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EFFICIENCY IMPROVEMENT OF THE CYCLIC STEAM TREATMENT OF WELLS IN THE UPPER PERMIAN DEPOSIT OF THE USINSKOYE FIELD BASED ON THE HYDRODYNAMIC MODEL

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ПОВЫШЕНИЕ ЭФФЕКТИВНОСТИ ПАРОЦИКЛИЧЕСКИХ ОБРАБОТОК СКВАЖИН ВЕРХНЕПЕРМСКОЙ ЗАЛЕЖИ УСИНСКОГО МЕСТОРОЖДЕНИЯ НА ОСНОВЕ ГИДРОДИНАМИЧЕСКОЙ МОДЕЛИ

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efficiency improvement, oil deposit, high viscosity oil, hydrodynamic model, modeling, simulator, cyclic steam treatment, thermal methods, thermal treatment, optimum process parameters, steam injection, soaking, production, heating, optimization, formation oil recovery, profitability.

Development of the Upper Permian high viscosity oil deposit is expected to involve thermal methods of enhanced oil recovery, in particular, cyclic steam treatment of wells.

The simulator used for the deposit modeling is to be capable of computing the change in the rock fluid thermal properties, and of solving the heat and mass transfer equations. The modeling of the cyclic steam treatments used CMG STARS, a numerical simulator with a wide range of applications including modeling of thermal processes.

The cyclic steam treatment includes three basic stages, such as the steam injection period, the soak period, and the production period. The number of cycles has been selected by computation on the basis of an optimum well operation. To determine the optimum quantity, computations with 7, 5 and 3 cycles were performed. Another predictive computation was performed for a well operation without cyclic steam treatments. The computations helped to determine the operation scenario with the highest cumulative oil production.

During the assessment of the cyclic steam treatment efficiency by using hydrodynamic modeling, we obtained dependencies on a number of geological and physical factors, such as steam dryness fraction, formation thickness, steam injection rate, soaking time.

The numerical experiments resulted in conclusions and recommendations concerning the case-by-case approach to selecting optimum parameters of the cyclic steam treatments for each individual well, taking into account the structure and specific features.

Factor analysis was used to select the optimum parameters for the cyclic steam treatment of the wells drilled in the Upper Permian deposit of the Usinskoye field. For comparison, three predictive scenarios of the well operation have been computed.

Cost-performance indicators of the well operation scenarios in the Upper Permian deposit of the Usinskoye field were evaluated, assuming that the wells will be operated in conditions of the natural recovery drive and multiple cyclic steam treatments, in the baseline and recommended scenarios.

Ключевые слова:
повышение эффективности, нефтяная залежь, высоковязкая нефть, гидродинамическая модель, моделирование, симулятор, пароциклическая обработка, термические методы, тепловое воздействие, оптимальные технологические параметры, закачка пара, выдержка, добыча, прогрев, оптимизация, нефтеотдача пласта, рентабельность.

Разработка верхнепермской залежи высоковязкой нефти планируется с применением термических методов увеличения нефтеотдачи – пароциклических обработок скважин.

При моделировании залежи должен использоваться симулятор, который позволяет рассчитывать изменения тепловых свойств флюидов породы, а также решать уравнения тепломассопереноса. Моделирование пароциклических обработок производилось в CMG STARS – это численный симулятор обширного спектра применения, в том числе он может использоваться и для моделирования тепловых процессов.

Пароциклическая обработка проходит в три основных стадии: период закачки пара; период выдержки; период добычи. Расчетным путем осуществлен подбор количества циклов на основе оптимальной работы скважины. Для определения оптимального количества проведены расчеты с 7, 5 и 3 циклами. Также выполнен прогнозный расчет работы скважины без пароциклических обработок. По результатам расчета выявлен режим с наибольшей накопленной добычей нефти.

При оценке эффективности пароциклических обработок скважин при помощи гидродинамического моделирования получены зависимости от ряда геолого-физических параметров, таких как степень сухости пара, толщина пласта, темп закачки пара, продолжительность пропитки.

По результатам численных экспериментов сделаны выводы и даны рекомендации по индивидуальным подходам к выбору оптимальных параметров пароциклических обработок для каждой отдельной скважины, с учетом ее строения и особенностей.

С помощью факторного анализа выбраны наиболее оптимальные параметры для пароциклической обработки скважин верхнепермской залежи Усинского месторождения. В качестве сравнения рассчитано три прогнозных варианта работы скважины.

Выполнена оценка технико-экономических показателей эффективности вариантов эксплуатации скважин верхнепермской залежи Усинского месторождения, предусматривающих работу скважин в условиях естественного режима и проведение многократных пароциклических обработок при базовом и рекомендуемом вариантах.

