ISSN: 2658–5782

Issue 1

2025

MULTIPHASE SYSTEMS

mfs.uimech.org

Mavlyutov
Institute of Mchanics

ISSN 2658–5782

20 (2025) 1: 26–32

Multiphase Systems

http://mfs.uimech.org/mfs2025.1.005
DOI 10.21662/mfs2025.1.005
UDC 622.276

Received 27.02.2025
Accepted 25.03.2025

The analysis of the development indicators of the Tournaisian deposit

A.E. Fetisov✉**, S.Z. Anokhina**

Ufa State Petroleum Technological University, Ufa, Russia

E-mail: andreyfetisov200026@mail.ru

The purpose of the present investigation is to analyze the development indicators of the Tournaisian reservoir of the Ural-Volga oil field. To complete this task, a large array of data is required, which has been obtained from the Technological Development Project. Numerical calculation is performed using software code implemented in the Python programming language with the material balance method. To minimize the material balance error in the software code, the optimize.minimize function of the SciPy library has been applied with the help of the L-BFGS-B method. The analysis of current development indicators has shown uneven development of the reserves of the Tournaisian oil deposit, as well as a positive effect of injection on the process of fluid displacement from the formation. In this paper, a material balance model has been constructed and adapted to the forecast date. As a result, the average error in the adapted parameters is 3,7%. To make a forecast for the development of the Tournaisian oil deposit, a dependence of the water cut of well production on the oil recovery factor based on core material has been constructed. The graphs of the arithmetic mean and maximum values of the absolute deviation module of the calculated water cut from the actual one, obtained due to a retrospective forecast of the synthesized from the Technological Development Project data of hydrocarbon fields at different stages of development are shown. It has been found that water cut of 98% achieved at a oil recovery factor equals to 0,335. The dependence of the reservoir flooding dynamics on the oil recovery factor has made it possible to forecast the technological development indicators, including the calculation of the dynamics of annual and cumulative oil production, as well as reservoir pressure. As a result of the calculation, the accumulated oil production has amounted to 649 thousand cubic meters with a water cut of 98%.

Keywords: the Tournaisian reservoir, development indicators, the material balance method, water cut forecast, oil recovery factor, relative phase permeability, numerical study

---

1. Introduction

Flooding of an oil deposit is one of the main problems faced by a subsoil user during field development. As a result of well flooding, the level of oil production decreases, which may lead to the unprofitable nature of the development of this well. In this regard, it is worth paying attention to the factors affecting water breakthrough to production wells and contributing to the growth of water cut [1].

The main factors affecting well flooding are:

- violation of the tightness of the production casing;
- water ingress through a leaky annular space from overlying or underlying aquifers;
- pulling up the bottom water cone;
- ingress of contour or injected water;
- behind-the-column circulation in the interval of the productive formation.

Currently, many hydrocarbon deposits are at the stage of declining oil and gas production, which is a consequence of intensive development at the initial stages. In this context, forecasting future production volumes is of particular importance. The volume of data accumulated over the years of operation allows us to adjust mathematical models to real conditions, as well as to develop forecasts for further operation, including the use of modern technologies for maintaining reservoir pressure.

To solve urgent problems, such as control and regulation of development processes, analysis of current indicators and forecasting of field development, various methods are applied such as: statistical, analytical, geological and hydrodynamic modeling.

Statistical forecasting methods with displacement characteristics are widely implemented to forecast technological indicators of hydrocarbon deposit development in the conditions of imperfect geological and field information. For deposits in the early stages of development, displacement characteristics obtained on the basis of analysis of actual field data may have low predictive ability [2].

The main advantage of these methods is the high adequacy of the description of actual values from the Technological Development Project (TDP) [1] by the mathematical model due to its low requirements for the volume of input data [3].

In the work [4] the displacement characteristics, which are functional dependencies of technological indicators of development and description of fluid filtration in the reservoir for a given development system, can be determined basing on the analysis of the actual values of TDP and actual values of hydrocarbon deposits; results of the laboratory studies of core and formation fluids of hydrocarbon deposits; data from analog deposits. But the efficiency of determining displacement characteristics is significantly affected by the quality of geological and production data and the current state of field development.

