ORIGINAL ARTICLE

DOI: https://doi.org/10.18599/grs.2021.3.10 Russian Original 2021. Vol. 23. Is. 3. Pp. 73–82

Prediction of reservoir pressure and study of its behavior in the development of oil fields based on the construction of multilevel multidimensional probabilistic-statistical models

*V.I. Galkin, I.N. Ponomareva, D.A. Martyushev**
Perm National Research Polytechnic University, Perm, Russian Federation

---

Abstract. Determination of the current reservoir pressure in oil production wells selection zones is an urgent task of field development monitoring. The main method for its determination is hydrodynamic studies under unsteady conditions. At the same time, the process of restoring bottomhole pressure to the value of reservoir pressure often lasts a significant period of time, which leads to long downtime of the fund and significant shortfalls in oil production. In addition, it seems rather difficult to compare reservoir pressures with each other in the wells due to the different timing of the studies, since it is impossible to simultaneously stop the entire fund for measuring the reservoir pressure in the field. The article proposes a new method for determining the current reservoir pressure in the extraction zones, based on the construction of multidimensional mathematical models using the data of geological and technological development indicators. As the initial data, the values of reservoir pressure, determined during processing of the materials of hydrodynamic studies of wells, as well as a set of geological and technological indicators, probably affecting its value, were used (initial reservoir pressure for each well, the duration of its operation at the time of study, liquid rate, bottomhole pressure, the initial and current permeability of the collector in the drainage area, gas-oil ratio, accumulated values of production of oil, liquid and water, skin factor). In the course of the research, several variants of statistical modeling were used, in the process of which the regularities of the reservoir pressure behavior during the development of reserves were established, individual for the object of development. The obtained models are characterized by a high degree of reliability and make it possible to determine the desired value with an error of no more than 1.0 MPa.

Keywords: statistical analysis, well testing, significance level, well operation, formation permeability, current reservoir pressure

Recommended citation: Galkin V.I., Ponomareva I.N., Martyushev D.A. (2021). Prediction of reservoir pressure and study of its behavior in the development of oil fields based on the construction of multilevel multidimensional probabilistic-statistical models. *Georesursy = Georesources*, 23(3), pp. 73–82. DOI: https://doi.org/10.18599/grs.2021.3.10

Introduction

For effective monitoring of the oil fields development, the most important indicator, which must be constantly monitored and which characterizes the energy of the reservoir, is reservoir pressure (Dragunov et al., 2017; Olalere Oloruntobi et al., 2019; Karmanskiy et al., 2020; Saeed Rafieepour et al., 2020). In the practice of oilfield business, the results of hydrodynamic studies (HDS) of wells are often used to determine reservoir pressure. When conducting hydrodynamic testing, it is necessary to shut down production wells for a certain time, in some cases for a very long time, which is subsequently accompanied by oil shortages, and this is the main disadvantage of this method (Ponomareva et al., 2016; Davydova et al., 2018; Davydova et al., 2019; Martyushev et al., 2019). At present, especially in the study of low-rate wells, it is extremely rare that there is a complete recovery of the downhole reservoir pressure. However, in RD-153-39.0-109-01 (Methodology instructions for the integration and stages of the implementation of geophysical, hydrodynamic and geochemical studies of oil and oil-and-gas fields, RD-153-39.0-109-01, 2002) in clause 10.2 it is prescribed precisely measurement of reservoir pressure, which can only be performed with full recovery of the bottomhole pressure in a shut-in well. It should be noted that in practice the RD requirement for reservoir pressure measurement is never met due to a variety of production reasons, including, as already described, the very long time required to restore the bottomhole pressure to reservoir pressure, as well as a permanent but variable effect on operating pressure of surrounding wells. It is also an important point that it is impossible to simultaneously stop the entire stock of producing wells to measure reservoir pressure, and therefore, it is rather difficult to compare reservoir pressures with each other due to different duration of shut-in periods.

The analysis of foreign and domestic scientific literature made it possible to distinguish three groups for assessing reservoir pressure. The first group is a method for interpolating reservoir pressure measurements. The

---

*Corresponding author: Dmitriy Martyushev
E-mail: martyushevd@inbox.ru

main drawback of this method is a significant error, which arises due to the fact that reservoir pressure measurements were taken at different time intervals (Escobar et al., 2007; Vaferi et al., 2015; Elesin et al., 2018). The second group is the use of the superposition principle using production data from production wells (Ahmadi, 2017; Dyagilev et al., 2019). A significant error in calculations when using this method occurs on objects that are characterized by significant heterogeneity of reservoir porosity and permeability. The third group is the use of modern geological and hydrodynamic models (Abrosimov et al., 2018; Salam Al-Rbeawi et al., 2018). The disadvantage of this method is the complexity of creating and adapting geological and hydrodynamic reservoir models.

Other methods for assessing reservoir pressure can also be distinguished, for example, in the article (Escobar et al., 2007) to determine the average reservoir pressure for a reservoir, the authors propose to use the Tiab Direct Synthesis (TDS) method, but this method allows assessing only average pressure across the reservoir, and not specifically for each well.