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Introduction

A significant part of geological reserves in the fields of the Komi Republic is represented by high viscosity oil. Efficient recoveries of these reserves are possible through implementation of thermal methods for an enhanced oil recovery. Cyclic steam treatment (CST) is an effective method intended for thermal treatment of productive strata. The method has been successfully piloted at the Permo-Carboniferous deposit of the Usinskoye field and at the deposit of the Asselian-Sakmarian sequence of the Osvanjurskoye field. However, taking into account high cost of this type of treatment (cost of stationary steam generators (SG), their installation and connection, injection wellhead connection, construction of project wells), the operations have to be planned reasonably, including a justified choice of candidate wells for treatment and optimization of the operation parameters (a number of treatment cycles, steam dryness fraction, steam injection rate, soaking time etc.). This problem can be solved using the geological hydrodynamic model.

The provided results justify the planning stage of the cyclic steam treatments of the high viscosity oil wells in the Upper Permian deposit (P2u-IV) of the Usinskoye field using the geological hydrodynamic model.

Input Data

The process of creating a three-dimensional digital hydrodynamic model consists of a series of successive steps with typical methods, procedures and intermediate results.

A three-dimensional geological modeling of the Usinskoye field oil deposits was implemented using IRAP RMS software suite by ROXAR. The input data for modeling of petrophysical parameters consisted of the results of the stratum-by-stratum interpretation of data obtained from geoinformation systems (GIS) – porosity, permeability and oil saturation curves. Determination of porosity, permeability and oil saturation ratios was only performed in formations. Modeling in the impermeable part of the section was not performed.

In order to preserve the geological inhomogeneity of the Upper Permian deposits of the Usinskoye field, the procedure of transition from the detailed geological model to the more generic hydrodynamic model (rescaling) was not performed.

The isothermal model of the two-phase three-component filtration of *dead* oil was selected as the hydrodynamic model of P2u-IV object. The choice was based on such factors as absence of free gas, absence of gas injection, and the condition that throughout the entire history matching period, the development was conducted at the formation pressure exceeding the saturation pressure.

Modeling of P2u-IV deposit development involved creation of an isothermal *Black Oil* model in the format of IMEXCMG simulator. Thermal methods of the oil recovery enhancement will be used for the deposit development. Thus, the simulator used as a computation module is to be capable of computing the change in the rock fluid thermal properties, and of solving the heat and mass transfer equations. CMG STARS simulator of thermal (non-isothermal) and special processes fully meets these requirements.

The modeling involved normalization of basic dependencies of relative phase permeabilities (RPP), as well as modification of RPP curve shape on the basis of actual water flooding dynamics of the producing wells. Capillary pressure curves were not modified.

In the hydrodynamic model, the history match took into account the operation results for nine wells. The history matching task was to reproduce the development history since 1986 (32 years).

The following input data were used [1]:

– well trajectories, coordinates of well bottoms and intersections according to the field's geological model;

– dynamics of oil, water and liquid outputs from the database according to the monthly and yearly reporting, from the beginning of development as of January 1st, 2019

– dynamics of the well perforation and isolation intervals, and well interventions;

– results of the production well logging;

– dynamics of formation and bottom-hole pressures by wells, obtained from hydrodynamic tests of the wells.

The appearance and section of P2u-IV formation hydrodynamic model exemplified by the oil saturation cube are shown in Fig. 1.

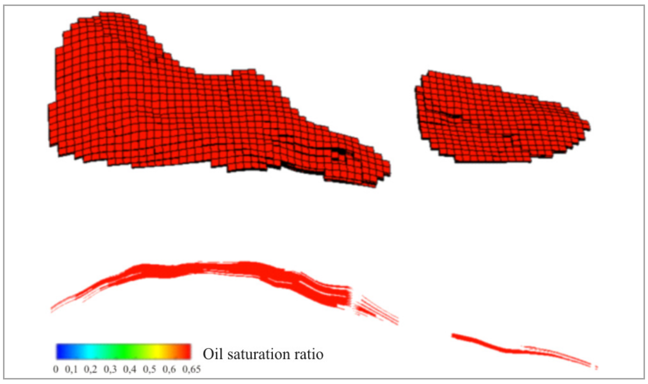

Fig. 1. Appearance and section of P2u-IV formation hydrodynamic model exemplified by the oil saturation cube