In practice, the determination of displacement characteristics using actual values of technological indicators of hydrocarbon deposit development has become widespread [3]. However, the received functional dependencies may have low predictive ability in the case of deposits at early stages of development.

The analytical methods of predicting water cut are among the main methods because they help an engineer to make calculations in the field with a satisfactory degree of convergence of results. There are various analytical methods for forecasting the development of deposits, a classic example of which is the material balance. This is a universal method that allows to take into account the fluid that is in the formation, as well as extracted from the reservoir during development. The examined Schilthius material balance method [5] provides conducting the necessary calculations.

Geological and hydrodynamic modeling is an integral part of the analysis and design of oil field development; the use of modeling and its role are determined by the features of the geological structure and the state of development of production facilities [6]. The main objective of the modeling is to justify geological and technical measures in the medium and long-term development prospects, and to optimize development systems for depleted fields using modern technologies for optimizing flooding and tertiary methods for enhancing oil recovery.

There are many approaches to forecasting the performance of oil fields [7–10]. This research considers the material balance method [5], which allows for a detailed description of the process of fluid displacement from the reservoir. This method is one of the most promising for analyzing and predicting development indicators. It is based on the law of conservation of mass. Calculations let the fluid contained in the system, as well as entering and exiting it. For a better understanding, the reservoir can be imagined as a large elastic reservoir, the contents of which change during the development of the field. The fluid in the reservoir can compress and expand along with its storage [11].

Thus, the purpose of the present paper is to analyze the development indicators of the Tournaisian reservoir of the Ural-Volga oil field.

2. Problem statement

This research work deals with the material balance method based on the Schilthius equation [5], which can be written as follows:

$$N(B_t - B_{ti}) + NmB_{ti}\left(\frac{B_{gc} - B_{gi}}{B_{gi}}\right) +$$

$$+N\frac{B_{ti}S_{wio}}{1-S_{wio}}\left(\frac{B_{tw}-B_{twi}}{B_{twi}}\right) + N\frac{mB_{ti}S_{wig}}{1-S_{wig}}\left(\frac{B_{tw}-B_{twi}}{B_{twi}}\right) +$$

$$+N\left(\frac{1}{1-S_{wio}} + \frac{m}{1-S_{wig}}\right)B_{ti}c_f\Delta P =$$

$$= N_pB_o - N_pR_{so}B_g + [G_{ps}B_g + G_{pc}B_{gc} - G_iB'_g] -$$

$$-(W_e + W_i - W_p)B_w,$$

where B_g is the gas volume factor, B_{gc} is the gas volume factor in the gas cap, B'_g is the injected gas volume factor, B_o is the oil volume factor, $B_t = B_o + (R_{si}?R_{so})B_g$ is the composite oil volume factor, B_{ti} is the initial value of B_t, $B_{tw} = B_w + (R_{swi}?R_{sw})B_g$ is the composite water volume factor, B_w is the water volume factor, c_f is the compressibility of the reservoir (rock), G is the initial gas reserves in the reservoir, G_i is the cumulative gas injection, G_{pc} is the cumulative gas production from the gas cap, G_{ps} is the cumulative production of gas dissolved in oil (evolved gas), m is the ratio of the gas volume to the volume of oil in the reservoir, N is the initial oil reserves in the reservoir, N_p is the cumulative oil production, R_{so} is the gas content of oil, R_{si} is the initial gas content of oil, R_{sw} is the gas content water, R_{swi} is the initial gas content of water, S_g is the gas saturation, S_o is the oil saturation, S_w is the water saturation, S_{wi} is the initial water saturation, S_{wig} is the initial water saturation of the gas cap, S_{wio} is the initial water saturation of the oil zone, We is the accumulated volume of aquifer water injected into the formation, W_i is the accumulated water injection, W_p is the accumulated water production, ΔP is the pressure change, P_1 is the initial reservoir pressure, P is the reservoir pressure.

3. Methods and approaches

To analyze the development indicators of the Tournaisian reservoir of the Ural–Volga oil field, a large array of data is required, which have been obtained from TDP [1]. The calculation of the above equation is performed using a program implemented by the author of this work in the Python programming language [12, 13]. The variables for the material balance equation are given in Tab. 1.

