POSSIBILITIES FOR IN-OPERATION CONTROL OF REMAINING RECOVERABLE RESERVES AT VARIOUS STAGES OF OIL PRODUCTION OBJECTS DEVELOPMENT

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ВОЗМОЖНОСТИ ОПЕРАТИВНОГО КОНТРОЛЯ ОСТАТОЧНЫХ ИЗВЛЕКАЕМЫХ ЗАПАСОВ НА РАЗЛИЧНЫХ СТАДИЯХ РАЗРАБОТКИ НЕФТЯНЫХ ЭКСПЛУАТАЦИОННЫХ ОБЪЕКТОВ
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Estimation of oil recovery factors on the basis of geological and hydrodynamic simulation is very cost- and time-consuming. As a result, re-estimation of recoverable hydrocarbon reserves is performed over long periods of time without any more short-term corrections of estimates. The approved oil recovery factors can be outdated due to the changes in the economic conditions of development or a misalignment between actual development and design conditions. For reliable estimation of remaining recoverable reserves at oil production objects, it is critically important to establish in-operation control of oil recovery factors reliability, including their objective achievability within specific time frames.

Based on the example of Perm region oilfields, the paper analyzes the practice of annual geological and financial estimating of the reserves according to international standards. A conclusion has been made that it is necessary to perform similar control of recoverable oil reserves estimated with respect to the Russian classification. Several options of in-operation control are available for approved oil recovery factors: use of analog-statistical methods, displacement characteristics, production decline rate analysis. The methods are based on various physical regularities, their effectiveness to a large extent depending on the quality of input information and the stage of production object development, as well as on the economic conditions.

Case studies are used to analyze the effectiveness of control of the approved oil recovery factors. For early development stages, use of multivariate analog-statistical dependencies drawn from geological parameters built for specific production objects was found to be the most effective method. The long history of Perm Krai oil fields development and a relatively large number of production objects at late stages of recovery make this statistic approach feasible.

At late stages, more reliability can be obtained by using methods based on the displacement characteristics and oil production decline rate taking into account the economic limit of development. The suggested control method involves use of statistic dependencies relying on both geological and technological parameters. Comprehensive use of multiple method approaches helps achieve a more reliable estimation of the remaining recoverable reserves at the production objects.
Introduction

In determination of remaining recoverable reserves (RRR) and oilfield development design, the main parameter driving the reliability of predictive calculations is accuracy of oil recovery factor (ORF) estimation. ORF value describes the share of initial recoverable reserves (IRR) which can be extracted out of the reservoir, from the initial oil in place (IOIP) in the course of development of the reservoir using state-of-the-art proven production technology and technique until economic limit is achieved, observing the requirements for protection of subsurface resources and the environment.

The most common method for ORF estimation is digital geological-hydrodynamic simulation (DGHS) which suggests simulation of oil reservoir development processes using software tools. This method has been implemented in the oil producing industry of Russia since 1990s, and is recommended for use by the current regulation [1]. DGHS provides a basis for calculation of various scenarios for development of oil reservoirs with varying number of production and injection wells, recovery rates etc. Examples of effective use of DGHS during oilfield development design are given in [2–4], including those applied in Perm Krai territory [5–10]. The most cost-effective oilfield development option must be approved by governmental authorities, each production object being attributed a design ORFdesign.

Undoubtedly, DGHS is the most reliable way for determining ORF, provided that qualified geological technology data is available. However, this method is very cost- and time-consuming, which leads to long intervals between ORF design calculations, in most cases exceeding 10 years. As a result, over time the approved ORFdesign can become largely outdated due to a variance between the design and actual development parameters and because of the changes in the economic conditions of development. Taking this into account, it is extremely important to establish in-operation controls for reliability of ORFdesign in production objects, including its objective achievability within specified timeframe.

The subjectivity of ORF estimation in a production object is much higher than the subjectivity of IOIP estimation, at least due to its dependency on the well spacing and development system. Reliable ORF determination is only possible when using a scientifically justified methodological approach that takes into account the entirety of geological and technology conditions of oil production objects development.

Impact of oil reserves geologic certainty degree on effectiveness of ORF in-operation control methods

Several options of in-operation control are available for estimation of the approved ORFs: use of analog-statistical methods, displacement characteristics, oil production decline rate analysis. The methods are based on various physical regularities, their effectiveness to a large extent depending on the quality of input information and the stage of the production object development. Combined use of various approaches provides for a more reliable RRR estimation at the production objects.