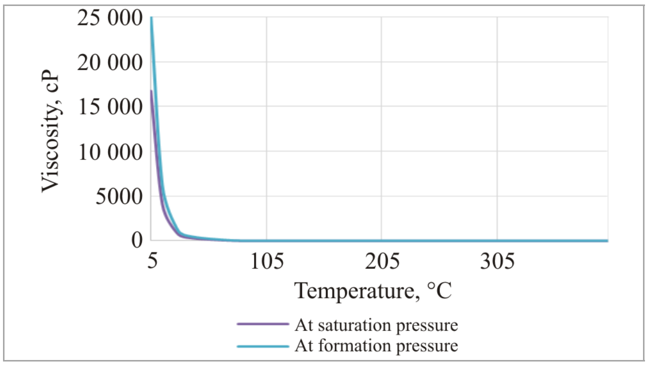

Fig. 2. Dependency of oil viscosity on temperature

Table 1

Input data for CST modeling

Parameter	Indicator
Formation properties	
Thickness, m	12 (9–14)
Horizontal permeability, μm^2	0.760
Porosity, %	25.6
Bulk elasticity, 1/kPa	$5.8 \cdot 10^{-5}$
Thermal conductivity, J/(m·day·°C)	$2.16 \cdot 10^{5}$
Heat capacity, J/(m^3 · °C)	$3.35 \cdot 10^{6}$
Enclosing rock properties	
Thermal conductivity, J/(m·day·°C)	$2.16 \cdot 10^{5}$
Heat capacity, J/(m^3 · °C)	$3.35 \cdot 10^{6}$
Oil properties	
Model type	“Dead” oil
Molecular weight, kg/gmol	0.455
Density in formation conditions, kg/m^3	913.0
Viscosity in formation conditions, mPa·s	242.3
Saturation pressure, MPa	3.6
Gas-oil ratio, m^3/t	12
Formation volume factor	1.031
Bulk elasticity, 1/kPa	$5.8 \cdot 10^{7}$
Thermal expansion, 1/°C	$6.84 \cdot 10^{-4}$
Thermal conductivity, J/(m·day·°C)	$1.495 \cdot 10^{5}$
Heat capacity, J/(m^3 · °C)	1.15
Formation conditions	
Pressure, MPa	11.6
Temperature, °C	20
Oil saturation	0.61

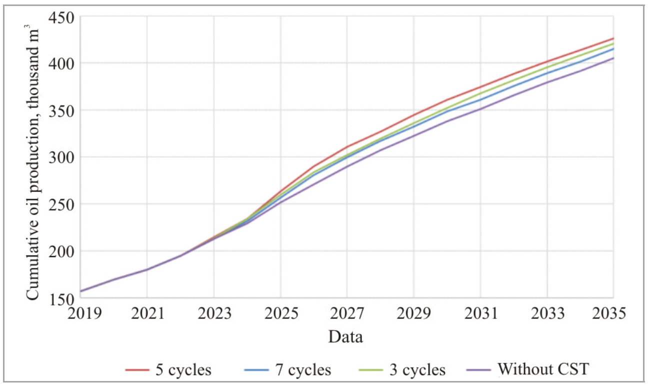

Fig. 3. Cumulative oil production computed with 3, 5, 7 cycles and without cyclic steam treatment

The hydrodynamic model of object P2u-IV was based on dependencies of viscosity on temperature, thermal properties of formation, oil and water by analogy with those of the Permo-Carboniferous deposit of the Usinskoye field. The dependency of viscosity on temperature is shown in Fig. 2.

The input data for modeling of well CST in CMG STARS software module are provided in Table 1.

Well CST Process Modeling

CST modeling was performed using CMG STARS software module which can simulate compositional, thermal, geomechanical (fracturing, compaction, caving of rock) processes in presence of disperse components (polymers, gels, rock particles, emulsions, foams) or without them, and interbedding combustion process.

The development of the Upper Permian high viscosity oil deposit is expected to include thermal methods of enhanced oil recovery, specifically CST. CST modeling was performed on 9 wells, 4 out of which were active producing wells (treatments starting from 2022), reactivation of one well in 2022, transitions from the underlying object for one well from 2022–2024, one project producing well in 2024, according to the project document [2].

Cyclic steam treatment undergoes three basic stages, such as the steam injection period, the soak period, and the production period.

The selection of a number of cycles was performed by computation on the basis of optimum well operations. In order to determine the optimum number, computations with 7, 5 and 3 cycles were performed. The predictive computation of the well operation without cyclic steam treatments was also performed. According to the computation results, the highest cumulative oil production corresponds to 5 CST cycles (Fig. 3).