Table 1. Energy state indicators of the Tournaisian stage

Indicator	The object as a whole
Initial reservoir pressure, MPa	19,0
Average weighted reservoir pressure, MPa	18,2
Change, MPa / %	0,8 / 4,2
Accumulated compensation, %	167,0
Current compensation, %	283,4
Number of operating wells	
mining	15
injection	5

Table 2. Adaptable parameter boundaries

Adaptable parameter	**Border (multiplier)**	
	Lower limit (units)	**Upper limit (units)**
Reservoir pressure	0,01	100
Initial Recoverable Reserves	0,99	1,01
Compressibility coefficient of the formation	0,1	10

Having calculated all the necessary coefficients for each of the years of field operation (1984–2011), the final material balance equation is compiled and solved relative to the volume of initial reserves N.

Thus, when comparing the obtained values of the equation and the actual values of N given in the development project, the correctness of the obtained reservoir model can be verified.

Having received a table for the initial reserves N, a deviation is observed from the indicators presented in the TDP. These deviations can be explained by the inaccuracy of determining the coefficients, as well as inaccurate measurements of reservoir pressures. To solve this problem and correctly adapt the model, the following method is proposed.

By solving the material balance equation relative to zero, the obtained values of the above parameters allow us to minimize the error, thereby adapting the model under consideration to real conditions. The following boundaries of the adapted parameters are used in the work (Tab. 2).

To minimize the material balance error, the optimize.minimize function of the SciPy library has been applied in the program code, using the L-BFGS-B method. The BFGS-B method is an iterative method of numerical optimization, named after its researchers: Broyden, Fletcher, Goldfarb, Shanno [14]. This method belongs to the class of so-called quasi-Newton methods. Unlike Newtonian methods, quasi-Newton methods do not directly calculate the Hessian of the function, i.e. there is no need to find partial derivatives of the second order. Instead, the Hessian is calculated approximately, based on the steps taken so far, since this method allows us to optimize the function in the presence of boundary conditions for the adapted parameters.

As a result of optimization, the following values of the parameters under consideration have been obtained (Tab. 3).

4. Numerical results

The recoverable oil reserves of the Tournaisian stage were practically independent of the year of operation and their value was approximately equal to 1,84 million m^3. The graph of the drop in estimated and actual reservoir pressures is shown in Fig. 1.

The average values of the parameters from 1987 to 2017 years of development have been selected as optimized parameters, since small values of cumulative production in the first years of development can lead to a significant error in solving the material balance equation.

Based on the above, the material balance model can be considered adjusted, since it describes the development history and the mechanism of displacement of reservoir fluid with satisfactory accuracy. The next stage of the work is forecasting the development of the field.

For a more correct and accurate development forecast, it is necessary to set parameters that would fully reflect the process of fluid displacement from the formation. So it is significant to calculate the oil recovery factor (ORF) from the formation. By comparing calculated and actual coefficients, the mathematical model of the reservoir can be adjusted to historical development data [15].

To calculate the numerical ORF, it is necessary to know the characteristics of oil displacement by water. An extremely important parameter in constructing displacement

Table 3. Adaptable parameters

Reservoir pressure, (atm)	**Initial recoverable reserves, (million m^3)**	**Compressibility coefficient, $(10^{-5} \cdot 1/\text{atm})$**
192,0	0,00	20000000
169,8	1,94	451,4
166,2	1,94	385,0
160,0	1,94	307,9
154,1	1,94	259,0
149,9	1,94	234,7
148,8	1,94	234,6
148,5	1,94	234,6
149,1	1,94	234,7
150,7	1,94	236,4
152,6	1,94	245,8
153,6	1,94	258,7
154,0	1,94	265,3
154,1	1,94	259,8
153,2	1,94	251,6
151,8	1,94	236,0
152,1	1,94	234,6
152,3	1,94	234,4
151,7	1,94	234,4
152,8	1,94	234,3
152,9	1,94	234,3
152,9	1,94	234,3
151,9	1,94	234,3
151,6	1,94	234,4
153,5	1,94	234,4
154,9	1,94	234,5
157,6	1,94	234,6
160,9	1,94	259,0
167,0	1,94	306,0
171,9	1,94	352,7

