Choosing a strategy for the development of hard-to-recover oil reserves based on integrated modeling

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Abstract. The article presents an integrated approach to the selection of the most optimal option for involving in the development of oil reserves confined to thin-layered clay-bearing reservoirs, based on integrated modeling. Previous studies of facies, geological and petrophysical reservoirs of the reservoir under consideration using a newly sampled core made it possible to reconsider the prospects for oil production, which was previously considered unprofitable. The use of the spectral method made it possible to take into account the high anisotropy of properties and achieve a highly detailed geological model, on the basis of which an increase in the initial geological reserves (IGZ) by more than 50% and their belonging to the category of hard-to-recover (TRIZ) is justified. The assignment of the deposit to the category of TRIZ made it possible to apply a preferential coefficient to the mineral extraction tax, which increased the economic attractiveness of the project. To reduce the risk of involvement of the underlying water-saturated interval, studies of the elastic-deformation properties of the reservoir rocks were carried out, on the basis of which a geomechanical model was built to select the optimal parameters for the hydraulic fracturing (HF) operation. To select the optimal location of production and injection wells, as well as the parameters of their injection using a hydrodynamic model, a feasibility study of development systems using directional (DW) and horizontal wells with multi-stage hydraulic fracturing (HW+MHF) was carried out. An integrated approach made it possible to develop solutions to more than double the oil recovery factor (ORF) and net present value (NPV) of the project.

1 Introduction

Recently, there have been significant changes in the resource base of the oil provinces of the Russian Federation in the direction of a significant decrease in "easy-to-recover" oil [1;2]. Thus, in the structure of production and reserves of producing enterprises of the West

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Siberian oil and gas province, the percentage of hard-to-recover, confined to low-permeability reservoirs continues to grow [3]. Despite the higher capital and operating costs for the development of such reservoirs, the emergence and mass introduction of hydraulic fracturing technology and horizontal wells with multi-stage hydraulic fracturing made it possible to achieve profitability of production [4]. Not unimportant role in this was played by the possibility of using tax benefits for the extraction of hard-to-recover to increase the economic evaluation of the project. With the commissioning of similar reservoirs [5], the "shale revolution" in the United States is associated, which made it possible to significantly increase the volume of oil production in a short time. In view of the high risks of non-confirmation of projected production levels, which can lead to the unprofitability of the entire project, a large role was assigned to optimizing the method of developing reserves in order to achieve maximum values of the oil recovery factor and net present value. Recently, computer modeling of reservoir systems using multivariate calculations has become the main way to predict and justify the optimal development parameters. However, as a rule, each model solves only one problem, the results generated at one of the stages are not always inherited when moving on to modeling the next process. The article describes the use of a single integrated reservoir model to substantiate the optimal methods for putting hard-to-recover oil into operation.

According to previous studies using an additionally sampled core, petrophysical dependencies [6] were updated and geological features of the reservoir structure were established [7]: thin-layered interbedding of sandstone, uneven-grained siltstone and clay interlayers; high anisotropy of reservoir properties; low density of initial geological reserves, which require adjustments to standard modeling methods traditionally used to solve similar problems.

2 Materials and methods

The use of methods of the classical theory of geostatistics based on variogram analysis to build models of reservoirs characterized by high anisotropy of properties has a number of limitations. Therefore, to construct the lithology cube, the spectral modeling method was used, based on the restoration of the logging curve due to the propagation of its components, determined by the theory of the spectral representation of random functions. The advantage of using this technique [8-9] is obtaining detailed (average simulation cell size 50 * 50 * 0.2 m) implementation of cubes of geophysical properties, linking the results with previously accepted ideas about the structure of the reservoir, consistency of calculated and actual well logging data in wells that did not participate in modeling and convergence of the average parameters of reservoir properties. It is also noted that the use of spectral modeling takes into account the zonal variability of the reservoir, since explicitly takes into account the deterioration of reservoir properties, determined by the decay of the amplitude of the logging. The quality control of the lithology cube was carried out by calculating the logging cubes with a selective exclusion of 2-3% of wells from the constructions, followed by a comparison of the actual and model curves (figure 1).

The use of hydraulic fracturing is limited due to the risk of fracture penetration into the underlying water-saturated horizon, separated by an unseasoned shale barrier 1–16 meters thick. To avoid its joining, it is necessary to control the crack propagation along the vertical. An unjustified increase in the amount of proppant (proppant) will lead not only to an increase in the drainage area, but also to the risk of joining water-saturated intervals.