If the number of treatments is higher, the steam injected into the well does not have enough time to soak in and heat up the near-wellbore area. Further production in the well will require withdrawal of water condensate prior to obtaining a small increment in oil output.

The well operation output is assumed as the minimum profitable output to be achieved for implementation of an injection cycle (Fig. 4).

Fig. 5 shows CST stages and the extent of the oil viscosity change as a function of the formation temperature increase in well No. 1000 region.

Factor Analysis of CST Efficiency

During the assessment of the cyclic steam treatment efficiency using hydrodynamic modeling, dependencies on a number of geological and physical factors were

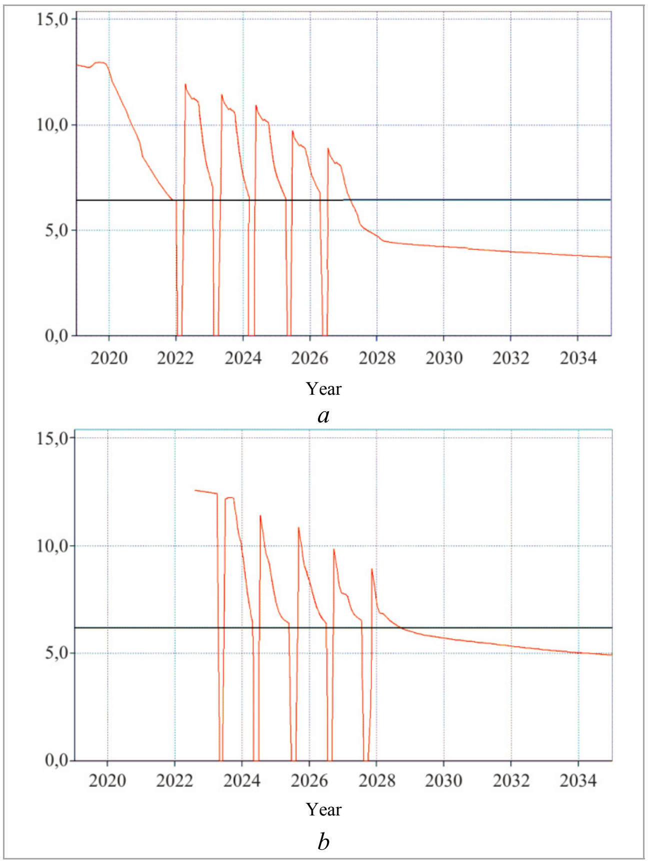

Fig. 4. Oil withdrawal curve at 5 cycles: operating well No. 1000 (*a*) and project well No. 43 (*b*)

obtained, such as steam dryness fraction, formation thickness, steam injection rate, soaking time [3–8].

Impact of steam dryness fraction. Four steam dryness fraction values were considered (50, 70, 90 % and 0 % is hot water) at the same steam injection rate. The computation results are shown in Fig. 6 (*a*).

The obtained data suggests that an increase in steam dryness is associated with an increase in oil production. If the steam dryness fraction increases at a constant injection rate, heat is injected in the well, which results in an increase of the heated-up area of the formation and thus, the amount of heated oil.

Mean formation temperature increases during the injection stage and later decreases following the same trend during the stage of soaking and production at all considered steam dryness fraction values. The temperature difference is caused by gradual commissioning of the wells and their cyclic steam treatments.

Owing to the latent heat of evaporation, water steam has a substantially larger heat content than hot water [9–12].

Impact of formation thickness. Three formation thickness scenarios were considered (9, 12 and 14 m) with all other parameters unchanged. The computation results are shown in Fig. 6, *b*.

As the formation thickness grows, the cumulative oil and water production decreases due to the decrease in the ratio of the heated formation volume to its overall volume.