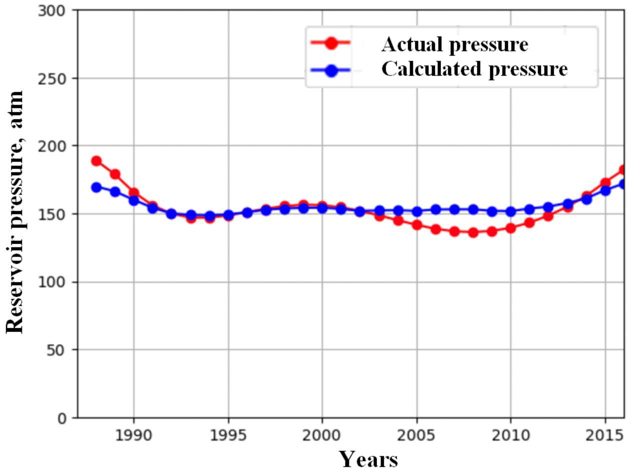

Figure 1. Dynamics of reservoir pressures (blue color is calculation; red color is actual)

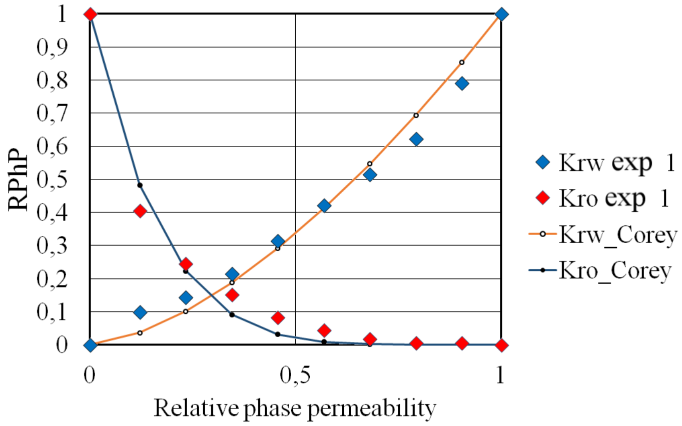

Figure 2. Relative phase permeability curves

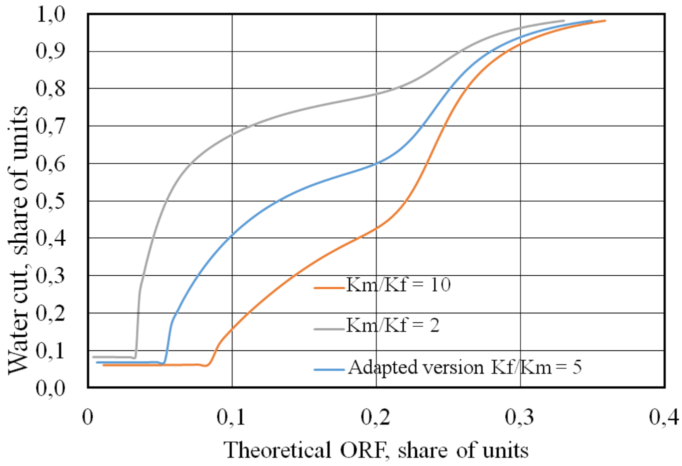

Figure 3. Comparison of permeability ratios

Table 4. Relative phase permeabilities for oil and water

Water saturation of pore space	RPhP for water	RPhP for oil
0,08	0	1
0,23321	0,02401	0,40534
0,28642	0,03534	0,24488
0,33963	0,05233	0,15049
0,39284	0,07687	0,08253
0,44604	0,1033	0,04289
0,49925	0,12595	0,01646
0,55246	0,15238	0,00513
0,60567	0,19391	0,00513
0,651	0,24488	0
0,8595	0,64321	0
1	1	0

characteristics is the relative phase permeability (RPhP),which is found with a calculation based on the data presented in the development project (Tab. 4).