Presently the in-operation control of hydrocarbon reserves' status is first of all associated with the geological and economic estimation of reserves (GEER) after the international standards. Regional oil producers perform GEER on an annual basis, the results being subject to approval by international auditors as an annual statement on reserves [11–13]. The authors find that the practice of in-operation (annual) control should be likewise in place for control of RRR in the oilfields approved according to the Russian classification.

A distinctive feature of the Russian (formerly Soviet) classification of hydrocarbon reserves is its focus on the degree of geologic certainty. The need to take into account the cost of reserves and to coordinate with the essential international classifications resulted in the modifications of the Russian classification that have been endorsed for implementation by the instruction of the RF government since 2002 [14]. Economic reserve estimation criteria must be among the priorities to help the state implement a more effective policy for stimulation of investments in oil and gas industry [15]. As of today, efforts in this area resulted in the “Classification of reserves and resources of oil and fuel gases” (2013) [16].

Such sources as [15, 17, 18] pose the problems inherent in the current Russian classification, specifically its insufficient reliance on economic criteria. In-operation RRRs control, that takes into account the cost-effectiveness of their development, can significantly mitigate this problem. Effectiveness
of these ORF control methods is to a large extent determined by the degree of geological certainty of reserves at the production object and, accordingly, the stage of its development.

Due to the diversity of geological conditions and applied development systems, it is not always possible to uniquely determine the development stage of a field [19]. This task usually requires a comprehensive account of such parameters as average production rate, water cutting of well production, well stock transfer to mechanical method of production, and gas factor growth [20]. For Perm Krai, as of 2018, the development stages of production objects had the following distribution: 9.6 % objects – first stage; 21.6 % – second stage; 66.1 % – third stage; 2.7 % – fourth stage.

Use of analog-statistical methods in ORF estimation at production objects of early development stages

Apparently, during the process of oilfield development ORF is influenced by many factors: geological (determined by the nature of production objects) and technological (determined by development conditions). At initial development stages, reliability of information is often low, which, among other things, strongly deteriorates DGHS quality. In the opinion of the authors, in such conditions the most effective option is in-operation estimation of ORF on the basis of analog-statistical models.

Analog-statistical methods for ORF estimation have been used in Perm region since 1980s [21–24]. An acknowledged advanced method is to use multivariate analog-statistical dependencies which help estimate ORF_{st} on the basis of a set of geological and technical indicators. The statistical methods are more resistant to the quality of input factual information and can therefore be implemented on the basis of the data of averaged geological and technological oilfield development characteristics. Thus it is possible to use these methods to control DGHS reliability, which is particularly important for the design of new oilfields and in-operation RRR estimation.

The most comprehensive analysis of ORF_{st} estimation effectiveness using the analog-statistical methods in Perm Krai territory is given in [25]. Its conclusion is that it is difficult to adjust methods developed for other territories (Kazakh Institute of Oil and Gas, API, LLC TatRITEKneft and others) to the needs of Perm Krai. As a more justified option, it is proposed to apply statistical dependencies to the analysis of “regional” fields development and for specific production objects (Bsh, TI-Bb-MI, T-Fm) [25]. Due to the long history of oilfields development in Perm Krai and a sufficiently large number of objects at late stages of recovery, it is possible to implement this statistical approach. Examples of successful use of statistical dependencies for Perm Krai production objects are given in [25–28].

Analog-statistical dependencies must be regularly updated. Otherwise, the statistical methods fail to take into account the new development technologies and cause a systematic ORF underestimation. Therefore, if calculations are performed using relatively “old” dependencies, it is crucial to compare the obtained ORF_{st} estimates with the recently established ORF_{design} in analogous objects.

Use of displacement characteristics in ORF estimation at production objects of late development stages

In the case of steady dynamics of development parameters and remaining reserves recovery indicators, favorable conditions exist for the use of express estimation statistical models for solving in-operation design tasks [29]. One of the key characteristics influencing the forecast of reserves recovery in production objects is the dynamics of well production water cutting [30].

In [31, 32] models are provided for forecasting the dependency of water cutting dynamics (\(w\)) on reserves recovery (\(\eta\)) for reservoirs developed with flooding. Dependencies \(w = f(\eta)\) are built separately for terrigenous and carbonate deposits in various oil viscosity ranges, taking into account the well stock movement dynamics and influence of well interventions (WI) to reduce water influx. Examples of calculation results are given in fig. 1, a, b.