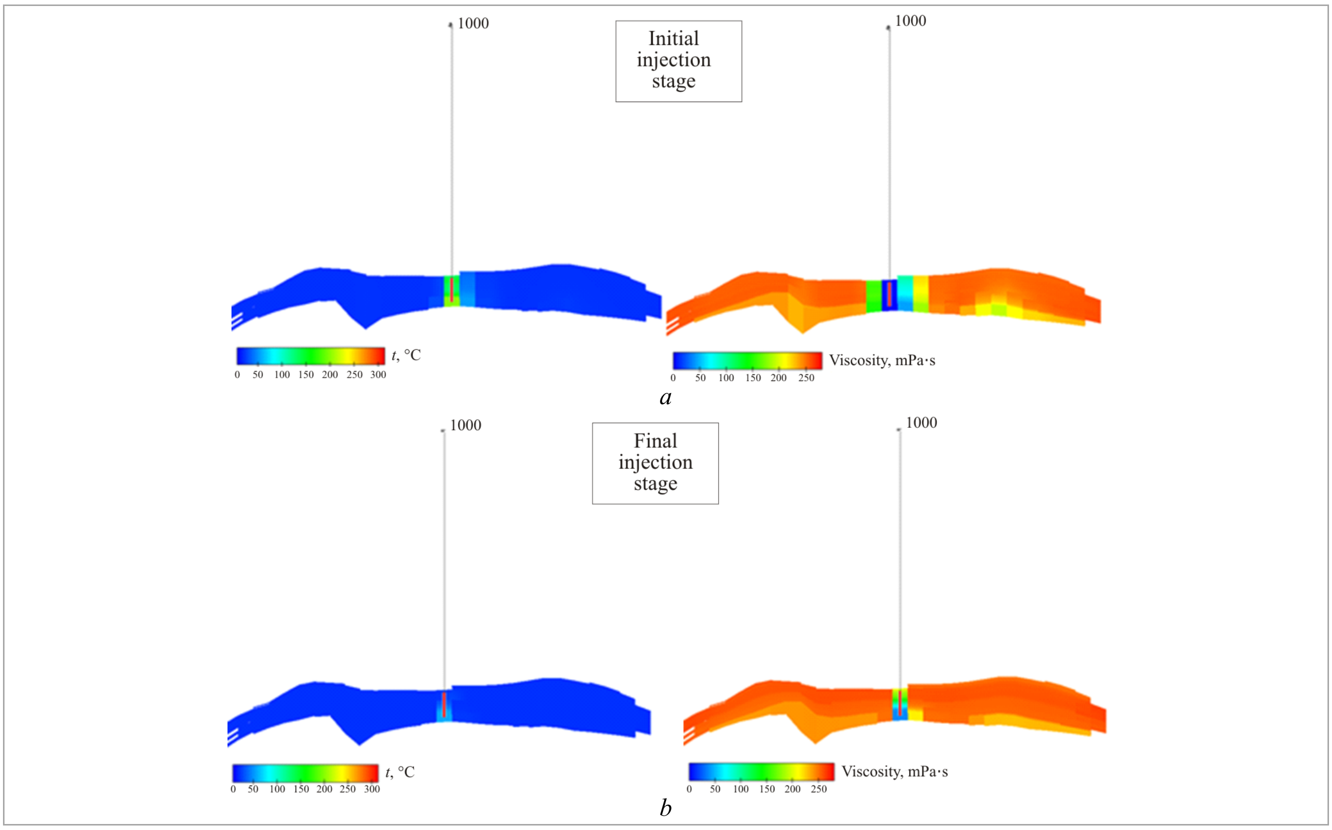

Fig. 5. Hydrodynamic model section for well No. 1000 exemplified by cubes of oil temperature (*a*) and viscosity (*b*)

