as there are unexplored zones that remain "invisible" in the hydrodynamic model, the construction of which assumes uniform inflow in a horizontal well. Well water breakthrough is also common in cases of oil-water contact along one or several ports.

Hydrodynamic Modeling Based on Marker Production Logging Data

The hydrodynamic model included the calculation of four options with different fractions of hydraulic fractures operating at the site: 100%, 80%, 66% and 33%. Hydraulic fractures in the model were disconnected at random with an appropriate probability. Out of more than 200 hydraulic fractures in the model with 100% successful hydraulic fracturing results, the worst model, with a 30% success rate, contained less than 70 operating hydraulic fractures.

Calculations were conducted without restrictions on the economically viable debit for the period of 30 years. The low permeability of the formation leads to a characteristic rapid fall in production during the first year of operation. This decline in oil production in the first year averages 70% from the initial levels. The average oil production rate of wells in the area over 10 years of development is reduced to about 1 ton / day, which is often taken as the economic limit of well profitability. Graphs shown in Figure 3 display significant decline in oil production through the first 3-5 years. Cumulative production losses relative to the base case with 100% of the operating ports of hydraulic fracturing can exceed 50% in the case of 1/3 of the working fractures.

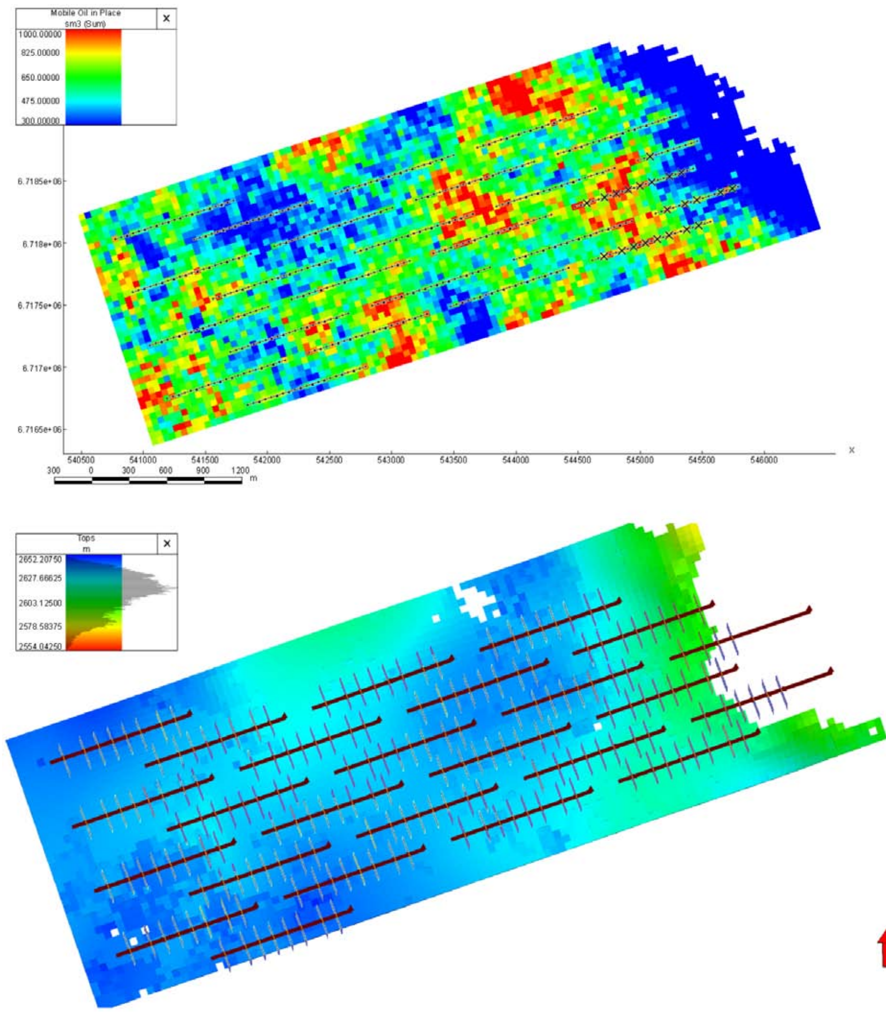

Figure 3—Calculation of the option with 100% working fractures in the program T Navigator