To substantiate the parameters of the hydraulic fracturing operation without the risk of joining water-saturated intervals, sampling and laboratory studies of the deformation characteristics of the core were performed. Information about the elastic-strength properties
of rocks was obtained during the experiment, during which the registration of axial pressure, deformation, axial and radial velocities and fracture pressure was carried out. To determine the fracture toughness on the samples, the "Brazilian test" was carried out, which makes it possible to study anisotropic rocks [10]. On the basis of the experiments performed, as well as the data of density and broadband wave acoustic logging, a geomechanical model was constructed that makes it possible to estimate the fracture geometry depending on the parameters of the hydraulic fracturing operation [11]. When switching to a well-by-well interpretation of geomechanical properties, lithological heterogeneity and anisotropy of reservoir properties obtained at the stage of geological modeling were taken into account.

To substantiate the optimal development scheme on a hydrodynamic model based on the obtained cubes of geological properties, a series of calculations was carried out to assess the production profile of various well systems, which are the basis for evaluating economic indicators. The economic evaluation was carried out in relation to the scenario approved by the design and technical documentation - an inverted seven-point grid with a distance between directional wells equal to 500m.

The optimization was carried out in three stages by evaluating the production profile calculated using the "black oil" model, based on the numerical solution of a system of equations describing a three-phase (water, oil, gas), three-component (H2O, C1-4, C5+) fluid flow in a porous environment, and the economic evaluation obtained on its basis. At each stage of modeling, the task of substantiating the best, from a technical and economic point of view, parameter of the development system was solved. The tasks of the first stage are the rationale for the use of horizontal wells with multi-stage hydraulic fracturing, determining the need for organizing a reservoir pressure maintenance system (RPM), and choosing the orientation of horizontal wells. At the second step, the problem of increasing the efficiency of the development of the object through optimization (OPS) was solved. During the final stage, the problem of substantiating the optimal technological parameters...
of wells was solved - the length of horizontal wells and the density of the hydraulic fracturing sleeves [12]. The geometry of hydraulic fracturing fractures for all types of wells was set taking into account the results of geomechanical modeling.

3 Results

The initial in-place reserves calculated using the geological model exceeded those estimated when calculating the reserves by 52.7%. First of all, the increase in reserves is associated with the allocation of new productive intervals (NLT) and an increase in the area of oil-bearing capacity (S) due to the exclusion of previously existing clay zones. Due to the additional isolation of low-permeability intervals, the average porosity (Kp) and oil saturation (Kn) decreased. Factor analysis of changes in stocks is correct in figure 2.

![Factor analysis of reserves calculation.](image)

Variable calculations of the geometry of a hydraulic fracturing fracture depending on the parameters of the operation showed that even with the minimum parameters of the hydraulic fracturing operation (5 tons of proppant, pad volume 2.5 m3, fluid flow rate 2.5 m3/min), there is a risk of fracture breakthrough into water-saturated intervals. To minimize the risks, an analysis was made of the effect of using a linear gel at the buffer stage. This makes it possible to limit the vertical growth of the fracture (figure 3) and prevent the involvement of the underlying formation, without reducing the fracture half-length. The adopted design was tested and confirmed by the parameters of the wells after the geological and technical intervention and the study by the method of repeated pulsed neutron-neutron logging.
At the first and second steps of hydrodynamic modeling, the length of horizontal wells was assumed to be 800 m, the density of hydraulic fracturing stages was 1 stage per 100 m of horizontal wells, the distance between wells was 500 m, the distance between rows was 300 m, the fracture geometry was laid based on the previously obtained results (half-height 23 m, half-length 57 m, width 1.82 mm). Well operation is controlled by bottomhole pressure equal to 50 atmospheres for production wells and 350 atmospheres for injection wells. The estimated development systems can be conditionally divided into three groups: basic - using directional wells + hydraulic fracturing, using horizontal wells with multi-stage hydraulic fracturing oriented across the direction of predominant fracture propagation and using horizontal wells with multi-stage hydraulic fracturing oriented along the direction predominant crack propagation. The comparison involved 8 well placement options:

- A row system of horizontal wells with multi-stage hydraulic fracturing, directed across the predominant direction of development of hydraulic fractures using horizontal wells to maintain reservoir pressure (HW+HW_p) and to deplete (HW_p).
- A row system of horizontal wells with multi-stage hydraulic fracturing, directed across the predominant direction of development of hydraulic fracturing fractures using directional wells to maintain reservoir pressure (HW+HNS_p).
- A row system of horizontal wells with multi-stage hydraulic fracturing, directed along the predominant direction of development of hydraulic fracturing fractures using horizontal wells to maintain reservoir pressure (HW+HW_v) and to deplete (HW_v).
- A row system of horizontal wells with multi-stage hydraulic fracturing, directed along the predominant direction of development of hydraulic fracturing fractures, using directional wells (1:1) to maintain reservoir pressure (HW+HNS_v).
- A row system of horizontal wells with multi-stage hydraulic fracturing, directed along the predominant direction of development of hydraulic fracturing fractures, using directional wells (2:1) to maintain reservoir pressure (HS+2NNS_v).