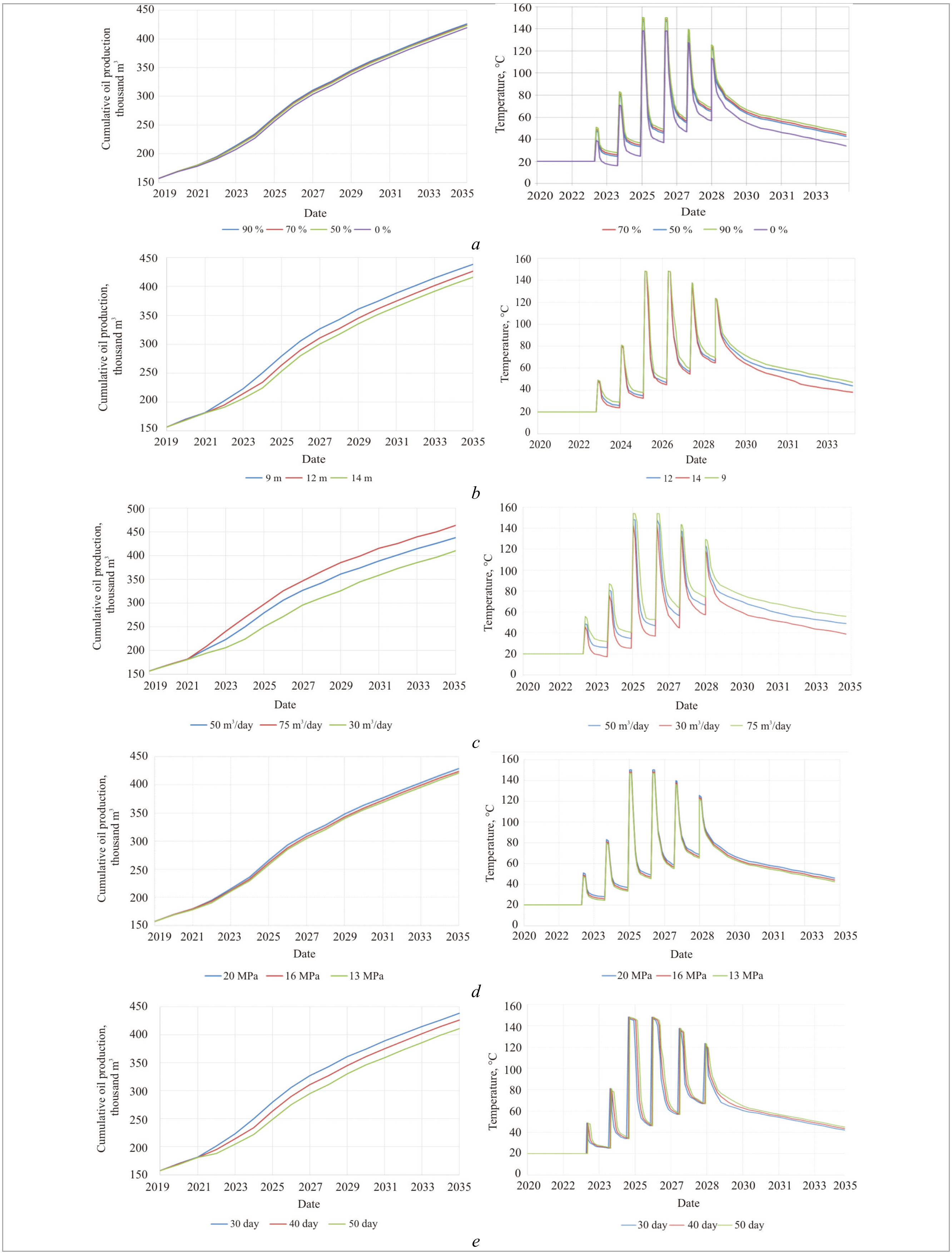

Fig. 6. Dependence of cumulative oil production and formation temperature: *a* – on steam dryness fraction; *b* – on formation thickness; *c* – on steam injection rate; *d* – on steam injection pressure; *e* – on soak time

Bottom-hole temperature decreases faster for thinner formations. The thinner the formation, the higher the amount of the heat loss to the overlying enclosing rock, and the higher the temperature gradient [13, 14].

Impact of steam injection rate. Three specific steam injection rate scenarios were considered, e.g. 30, 50 and 75 m^3/day. The data shown in Fig. 6, *c*, suggests that oil production grows significantly when the steam injection rate increases, since more heat and steam condensate is injected into the formation, which also leads to an increase of the heated-up formation volume [15–20].

The increased steam injection rate causes a decrease in the temperature drop per cycle. This dynamics reflects the fact that the higher steam injection rate brings more thermal energy to the formation, which slowly dissipates into the formation and enclosing rock [11, 12].

Impact of steam injection pressure. Three injection pressure scenarios were considered (13, 16.5 and 20 MPa). The computation results are shown in Fig. 6, *d*.

As can be seen from the obtained data, the increasing injection pressure caused an increase in the injected steam temperature at a constant injection rate and steam dryness fraction. A certain increase in the cumulative oil and water production is noted, as the steam injection pressure grows. However, the discovered effect appears to be negligible due to the stability of other contributing variables. As the bottom hole pressure grows, the latent heat of vaporization goes down, which decreases the overall amount of heat injected into the well and increases the heat loss to the enclosing rock, which depends rather on temperature than on the quantity of the injected heat. A higher formation temperature stimulated a higher oil production output in the well, so more heat was lost with the produced fluid at the initial stage of production [21–26].

Impact of soak duration. Three soak duration interval values were considered – 20, 30 and 40 days [27–32]. The obtained results are shown in Fig. 6, *e*.