Due to hydraulic fractures interference, there is a nonlinear dependence of the oil production decline on the proportion of operating ports. In the long term of 10 years of development, the estimated difference in cumulative oil production between the options decreases. During the first 2-3 years, the difference between the options with different fractions of hydraulic fractures operating is maximized. However, from an economic point of view, the net present value of the project is determined primarily by 3-5 year periods. Moreover, the model does not consider the effect of reducing the proppant conductivity over time due to various factors (leaching, crushing of proppant, indentation into formation, etc.), which also leads to a decrease in well production in the long term. Therefore, monitoring the operation of ports in wells is most important in the early years of development. Timely detection of broken hydraulic fractures will enable effective decision-making for maintaining or increasing the coverage area of the developed object.

The difference in discounted cumulative production between the scenario with 100% hydraulic fracturing ports and the scenario with half non-working ports in the studied hydraulic modeling sector is impressive – more than 94 thousand tons, corresponding to nearly 1 billion rubles. When using netback, this amounts to 12,500 rubles / ton. The immense amount of lost profit makes it feasible to use methods for identifying inactive and flooded ports of multi-stage hydraulic fractures, even at the stage of drilling and conducting multi-stage hydraulic fracturing, setting the construction potential of carrying out geological and engineering operations to put non-operational ports into operation, to isolate the flooded ports, etc. Calculation of the option with 100% working fractures in the program T Navigator is presented in Figure 3.

Calculation of the option with 33% of the working fractures in the program T Navigator is shown in Figure 4.