For the vast majority of production objects (see fig. 1, a) there is an alignment between the estimated and actual dynamics \(w = f(\eta)\). It is an evidence of reliable ORF_{design} estimation, which is a desirable condition for late development stages. Significant deviations from forecast models that are found in approximately 5 % cases are related to incorrect IRR and, consequently, ORF_{design}.
estimation. Actual water cutting is above model values for production objects with reserves recovery and ORFdesign overestimated vs. actual.

![Fig. 1. Dynamics of actual and model water cutting dependency on recovery of reserves at reliable (a) and overestimated (b) forecast of design ORF at the production object](image)

In Fig. 1, for objects with water cutting below 50 %, the following displacement characteristics have proven effectiveness in Perm region:

\[Q_o = f(\ln Q_f) – B.F. Sazonova,\]
\[\frac{Q_o}{Q_o} = f(Q_w) – S.N. Nazarova – N.V. Sipacheva,\]
\[Q_o = f(1/Q_f) – G.S. Kambarova,\]

where \(Q_o, Q_f, Q_w\) – cumulative production of oil, fluid and water, respectively.

The results of analysis of multiple materials dedicated to ORF feasibility studies and projects for further development of reserves suggest that all characteristics have a number of drawbacks related to the fact that they have been received using certain assumptions. Therefore, it is advisable to establish the applicability limits for displacement characteristics in various geological and physical conditions and reserve development stages [33, 34].

**Using results of annual geologic and economic estimation of reserves**

GEER provides an annual correction of values and categories of reserves on the basis of comprehensive analysis of geologic, technological and economic contributors. Revision is mandatory for all information influencing the state of reserves and their categories: licenses, mine allotments, calculation or recalculation of reserves, drilling, testing, perforation, 3D seismic survey, hydrodynamic tests, well commissioning and decommissioning. These activities are directly or indirectly influenced by economic forces which have to be taken into account by introducing the remaining economic reserves (RER) indicator. RER is the part of the reserves which is cost effective to recover as of the date of GEER. In the periods of relatively low oil market value, subsurface users benefit from recovery of conventional hydrocarbon resources only. Oil price rise leads to an increase in the quantity of unconventional resources that can be added to RER category [35, 36].

Economic indicators include:
- macroeconomic parameters (Dollar exchange rate, Urals oil price);
- taxes and deductions (production tax);
- key production indicators (price of hydrocarbons, operational and capital costs, costs of well
infrastructure development and abandonment, property tax).

For RER value determination, the concept of oil production profitability economic limit (EL), which represents the production volume below which the net cash flow from project implementation becomes negative. EL indicator value is composed from the hydrocarbons selling price, operational costs and production tax [37]. EL value is annually revised by the subsurface users on the basis of the current operational costs, price of hydrocarbons and tax imposed on their production.

IRR estimation is performed separately for the producing zone (PDP category, Proved Developed and Producing Reserves) and for the non-producing part of the reservoir. These are categories of proved reserves: Proved Developed Non-Producing Reserves (PDNP), Proved Undeveloped Reserves (PUD), and unproved reserves: Probable Reserves (PRB) and Possible Reserves (PSB) which will be treated as reserves by an international audit [35, 38]. ORFGEER values have to be justified separately for these categories.

During international audits PDNP, PUD, PRB, PSB category reserves estimation usually draws on expert opinions. ORFGEER is determined for each non-producing category of reserves based on the estimations obtained for the producing part of the reservoir taking into account the economic indicators. In the case of Perm region fields, “regional” statistical dependencies are used most of the time.

For the calculation of PDP category reserves, LUKOIL uses a software product MERAK PEEP (Schlumberger) which generates monthly updates for such technological indicators of production objects as oil production, fluid production, injected water volume, current operating well stock (fig. 2).

Average oil production for the past year is extrapolated to the minimum profitable yield by exponential function of the production decline rate curve. Oil production decline rate \( \Delta q \) is determined as actual for the preceding 3–5 years or based on an expert opinion.