Conclusions of the Numerical Experiments

The following conclusions have been made on the basis of the summarized data. First of all, the increase of the steam dryness fraction leads to the oil production growth, since it is associated with an increase of heat quantity per unit of the formation volume, because a large portion of thermal energy is injected as the latent heat of vaporization. Each volume unit of the injected steam contains more heat due to the presence of the latent heat, which leads to a higher oil output. Therefore, in order to increase oil output, it is recommended to use steam with a higher dryness fraction [33–35]. Secondly, the thermal energy density decreases for thicker formations. This is because more volume of the formation contacts the steam. Thus, an excessive formation thickness can lead to low oil output growth rates, since the heat density in such formations is extremely high, which leads to large heat losses in the enclosing rock [36–39]. Thirdly, a high steam injection rate facilitates the delivery of more heat to the formation and increases oil production. However, a very high steam injection rate can lead to the formation overheating, which, in turn, can cause large heat losses and reduce thermal efficiency of the process. An optimum steam injection rate helps to decrease heat losses and maximize the steam chamber volume [40, 41]. Also, the bottom hole pressure increase has a negligible effect on oil production, since the latent heat of vaporization decreases. The overall heat amount added by the steam to the formation increases insignificantly too [42, 43]. Finally, the efficiency of the cyclic steam treatment of the horizontal wells is improved by reducing the soak period duration, since it improves the thermal efficiency of multiple CST process due to better use of the injected heat [44].

Notably, the most efficient approach consists in a case-by-case selection of optimum CST parameters for each individual well, taking into account its structure and specific features [45, 46].

Predictive Computations

Based on the factor analysis results, the most optimum parameters for CST process were selected. For comparison, three predictive scenarios of the well operation were computed. Scenario 1 includes the process parameters defined in the industrial engineering documentation and based on the process in wells of similar fields. Scenario 2 includes the process implementation with parameters selected in the previous chapter of this work. The baseline scenario is the prediction of well operation dynamics without thermal treatments.

The process parameters for the basic and recommended CST scenarios are shown in Table 2.

Fig. 7 shows cumulative production curves for each scenario demonstrating that the selected parameters ensure a significant oil production increase for the well.

Therefore, according to the performed computations, five CST cycles with parameters shown in Table 2 are optimal for the Upper Permian deposit.

The comparison of the obtained results in the recommended scenario with the basic scenario of

Table 2

Process parameters for the basic
and recommended well CST scenarios

Parameter	Basic	Recommended
Number of CST cycles	5	
Injection period		
Working medium	Steam	Steam
Maximum injection pressure, MPa	15.0	20.0
Maximum injection rate, m^3/day	40.0	50.0
Steam dryness fraction, %	70.0	90.0
Injection time, days	30.0	30.0
Soak period		
Soak time, days	30.0	30.0
Production period		
Minimum bottom hole pressure, MPa	3.6	3.6
Maximum liquid withdrawal rate, m^3/day	110.0	110.0
Production time, days	330	330

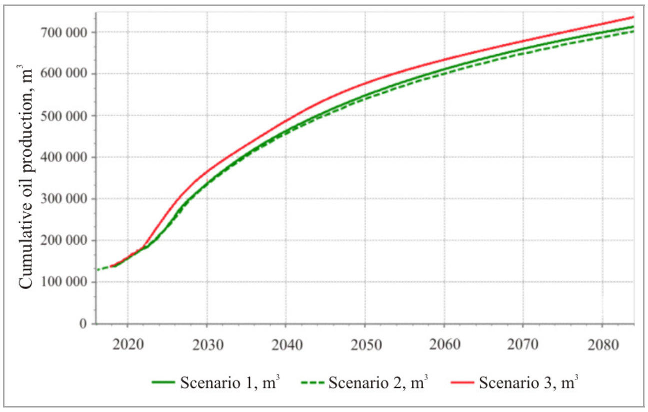

Fig. 7. Oil production dynamics comparison
for the three scenarios

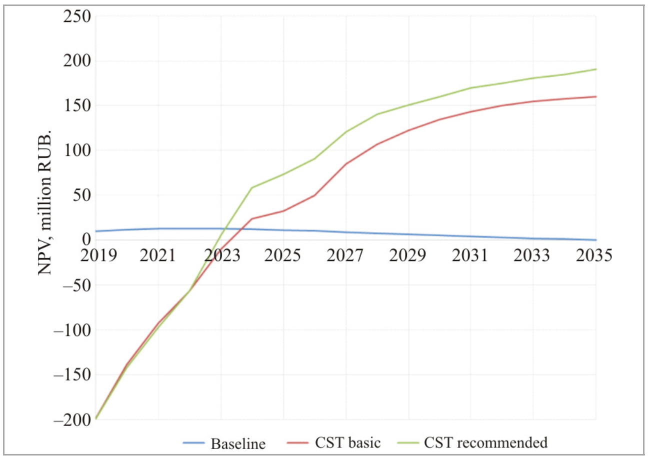

Fig. 8. Net present value for the three
prediction scenarios

treatment and the well operation without treatment shows that the performance of five well CST cycles in an optimum mode ensures an increase in the cumulative oil production. In the scenario of CST with the basic parameters for 17 years (2035) of the predictive computation, the cumulative production is 5 % higher.