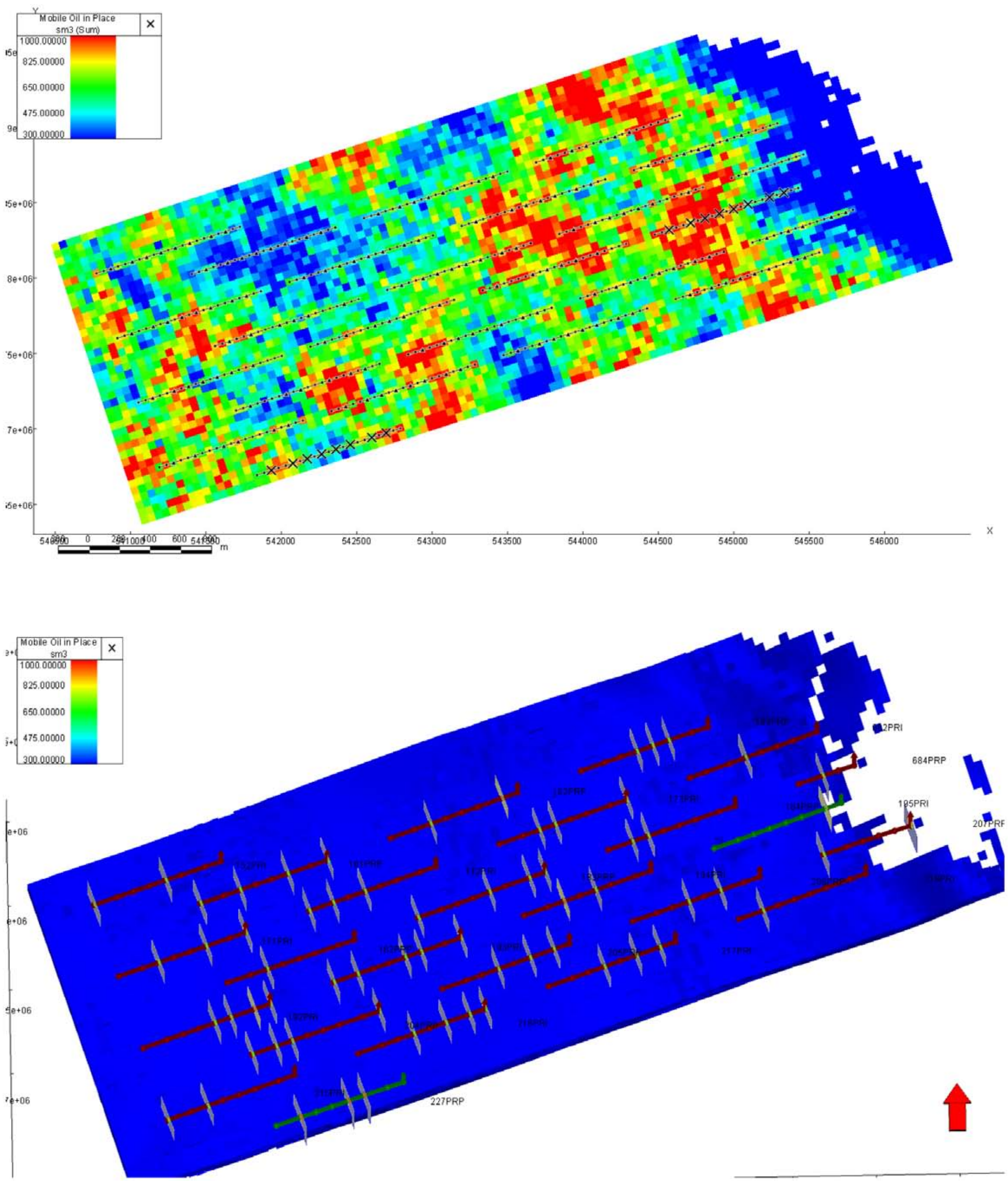

Figure 4—Calculation of the option with 33% of the working fractures in the program T Navigator

Description of a Marker Production Logging Method for Identifying the Operating Multi-stage Hydraulic Fracturing Ports

One of these methods is the technology of marker-reporters made from quantum dots and stabilized by a polymer shell. Quantum dots are nanocrystals that are 1-2 nanometers in size, obtained by colloidal synthesis and coated with a layer of adsorbed surface-active molecules. Quantum dots obtained by the method of colloid synthesis based on cadmium chalcogenides fluoresce in different regions of the electromagnetic spectrum, depending on their size. Marker-reporters created from quantum dots have the unique ability to absorb energy in a wide range of the spectrum and emit a narrow spectrum of light waves, which can be recorded using flow cytometry. Compared with the organic fluorophore dyes that are also used for tracing purposes in the oil industry, quantum dots are more chemically stable and have a fluorescence intensity several orders of magnitude higher.

The use of quantum dots in tracer-based technology is due to the large number of possible combinations, called signatures, in the marker-reporters synthesis (more than 60). Each stage or interval uses its own unique signature of the hydrocarbon and water formation fluid phases (Gurianov, Gazizov, Medvedev, Ovchinnikov, 2019).

Different types and combinations of marker-reporters with a size of 0.2-0.4 microns are introduced into the polymer coating of the proppant for multi-stage hydraulic fracturing or composite polymer for downhole cassettes. The polymer coating is gradually destroyed through contact with oil and water. The general scheme of marker horizontal well production logging is presented in Figure 5.