Obtaining generalized RPhPs occurs through the use of the Corey power model [16]:

$$Krw = KRWR \cdot (S^{norm})^{nw},$$

$$Kro = KRORW \cdot (1 - S^{norm})^{no},$$

$$S_i^{norm} = \frac{S_i - SWL}{1 - SOWCR - SWL}.$$

Based on the least squares method, the parameter values of nw and no, corresponding to the best approximation of the model curves to the experimental data, are obtained (Fig. 2):

$$Krw(S_i) = 0,277 \cdot \left(\frac{S_i - 0,178}{1 - 0,376 - 0,178}\right)^{4,44},$$

$$Kro = 1 \cdot \left(1 - \frac{S_i - 0,178}{1 - 0,376 - 0,178}\right)^{2,84}.$$

Using the dual permeability model [17], and also having the RPhP values for the pore space, a graph of the dependence of water cut on ORF can be obtained. As a result of the calculations, a water flow curve for the N field, considering filtration both in the matrix and in the fracture space, can be constructed. The water cut curve is constructed basing on core study data; at the initial moment of time, the water saturation of the reservoir exceeds the associated water saturation, thus the theoretical water cut curve does not start from zero. The nature of this curve is affected by the permeability of fracture and pore space. Studies are carried out for several permeability ratios as shown in Fig. 3.

With an increase in the ratio of matrix permeability to the fracture, a characteristic decrease in the convex part of the water cut curve and an increase in the ORF (upon reaching a water cut of 98%) occurs, which is obviously associated with the greater role of the oil-saturated matrix in the total inflow. In the case of a lower permeability ratio, the convex part rises and the ORF decreases (upon reaching

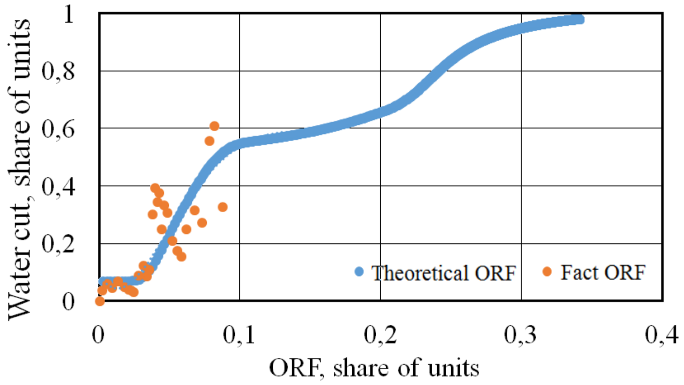

Figure 4. Comparison of permeability ratios

a water cut of 98%). Since a decrease in the ratio between the permeabilities of the matrix and the fracture results in an earlier breakthrough of water, which causes an increase in the water content of the product, affecting the decrease in the ORF.

In order to optimize the actual and theoretical ORF, the model parameters have been adapted. As a result, the following graph of the dependence of water cut on the ORF has been obtained (Fig. 4), corresponding to a permeability ratio of 5, which clearly describes the historical dynamics of water cut.

The calculation of the field development forecast will be performed basing on the recommended forecast option presented in the TDP. This option involves drilling three sidetracks and one horizontal sidetrack, as well as transferring two wells from other sites into production and putting one production well into production. Drilling of an injection sidetrack and commissioning of three injection wells. Maximum oil production is 600 thousand tons. The forecast is made until the water cut of the production reaches 98%. The block diagram of the calculation step of the algorithm for forecasting the development indicators of a field based on the material balance equation is presented in the work [18]. The calculation of the RPhP for oil and water has been carried out basing on the parameters no and nw adapted to the development history. The number of production and injection wells corresponds to the recommended development option. The productivity and injectivity coefficients are taken to correspond to the dynamics of annual fluid withdrawals and injection. For predictive calculations, boundary conditions at production wells are used in the form of constant fluid flow rate, and at injection wells they are used in the form of constant bottomhole pressure.

The values of reservoir pressures, cumulative oil production, and annual oil production are presented at Figs. 5, 6 and 7, respectively.

Next, a comparison has been made between the calculated forecast for the development of the Tournaisian deposit and the forecast according to the state plan presented in the field development project. The comparison is based on the main parameters: cumulative oil production, annual oil production, ORF, and water cut. For a visual