The best ratio of net discounted income / oil recovery factor (Figure 4) has a row system of horizontal wells with multi-stage hydraulic fracturing (HW+HNS_v), oriented parallel to the predominant direction of hydraulic fracturing development, using directional wells (1:1) to maintain formation pressure. The orientation of horizontal wells with multi-stage hydraulic fracturing parallel to the predominant direction of fracture development allows not only to improve the technical and economic assessment by increasing the LOR, but also to reduce the likelihood of a breakthrough of the injected water front through the auto-hydraulic fracture in the well of the formation pressure maintenance system. It will be oriented parallel to producing horizontal wells with multi-stage hydraulic fracturing. Despite the fact that the use of horizontal wells to maintain reservoir pressure increases the oil recovery factor due to more efficient placement, the high cost of drilling them negatively affects the economic component of the project.

At the second and third stages, the optimal OPS and completion performance indicators (the length of the horizontal section and the distance between the hydraulic fracturing sleeves) were determined in a similar way. The density of the well grid was selected by changing the distance between wells in a row (parameter A) and between rows (parameter B), with a step of 100 m. Three length options (800, 1,000, 1,200 m) and three options hydraulic fracturing density (1 stage per 50, 100, 150 m). The results of the assessment of technical and economic efficiency are presented in figure 5.

A decrease in the oil recovery factor with an increase in the distance between wells in a row is associated with a decrease in the efficiency of the reservoir pressure maintenance.
system under conditions of low reservoir properties and a large area of the development element. However, when the wells move closer to 300 m, it does not lead to a further increase, due to the rapid approach of the injected water front and watering of the wells, while the increase in the cost of implementing a denser grid of wells is not compensated by the increase in LP.

**Fig. 4.** Comparison of technical and economic indicators of development systems.

![Graph showing comparison of technical and economic indicators](image)

**Fig. 5.** Comparison of indicators depending: A) from OPS; B) well completion indicators

With an increase in the length of the horizontal section without changing the density of hydraulic fracturing due to an increase in the drained area, the NOR increases, but the oil recovery factor does not change significantly. Due to the increase in the density of hydraulic fracturing, the development of reserves is forced, which entails an increase in the oil recovery factor. But the effect of too close location of the hydraulic fracturing sleeves due to the interference of fractures and the rapid decrease in reservoir pressure, additional LP does not make it possible to recoup the costs of additional hydraulic fracturing operations.

**4 Discussion**
The construction of a correct geological model using the spectral modeling method made it possible to recalculate reserves and increase the density of initial geological reserves. Due to this, it became possible to justify the economic attractiveness of the project.

The conclusions made about the need to adjust the parameters of the hydraulic fracturing operation made it possible to minimize the risks of introducing water-saturated intervals and are consistent with the conclusions and experience of hydraulic fracturing using a linear gel [13]. However, under conditions of reservoir anisotropy and unseasoned clay bridge, constant calibration of the model is necessary, taking into account the results obtained.

The study confirmed the conclusions about the efficiency of horizontal wells with multi-stage hydraulic fracturing, made for similar geological conditions [14-16]. However, the possibility of improving the feasibility study of the project due to additional optimization of the density of the well grid and well completion parameters is additionally shown. The papers recommend the use of horizontal wells with multi-stage hydraulic fracturing, oriented orthogonally to the predominant direction of fracture development, however, the conclusion is made solely on the basis of the results of start-up flow rates. During long-term operation, due to faster watering, this option loses in terms of oil recovery factor to horizontal wells located along the predominant direction of fracture development with multi-stage hydraulic fracturing. In total, 26 variants of the production profile calculated using a geological and hydrodynamic model were considered to justify well designs and parameters of their location. According to the results of three stages of optimization, the most effective in terms of the accepted feasibility study was shown by a row system for developing horizontal wells with multi-stage hydraulic fracturing sleeves every 100 m, directed along the predominant direction of development of hydraulic fractures, using directional wells (1:1) to organize a reservoir pressure maintenance system.

5 Conclusion

The use of the spectral method of geological modeling made it possible to take into account the features of the reservoir under consideration - a thin-layered structure and high anisotropy of properties, which became the basis for the correct construction of geomechanical and hydrodynamic models. The parameters of the hydraulic fracturing operation were determined to achieve maximum sweep without involving the underlying water-saturated interval. It is recommended to use a linear gel to limit the height of a hydraulic fracture and to adapt the geomechanical model based on the results of the stimulations. The use of a grid of wells based on horizontal wells with multi-stage hydraulic fracturing is substantiated and the possibility of its optimization due to OPS and completion technological parameters is shown. The use of complex modeling of the reservoir system made it possible to increase the net discounted income by more than 2 times.

In the future, the results obtained can be applied to the development of reservoirs with similar geological and physical characteristics.

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