For objects at early stages of development, when production is unstable or unreliable due to a short operation period, the estimation should be preferably based on \( \Delta q \) equal to 15 % [39, 40]. For production objects at late stages of development, the basic principle of \( \Delta q \) determination is based on studying RRR reduction dynamics for the preceding development period (5–10 years). RER values are calculated on the basis of \( \Delta q \) until achievement of the economic production profitability limit (see fig. 2) [39–41]. Such approach for PDP category helps correct IRR taking into account the economic factors (cumulative production and RER).

WI planning for involvement of reserves into development is performed according to the company plans which can vastly differ from the design document provisions due to the current economic and technological situation. Initial yield for WI performed in PDP zone is determined on the basis of data analysis obtained from actually performed activities. The calculation has to take into account the specific indicators of RRR per well in WI area, as well as oil production decline rate and economic profitability limit [42].

In the global experience of the recent years, intelligent reservoir management technology gains an increasing popularity. The technology is based on continuous monitoring of production and injection wells operation through installation of sensors measuring their process parameters [43–47]. Such an approach improves integrity of actual production object information, significantly increases the accuracy of WI effectiveness forecast and, eventually, the RRR estimation reliability.

Thus, GEER results provide an in-operation estimation of reserves which account for the annual changes in the geological, technological and economic situation at each developed object. Unlike GEER, Russian classification takes these parameters into account only in the case of reserves recalculation.
or drawing up a new design document. Such annual estimation suggests the write-off of annual production from the State Register of Reserves. In fact such estimation does not meet the in-operation criteria as it does not reflect the current actual geological, technical and economic conditions of objects operation.

**Practical aspects of in-operation control of remaining recoverable reserves on the basis of integral analysis of technical and economic indicators of development**

For ORF in-operation estimation and control at various stages of oil production objects development, it is advisable to opt for the methods which are best suited to take into account the geological degree of certainty and reliability of geological, physical and technological nature of the objects.

At the first, initial stage of development many geological and physical parameters are determined on the basis of a small number of studies, often based on analogous objects. Technological indicators are studied during trial operation. ORF determination is possible using analog-statistical dependencies obtained for long-operated reservoirs of the region, with formulas that include geological and physical characteristics of formations and fluids. Such method has to take into account the approved ORF design for neighboring fields with similar geological and field conditions of development.

**Case study.** For a Tournaisian object located in the Vostochno-Tavdinskaya area of Vinnikovskoe field at the initial stage of development, the design document stated an ORF design equal to 0.43. The use of a “regional” statistical dependency gives an ORF st estimation of 0.302. Let us now compare the results with four analogous objects for which average ORF design = 0.389; ORF st = 0.352; ORF GEER = 0.234. Overall, an integrated analysis of the applied methods suggests that it is necessary to correct the development system for ORF design to be achieved.

At the second stage of development, when all the basic characteristics of the reserves are reliably determined, the analysis of current state of development helps specify its effectiveness and plan its further improvement. The main ORF design control method at this stage is building continuously operating DGHSs. For their control, analog-statistical dependencies can be used, involving the indicators descriptive of the development technology [25]. Effective use of displacement characteristics is based on the water cutting and reserve recovery indicators exceeding 40 and 50 % [32]. Realistic estimation of reserves quality is achieved by GEER, especially in terms of planning the priority WIs at currently non-producing reserves.

**Case study.** A Tournaisian object located in Sosnovskoe field with ORF design = 0.432 is at the second stage of development. The use of a “regional” statistical dependency gives an ORF st estimation of 0.353. Based on the results of economic estimation as of 1.01.2019, ORF GEER equal to 0.298 is forecasted. Three analogs are selected for the object, for which the average ORF design = 0.399; ORF st = 0.352; ORF GEER = 0.234. Overall, an integrated analysis of the applied methods suggests that it is necessary to correct the development system for ORF design to be achieved.

At the third stage, when all the basic characteristics of the reserves are reliably determined, the analysis of current state of development helps specify its effectiveness and plan its further improvement. The main ORF design control method at this stage is building continuously operating DGHSs. For their control, analog-statistical dependencies can be used, involving the indicators descriptive of the development technology [25]. Effective use of displacement characteristics is based on the water cutting and reserve recovery indicators exceeding 40 and 50 % [32]. Realistic estimation of reserves quality is achieved by GEER, especially in terms of planning the priority WIs at currently non-producing reserves.