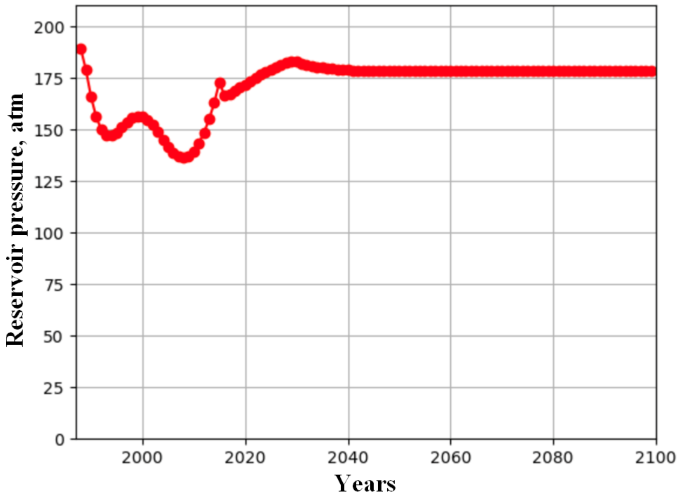

Figure 5. Dynamics of reservoir pressures

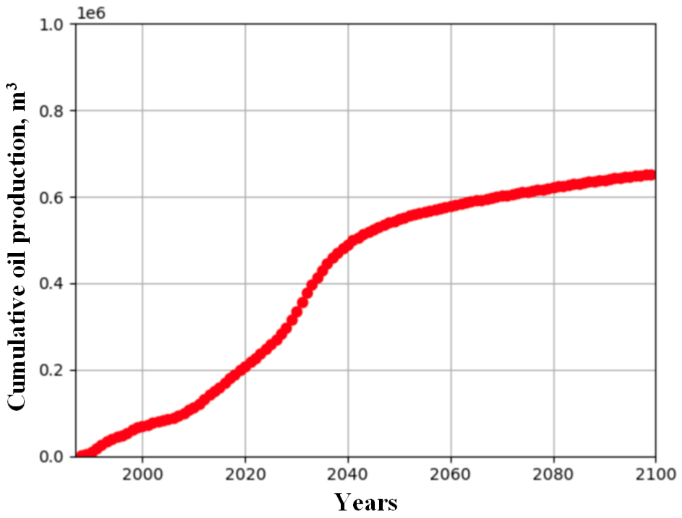

Figure 6. Dynamics of cumulative oil production

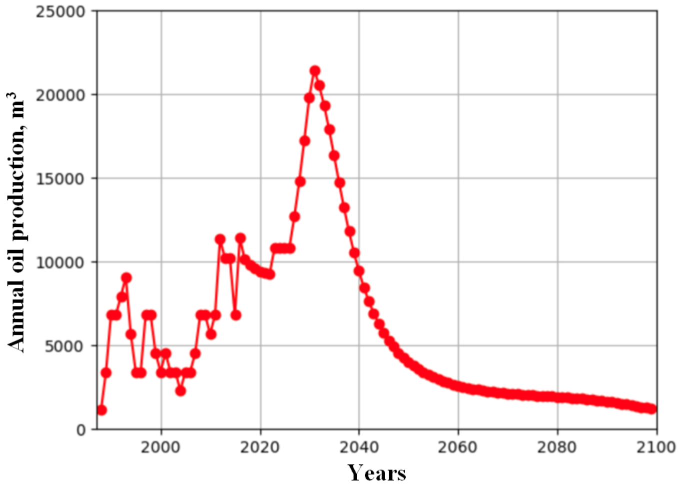

Figure 7. Dynamics of annual oil production

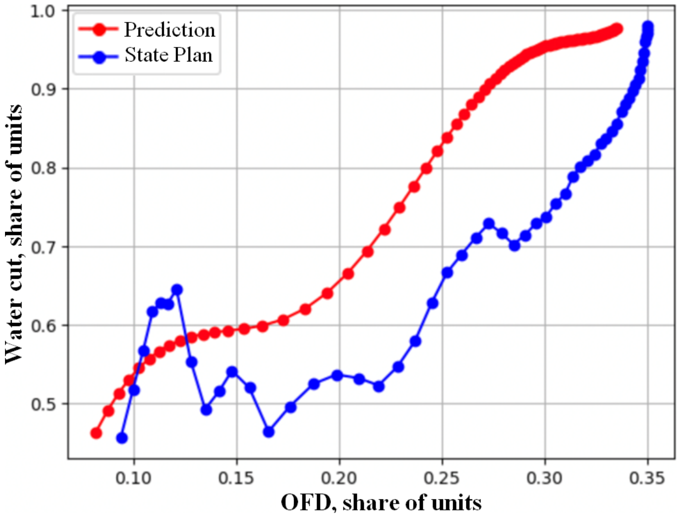

Figure 8. Dependence of water cut on ORF

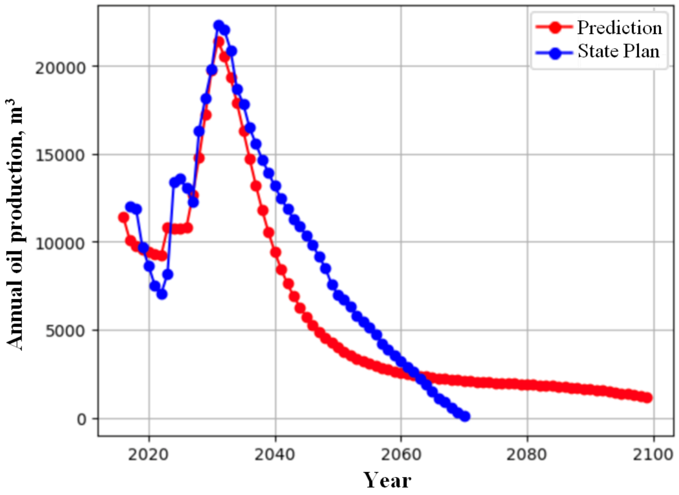

Figure 9. Dynamics of annual oil production

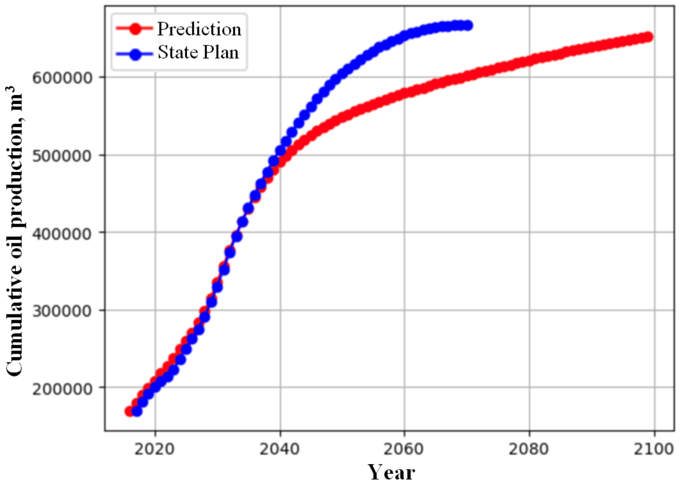

Figure 10. Dynamics of cumulative oil production

comparison of the calculated parameters, graphs of the dependence, reflecting the forecast made using the material balance method, as well as the forecast based on data from the state plan, are presented in Figs. 8, 9 and 10.

The difference in the behavior of the curves shown in the graphs can be explained by the inaccuracy of the parameters describing the reservoir, such as c_f, m, and by the inaccurate determination of the initial recoverable reserves. This is also influenced by the difference in depression on the reservoir for injection and production wells proposed in the state plan and in the forecast.

Of course, the inaccuracy of the injectivity and productivity coefficients of wells, selected on the basis of the calculated volumes of water injection and oil production, respectively, also has an impact. It is also worth noting that in the TDP the various geological and technical measures, including repair and insulation work, which also affect the achievement of the final ORF and the dynamics of annual and cumulative oil production, are provided. According to the author's calculation, performed with the help of the material balance method, when adapting the model from 1987 to 2017, these events have not been taken into account. Therefore the ORF achieved in the calculation (0,335 with a water cut of 98%) is representative for the development of the deposit using the existing development system with the introduction of design wells.

5. Conclusion

The analysis of current development indicators has shown uneven development of reserves of the Tournaisian oil deposit, as well as a positive effect of injection on the process of fluid displacement from the formation.

In this research a material balance model has been constructed and adapted to the forecast date. As a result, the average error in the adapted parameters is 3,7

To make a forecast for the development of the Tournaisian oil deposit, a dependence of the water cut of well production on the ORF has been constructed basing on the core material. Having investigated the obtained dependence, one can conclude that water cut of 98% is achieved at ORF equals to 0,335.

