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

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POВЫШЕНИЕ ЭФФЕКТИВНОСТИ ПАРОЦИКЛИЧЕСКИХ ОБРАБОТОК СКВАЖИН ВЕРХНЕПЕРМСКОЙ ЗАЛЕЖКИ УСИНСКОГО МЕСТОРОЖДЕНИЯ НА ОСНОВЕ ГИДРОДИНАМИЧЕСКОЙ МОДЕЛИ

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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.
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 Usinskiyoe 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.

### Table 1

| Parameter                          | Indicator                              |
|-----------------------------------|----------------------------------------|
| **Formation properties**          |                                        |
| Thickness, m                      | 12 (9–14)                              |
| Horizontal permeability, µm²       | 0.760                                  |
| Porosity, %                       | 25.6                                   |
| Bulk elasticity, 1/kPa             | 5.8·10⁻⁷                              |
| Thermal conductivity, J/(m·day·°C) | 2.16·10⁷                              |
| Heat capacity, J/(m³·°C)          | 3.35·10⁹                              |
| **Enclosing rock properties**     |                                        |
| Thermal conductivity, J/(m·day·°C) | 2.16·10⁷                              |
| Heat capacity, J/(m³·°C)          | 3.35·10⁹                              |
| **Oil properties**                |                                        |
| Model type                        | “Dead” oil                             |
| Molecular weight, kg/gmol         | 0.455                                  |
| Density in formation conditions, kg/m³ | 913.0                  |
| Viscosity in formation conditions, mPa·s | 242.3                   |
| Saturation pressure, MPa         | 3.6                                    |
| Gas-oil ratio, m³/ft              | 0.12                                   |
| Formation volume factor           | 1.031                                  |
| Bulk elasticity, 1/kPa            | 5.8·10⁻¹                              |
| Thermal expansion, 1/°C           | 6.84·10⁻⁴                            |
| Thermal conductivity, J/(m·day·°C) | 1.495·10⁷                            |
| Heat capacity, J/(m³·°C)          | 1.15                                   |
| **Formation conditions**          |                                        |
| Pressure, MPa                     | 11.6                                   |
| Temperature, °C                   | 20                                     |
| Oil saturation                    | 0.61                                   |

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
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.

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

**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 m³/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

| 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, m³/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, m³/day| 110.0 | 110.0       |
| Production time, days             | 330    | 330         |

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

| 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

| 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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