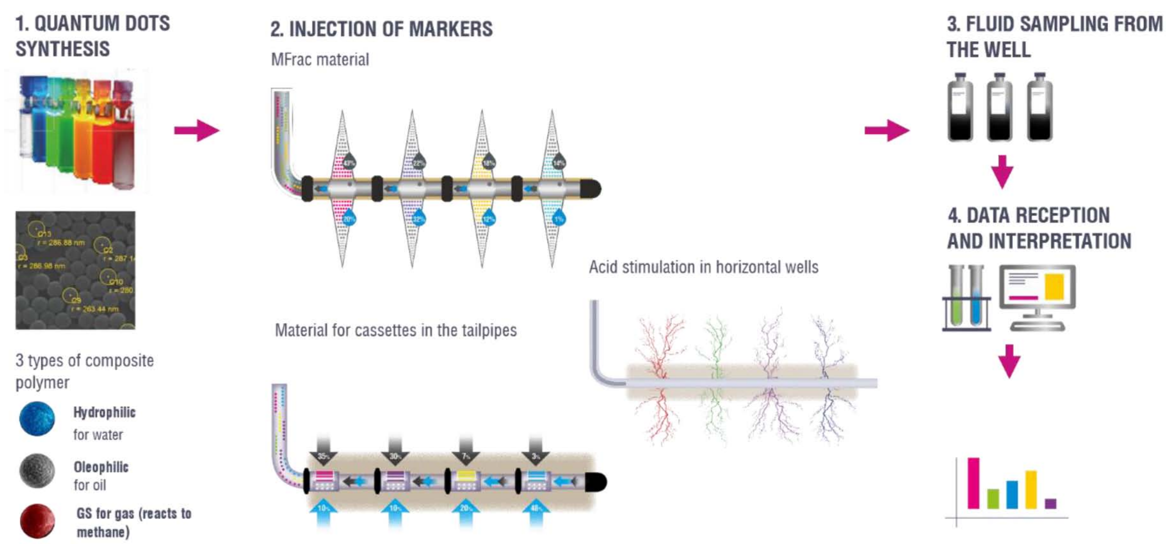

Figure 5—Scheme of marker horizontal well production logging

During the operation, marker-reporters are washed out with the formation fluid over a long period of time. During sampling from the wellhead and subsequent laboratory tests, the GEOSPLIT analytical hardware-software complex determines the concentration of markers corresponding to each code (Figure 6), which allows for an estimation of the quantitative distribution of oil and water phases for each horizontal well interval.

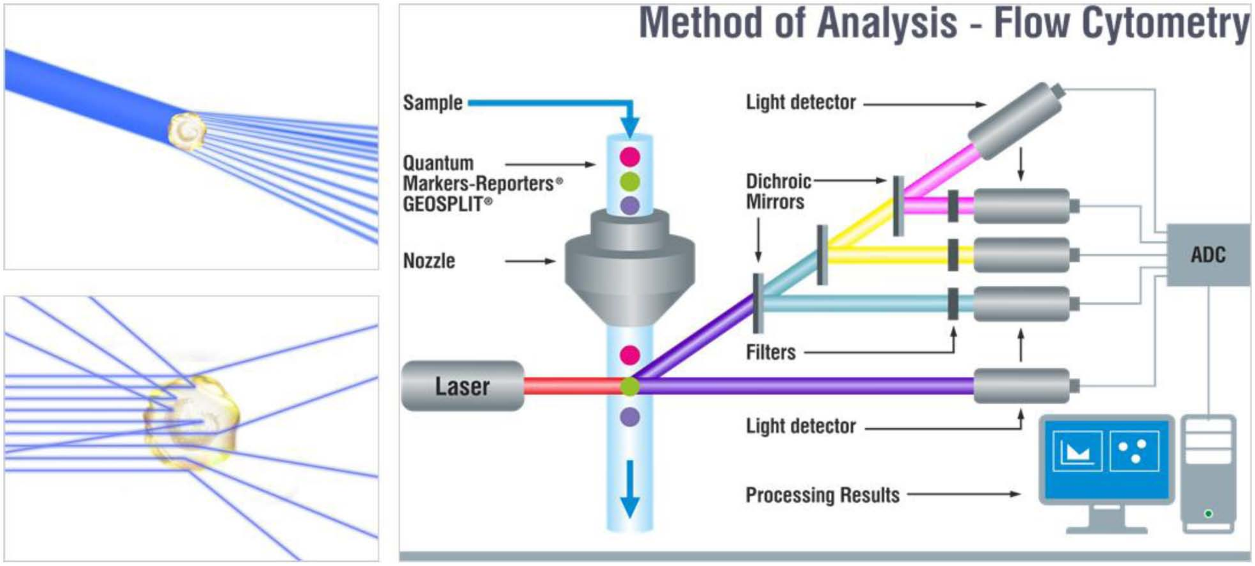

Figure 6—Scheme of the marker-reporters quantitative identification method with direct and side light scattering from a marker-reporter.

As shown in the images, each marker-reporter represents a point in the 15-dimensional space of coordinates, reacting to laser irradiation with manifestation in different wavelengths. Manually processing data on the quantitative determination of marker-reporters using only a hardware-software complex does not allow for an acceptable accuracy of determination. With a massive number of signals and a large number of signatures in the analyzed fluid sample, the task of quantifying and counting markers becomes difficult and time consuming. In addition, it is nearly impossible to completely eliminate human errors.