Computation of Key Cost Indicators

The main objective of the computations is to estimate the cost-performance indicators for the well operation scenarios in the Upper Permian deposit of the Usinskoye field. The scenarios under consideration are natural recovery drive and multiple cyclic steam treatments (basic and recommended scenarios).

The costs of an oilfield development for the scenario with CST includes the cost of stationary steam generators, their installation and connection, connection of injection well heads, and construction cost of project wells.

Operational costs include critical direct cost items, such as production and injection of steam (for CST of wells), electricity, oil treatment, oil collection, transportation, and salary. Fig. 8 shows the net present value diagram.

Table 3 shows the net present value magnitudes for the recommended CST scenario, CST scenario with the basic parameters and the baseline scenario of the well operation with the natural recovery drive over the period of 17 years.

Table 4 shows basic parameters of the cost computation.

The payback period amounted to 4 years for the recommended scenario with the capital investment of RUB 676.6 million and operating costs of RUB 546.3 million. For other scenarios, the payback period amounted to approximately 5 years.

The sensitivity diagram (Fig. 9) shows the dependence between the net profit and basic parameters, such as price of oil, capital and operating costs. The dependence takes into account *NPV* change in the recommended predicted scenario from the twenty-percent variance of the basic cost indicators. As it can be seen from the sensitivity diagram, if oil prices, capital and operating costs change by 20 %, the oil price is the most significant parameter.

Conclusion

The study analyzed the efficiency of the cyclic steam treatments of wells in the Upper Permian deposit of the Usinskoye field taking into account the influence of geological, production, cost and performance factors. Based on the use of the hydrodynamic model, it was proved that the use of the cyclic steam treatments of wells helps to improve the formation coverage and oil recovery by multiple times. According to the implemented multivariate computations, the best process parameters for the multiple cyclic steam treatments were justified.

We offer the analytical overview of the literature in modeling and optimization of wells CST, the existing

Table 3

Net present value for the three scenarios

Scenario	*NPV*, million RUB
1. Baseline without CST	1.14
2. CST with basic parameters	160.01
3. CST with optimum parameters	190.53

Table 4

Computation of cost indicators

Indicator	Value
Oil in domestic market (including VAT), RUB/t	14,500
Discount rate, %	15
– Income tax, %	20
– VAT, %	20
– Barrelage tax, RUB/t	9140
– producing a directional oil well, RUB/m	71,038.4
– transition to another horizon, thousand RUB/well-operation	5276
US Dollar exchange rate, RUB/Dollar.	65

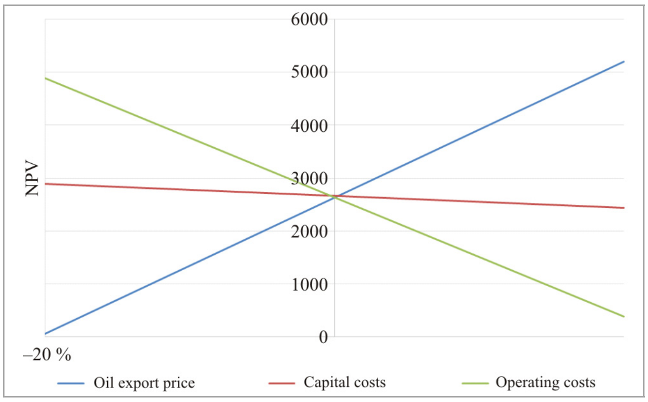

Fig. 9. Sensitivity analysis

well CST models, and the search of the best scenario and specific implementation features.

The geological structure of the field has been described. General characteristics of the field, deposit structure, stratigraphy, tectonics and oil content were provided. Special focus was made on the properties and composition of the produced fluids.

The Upper Permian deposit of the Usinskoye field has been analyzed in terms of its condition by 2019, with details of oil, gas and water production volumes. The development efficiency has been assessed. We analyzed the geological, engineering measures and reasons of the well's water flooding. The analysis suggests the further growth of the product water cut and deterioration of well CST efficiency. Therefore, certain recommendations are to be observed in order to increase CST profitability for the wells.

The conclusions section contains an assessment of the cost-performance indicators for the three operation scenarios of the deposit. According to the computations, the development using CST is much more efficient and ensures an additional increment in the cumulative oil production.

According to the cost-performance computations, the implementation of the cyclic steam treatments of the wells in the Upper Permian deposit of the Usinskoye field would help to obtain a higher net present value compared to the well operation with the natural recovery drive.

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