Based on the obtained dependence of the reservoir flooding dynamics on the ORF, a forecast of the technological development indicators has been made. This forecast includes the calculation of the dynamics of annual and cumulative oil production, and reservoir pressure. As a result of the calculation, the accumulated oil production has amounted to 649 thousand cubic meters with a water cut of 98%. The forecast data do not take into account various geological and technical measures aimed at eliminating water breakthroughs, as well as leveling the inflow profile, in connection with which the recovery factor obtained in the author's calculation is somewhat less than the recovery factor presented in the state plan. Nevertheless, this calculation is representative for the development of a deposit using an established system with the introduction of design wells.

References

[1] Géron Au. Hands-On Machine Learning with Scikit-Learn and TensorFlow. O'Reilly Media, Inc., 2017. 572 p.

[2] Fetisov A.E., Khatmullina R.S. Research of numerical indicators for the development of the Asselskaya area of Orenburg oil and gas condensate field using the material balance method. Multiphase Systems. 19 (2024) 1. 1–6.
DOI: 10.21662/mfs2024.1.001

[3] Kharisov M.N., Karpov A.A., Petrov S.V., Darii S.D. [Algorithm for the Determination of Displacement Characteristics] *Algoritm opredeleniya optimal'nykh kharakteristik vytesneniya*. Neftyanoe khozyaistvo — Oil Industry. 2018. No. 5. Pp. 56–59 (in Russian).
EDN: XNSWVV

[4] Garifullin A.Sh., Kurmakaeva S.A., Rodin V.I. The Use of Empirical Dependences in the Design of the Krasnokholm Group Field Development. Collection of Scientific Papers: Problems of Geology and Development of Oil Fields in Areas with Dwindling Resources. Ufa, BashNIPIneft' Publ. 1989. Pp. 81–86 (in Russian).

[5] Schilthuis RJ. Active Oil and Reservoir Energy. Transactions of the AIME. 118 (1936) 01. 33–52.
DOI: 10.2118/936033-G

[6] Zakirov R.Kh. Role of geological-hydrodynamic modelling at designing of oil field development // Georesources. 32 (2009) 4. Pp. 34–36 (in Russian).
EDN: kxykgl

[7] Muskat M. The Flow of Homogeneous Fluids through Porous Media. McGraw-Hill Book Company, 1937. 763 p.

[8] Peaceman D.W. Fundamentals of Reservoir Engineering. Elsevier Scientific Publishing Company, 1977. 176 p.

[9] Mohaghegh S. Data-Driven Reservoir Modeling: A New Paradigm in Reservoir Management. Society of Petroleum Engineers, 1945. 166 p.

[10] Arps JJ. Analysis of Decline Curves. Transactions of the AIME. 160 (1945) 01. Pp. 228–247.
DOI: 10.2118/945228-G

[11] Technological project for the development of ONGCM. LLC VolgoUralNIPIgaz, 2012 (in Russian).

[12] Lutz M. Learning Python, 4th edition. O'Reilly Media, Inc., 2009. 1213 p.

[13] Nocedal J., Wright St.J. Numerical Optimization, 2nd edition. USA: Springer, 2006. 684 p.

[14] Fanci J.R., Christiansen R.L. Introduction to oil production technology. Hoboken, NJ: John Wiley & Sons, 2009. 290 p.

[15] Mishchenko I.T. Calculations in oil and gas production. Moscow: Neft' i gaz. 2008. 296 p. (in Russian).

[16] Corey A.T. The Interrelation between Gas and Oil Relative Permeability. Producers Monthly. 19 (1954) 1. 38–41.

[17] Gu Sh., Liu Yu., Chen Zh., Ma C. A method for evaluation of water flooding performance in fractured reservoirs. Journal of Petroleum Science and Engineering. 120 (2014). 130–140.
DOI: 10.1016/j.petrol.2014.06.002

[18] Dake L.P. Fundamentals of reservoir engineering. Amsterdam: Elsevier, 2003. 496 p.

Information about the Authors

Andrey E. Fetisov
Ufa State Petroleum Technological University, Ufa, Russia
`andreyfetisov200026@mail.ru`
ORCID: 0009-0004-4659-3902

Svetlana Zagirovna Anokhina
Ph.D. (Philological)
Ufa State Petroleum Technological University, Ufa, Russia
`Globusextern@yandex.ru`
ORCID: 0000-0002-7436-120X