The developers of the marker technology proposed an innovative data processing approach based on artificial intelligence. The program created by the developers of marker technology is based on machine-learning using the "Random Forest" algorithm. Simply speaking, the principle of this operation can be described as follows: initially, the neural network is trained on "referee" samples of marker-reporters. From this, the so-called "decision tree" is built, where at each depth stage the parameters are sorted by a certain parameter such as whether a particle is excited in a certain range of the electromagnetic spectrum or not. The depth of the "tree" may be different each time. The software creates an expansive variety of "trees" that all differ in structure. As a result, when passing through such a tree, the marker of the desired code falls into a strictly defined "basket". The trained algorithms understand which basket each particular marker code should fall into. Then a mixture of a large number of markers is examined on the created tree and sorted, i.e. the algorithm considers the number and type of markers in the mixture. Each tree makes its decision, or conditionally speaking, "votes" on the composition of the mixture. The use of formation fluid for training precisely from those proppants that were injected into the well allows a high accuracy to be achieved in data interpretation. In general, machine learning algorithms allow for processing a large array of data with a given accuracy in a short time frame and eliminate the "human factor".

The scheme of the "Random Forest" algorithm application and the schematic image of marker-reporters' identification using the hardware-software complex and the software with machine-learning are presented in Figure 7 and Figure 8 correspondingly.