**Case study.** Object Bsh of Asulskoe uplift at Batyrbaiskoe field is at the third stage of development. Recovery from IRR is 62 % at water cut 40 %; ORF design = 0.382. Based on the statistical dependency for carbonate deposits with reservoir pressure maintenance system, ORF st is forecasted as equal to 0.264. For the three displacement characteristics, the arithmetic mean ORF value amounts to 0.241. GEER results suggest that ORF GEER amounts to 0.247, given this production rate and accounting for WI planned by the company. Integrated analysis with independent methods shows their high repeatability (0.264; 0.241 and 0.247), which is much lower than the approved ORF design, meaning that its achievability in the current state of development is doubtful.

The fourth, conclusive stage of development is usually characterized by reliable geological reserves and possesses a history of production over a long period. Further development of objects is performed in conditions of high water cutting, diminishing well stock, focal water flooding and a number of other phenomena typical of the
conclusive stage. Many oilfields at this stage are being developed since 1950s-1970s, the time when control over technological production indicators was sporadic in general. For such “old” fields, it is quite challenging to include their history of development in DGHS process. Consequently, the estimation of recoverable reserves using hydrodynamic simulation should be combined with alternative ORF estimation methods.

At this stage of development, RRR calculation using displacement characteristics helps determine their value for the production object as a whole and for individual parts of the reservoir, wells and foci. The use of the results of geological and economic estimation of reserves in this period is of critical importance, since in-operation control of reserves and their profitability enables management of the producing well stock [42]. Annual calculation of economic recovery limit and economic water cut limit provides a basis for justified well stock shutdown, conservation and abandonment activities. This, in turn, enables operational cost improvement and makes oil production profitable over long periods of time.

Case study. Object Tl-Bb-Ml of Asulskoe uplift at Batyrbaisskoe field is under development since 1962, recovery of reserves from IRR amounts to 81% at ORF_design = 0.402. Current water cut in wells is 42% (given historical maximum 58%), a very low value for the fourth stage of development that gives a reason to suspect underestimation of actual IRRs. Using an analog-statistical dependency, as estimate of ORF_{st} = 0.408 was obtained for Visean deposits taking into account the technological development indicators. At high recovery and water cut, displacement characteristics can be quite informative; average ORF estimation for the three characteristics amounted to 0.493. GEER results suggest that, taking into account WI planned by the company, given the established production rate, ORF_{GEER} = 0.405. Analysis of results using the three alternative estimation methods (0.408; 0.493; 0.405) shows that ORF_{design} = 0.402 is achievable and can even be exceeded given the existing production effectiveness.

Using the same reservoir as an example, we shall now consider how RRR value is influenced by the annual production decline rate (Δq), economic production profitability limit (EL) and well stock decrease. Δq value for this production object during 2018 GEER was assumed equal to 8%. Taking into account the stable high level of production, Δq may be corrected downwards to 7%. This leads to RRR increment of about 15%. EL indicator for 2018 has decreased from 3.3 to 2.5 t/day/well, which results in RRR increase by 1%. Timely decommissioning of wells found unprofitable based on EL helps prolong the profitable period of reservoir development and obtain an additional 10% RRR. Thus, rational management of reserves at production objects significantly increases profitable RRRs and their ultimate oil recovery.

Conclusions

The main problem in estimating ORF using the method of geological and hydrodynamic simulation is its high cost that excludes in-operation control of the current hydrocarbon reserves. Over time, the approved ORFs can become considerably outdated due to the change in economic conditions of development or discrepancy between the actual and design development conditions. Therefore, for the reliable estimation of production objects’ RRRs it is crucial to establish in-operation control of ORFs validity, including their objective achievability within specified time frame.

In-operation controls can comprise methods based on generalization of various physical regularities (analog statistics, displacement characteristics, production decline rate analysis). Advisability of a method depends on the stage of development and degree of geological certainty. For early stages of development, it is recommended to use multivariate analog-statistical dependencies based on the geological indicators constructed for specific production objects. At later stages, higher reliability can be provided by methods based on displacement characteristics and oil production decline rate, taking into account the economic development profitability limit. Statistical dependencies alongside geological and technological development indicators can be used as a control.

Integrated use of various methodological approaches improves RRR estimation reliability at production objects. A comparative analysis between ORF_{design} and results of estimation that employed alternative methods helps forecast its current achievability and introduce necessary corrections into the development system.
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Пожалуйста, цитируйте эту статью в английском языке как:
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