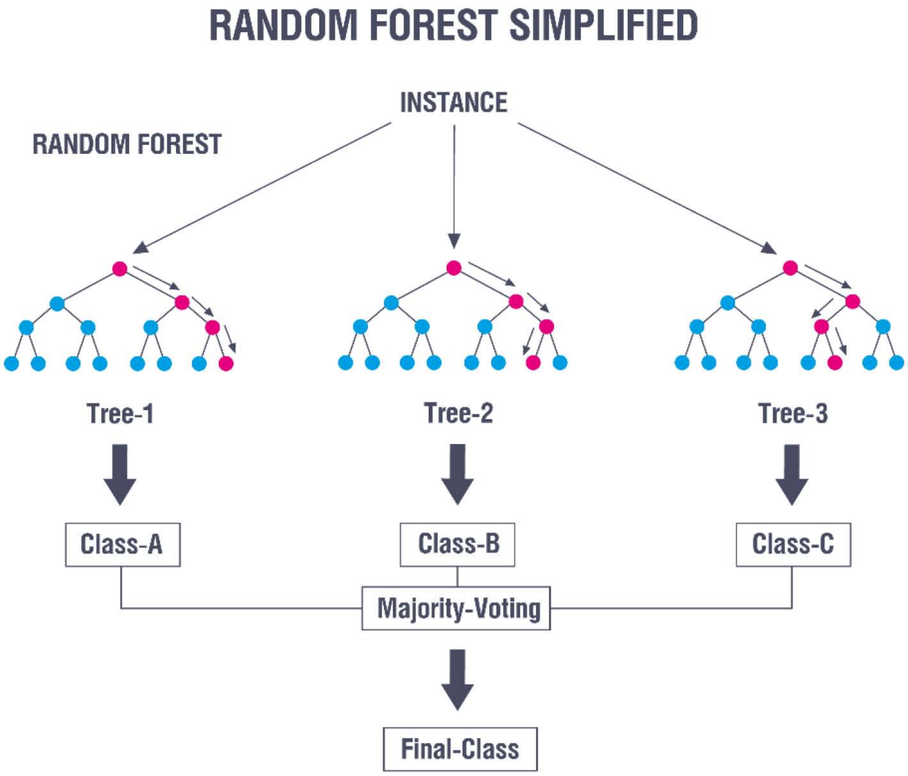

Figure 7—Scheme of the Random Forest Algorithm Application

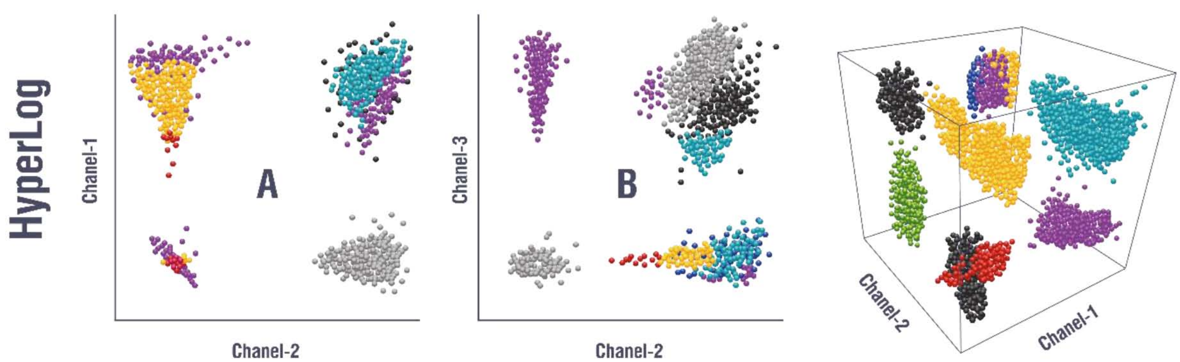

Figure 8—Schematic image of marker-reporters' identification using the hardware-software complex and the software with machine learning

There are several advantages to using quantum marker-reporters:

1. Monodispersity of markers in size

   The lack of the tracers' monodispersity causes significant errors that inhibit reliable quantitative analysis, as particles of different sizes have different sedimentation rates and, as a result, different relative flow rates in the well. Particles that are smaller in size will be carried away by the fluid flow faster than larger particles. In addition, particles of different sizes are distinguished by their ability to move with the formation fluid in the reservoir (Figure 9).
2. Automatic marker identification in formation fluid samples

   The identification of markers is carried out using the automated hardware-software complex in the mode of the item-by-item analysis without using microscopes. During the sample analysis, a strict number of marker-reporters are identified in each sample, thus ensuring accurate tests and eliminating errors associated with the human factor.

3. Uniform release of markers over an extended period of time.
   Marker-reporters injected into the proppant polymer matrix or granulated composite polymer for downhole cassettes ensure the stability of their release from the polymer coating.
4. Many marker signatures (codes)
   Currently, there is the possibility of synthesizing more than 60 unique signatures of markers for hydrophilic and hydrophobic polymer coatings, which allows one-time diagnostics and monitoring of a significant number of horizontal well intervals or MFrac stages.
5. No restrictions related to the application of markers in reservoir conditions
   Markers show high physical and chemical stability, as well as resistance to aggressive media and reservoir thermobaric conditions.

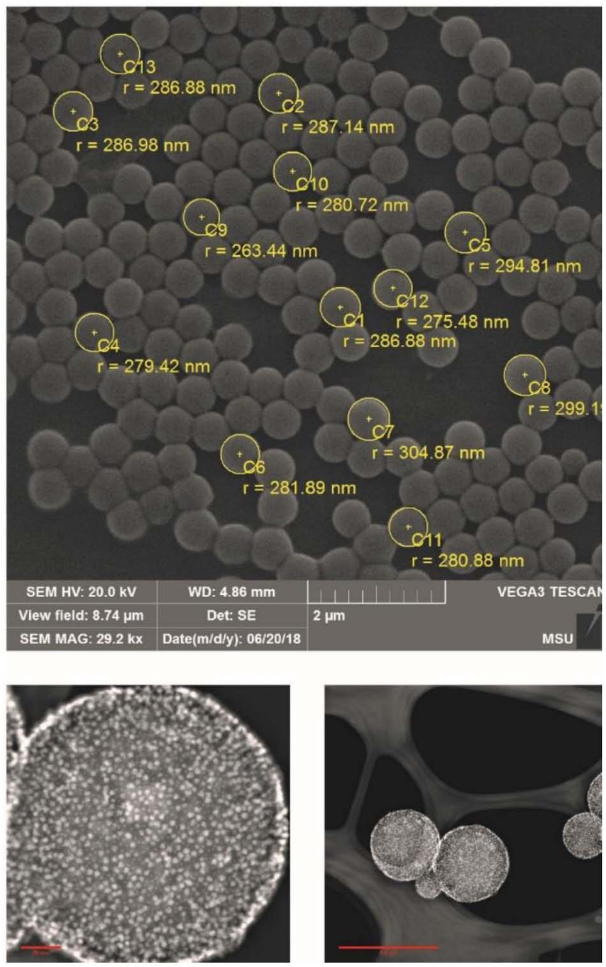

Figure 9—Photographs of marker-reporters with quantum dots made by scanning electronic microscope VEGA TESCAN.

Statistic Profiles

The marker production logging technology was applied in more than 60 horizontal wells in various geological and geographical conditions. Based on the statistical data analysis, the following was established:

1. Horizontal well (HW) inflow profiles typically change over time;
2. The estimated number of operating ports in a horizontal well with multiple hydraulic fracturing does not exceed one third of the total number of stages;
3. The most typical inflow profiles of the studied wells are:

- L-shaped (the "toe" of the horizontal section predominantly operates) (Figure 10)
- U-shaped (the "heel" and the "toe" of the horizontal section predominantly operate (Figure 10)
- J-shaped (the "heel" of the horizontal section predominantly operates (Figure 11)

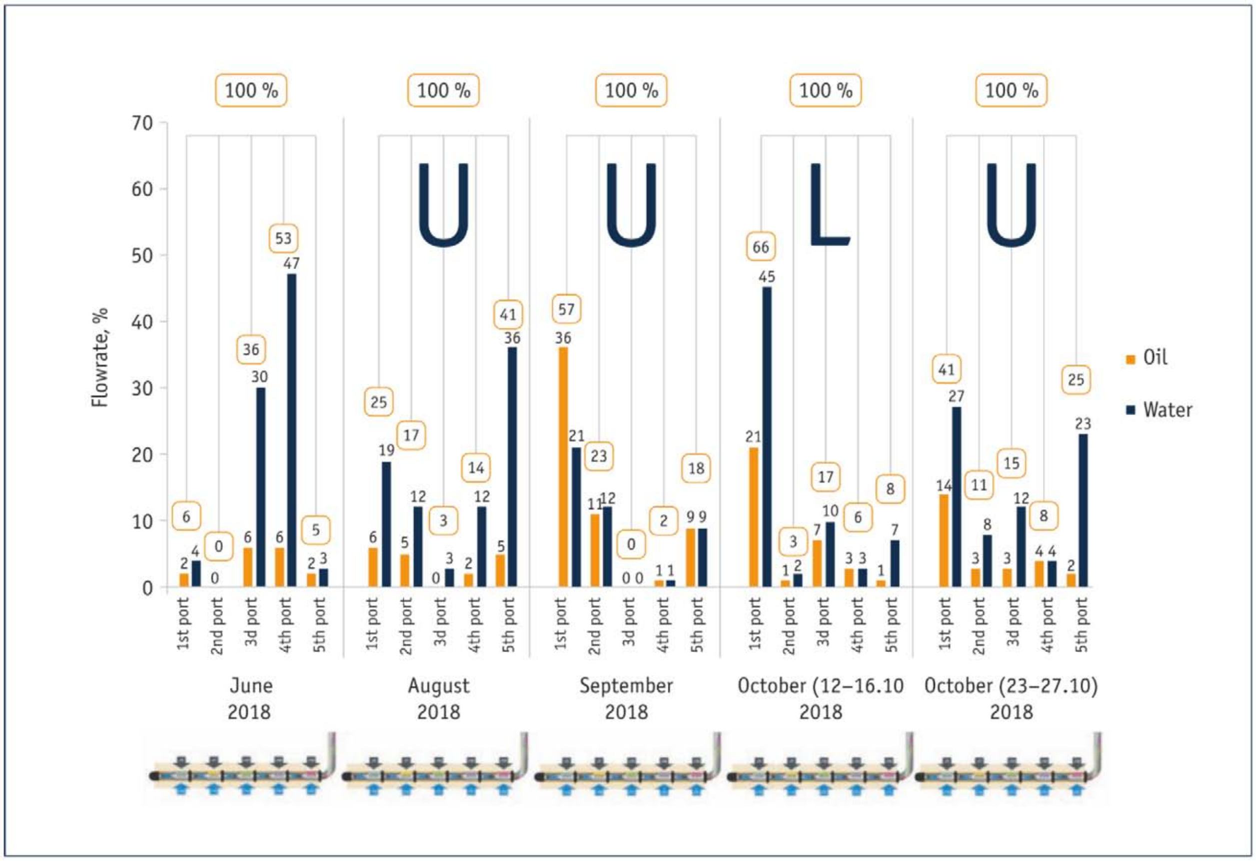

Figure 10—U-shaped Profile of the Well in Western Siberia with a 5-stage MFrac

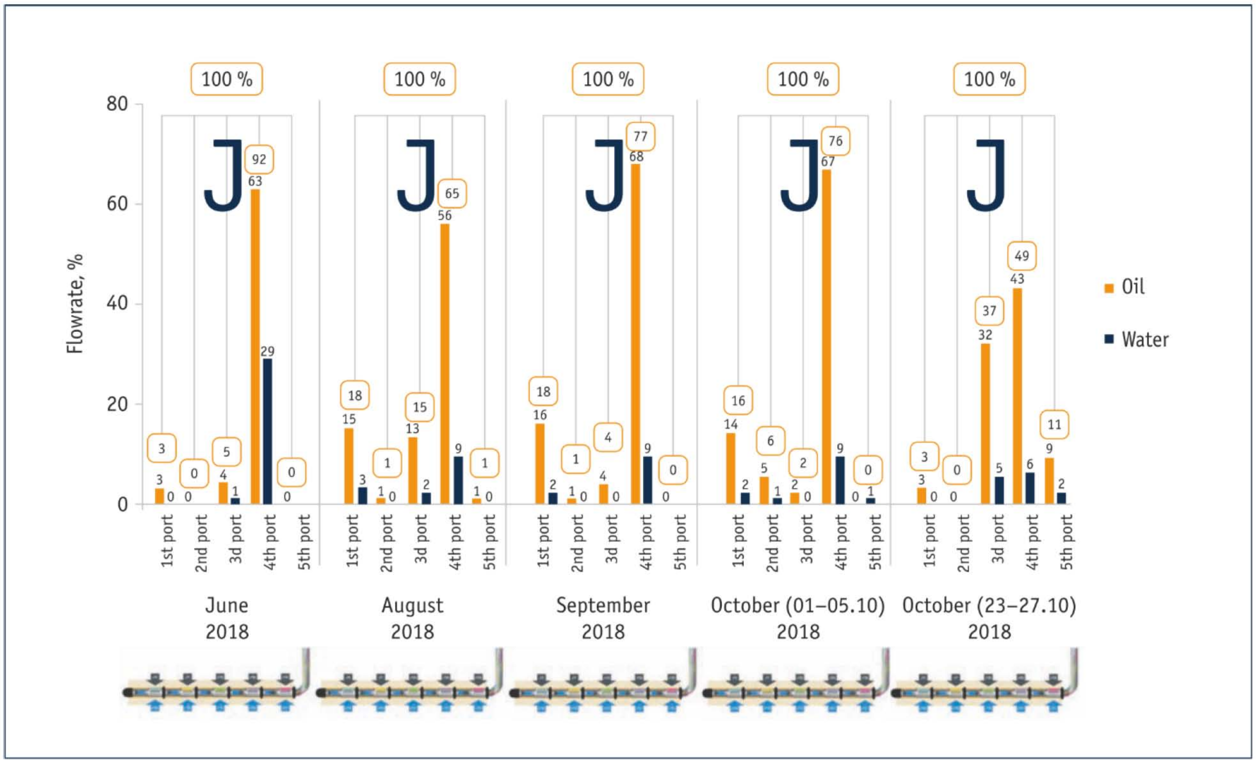

Figure 11—J-shaped Profile of the Well in Western Siberia with a 5-stage MFrac

Conclusion

The combined application of production logging with the possibility of fractures modeling and high-tech methods for marking each port with unique codes for oil, water and gas in injection and production wells provides unique opportunities for solving applied problems related to localizing residual reserves and maintaining the field site development efficiency. This also contributes to the development of methods for involving the maximal number of MFrac stages in the operation. It has been identified that obtaining analytical data on horizontal well operation enables the solving of field development problems at a qualitatively new level, including:

- visualizing the formation indicators;
- formation reserves management by adjusting the injectivity of injection wells;
- efficient planning of geological and technical measures in the studied formation areas;
- confirmation of the horizontal well optimal length and the number of fracturing ports;
- adapting the existing geological and hydrodynamic models, considering the analytical data on the inflow profiles, etc.

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