The most accurate method is described in (Akinbinu, 2010), in which the author uses correlation analysis in combination with stepwise multiple regression statistical technique to determine the fracture gradient, pore pressure and true vertical depth of field, determined by oil and gas generation data, to investigate the correlation that exists between these properties. However with this mathematical analysis, the author does not estimate the current reservoir pressure, but its change after hydraulic fracturing.

Thus, based on the analysis of domestic and foreign scientific literature, it has been established that the problem of determining the reservoir pressure during the operation of wells remains relevant today (Childers et al., 2020; Nur Wijaya et al., 2020).

The authors in the article propose to use indirect methods – methods of mathematical statistics to assess reservoir pressure. Below is description of the proposed method for determining the current reservoir pressure.

Materials and methods

The proposed method was developed on the basis of production data from the wells of the oil field named after Sukharev. This field is characterized by the presence of a significant amount of residual reserves and significant experience in conducting hydrodynamic studies with the determination of reservoir pressure.

The oil field named after Sukharev is located in the northern part of the Perm Territory. Commercial oil production is carried out from three objects: carbonate deposits C_2b (Bsh) and D_3fm (Fm), terrigenous deposits C_2v (Bb). Brief geological and physical characteristics of the objects are given in Table 1.

The main idea of the study is as follows: data on actual reservoir pressures are collected for all wells of the field, which were measured during hydrodynamic studies. Also, numerous geological and commercial material was collected for these wells – the values of indicators characterizing well performance during the periods of these studies.

At the initial stage, a correlation analysis is performed, which allows to determine the indicators having significant effect on the reservoir pressure value (Rastorguev, 2019). Further, using step-by-step regression analysis, multidimensional reservoir pressure prediction models are built (Kochnev et al., 2018; Galkin et al., 2019; Virstyuk et al., 2020).

The following production parameters were used to develop a method for predicting reservoir pressure:

- current reservoir pressure, determined during well testing (P_{ResT}, MPa) – predicted value;
- initial reservoir pressure (determined by the first well test) (P_{Res0}, MPa);
- duration of well operation since commissioning after drilling (T, days);
- current flow rates of liquid (Q_L, m^3/day) and oil (Q_O, t/day);
- bottomhole pressure (current) (P_{bh}, MPa);
- initial permeability, determined by the first well test (K_0, mD);
- current permeability (K_C, mD);
- condition of the bottomhole zone (skin factor) (S, dimensionless value);
- oil production (cumulative) (Q_{Ocum}, t);
- liquid production (cumulative) (Q_{Lcum}, m^3);
- water production (cumulative) (Q_{Wcum}, t);
- gas / oil ratio (GOR, m^3/t).

During the studied period at the wells of the Sukharev field conducted 185 hydrodynamic studies with determination of reservoir pressure, therefore, 185 values of each of the 12 listed indicators were used for the analysis.

As noted earlier, step-by-step regression analysis (SRA) was used to build the models. P_{ResT} acts as a

Item	Characteristics	The reservoir value		
		D_3fm	C_2v	C_2b
1	Depth of occurrence, m	2472.9	2449.9	2056.2
2	Oil viscosity res. cond's, mPa · s	2.46	2.53	17.5
3	Gas/oil ratio, m^3/t	68.1	66.5	21.3
4	Initial reservoir pressure, MPa	21.46	19.83	18.46
5	Bubble point pressure, MPa	11.98	12.88	10.14

Tab. 1. Brief geological and physical characteristics of the Sukharev oil field reservoirs

dependent feature, and the values of P_{Res0}, T, Q_L, Q_O, P_{bh}, K_0, K_C, S, Q_{Ocum}, Q_{Lcum}, Q_{Wcum} and GOR act as independent factors. It should be noted that the theory of constructing multivariate statistical models implies the use of independent parameters as input data. In this case, the specified requirement cannot be fully met, since at the stage of planning the study, the list of those parameters that will be included in the model is unknown. In addition, almost all parameters that characterize the development and operation of oil deposits are to some extent dependent on each other, since they describe different components of a single reservoir-well hydrodynamic system.

It should also be noted that the list of input indicators does not include parameters characterizing the presence of adjacent wells, their purpose and operational features. Currently, there is no unambiguous way to account for the work of an element of the development system that does not load or complicate the developed model, research in this direction is only underway. However, it is likely that if the surrounding wells affect the operation of the well – the object of research, this should affect the values of its performance indicators (the so-called well interference phenomenon), that is, indirectly, this influence is taken into account in the model.

The choice of statistical modeling as a tool is due to the fact that it is a multidimensional model (multiple regression) that allows taking into account the cumulative influence of all independent factors on a dependent variable (Aaditya Khanal et al., 2017; Chernykh et al., 2017; Galkin et al., 2019). And the multiple regression equation obtained as a result of modeling can be used as a mathematical basis for the method of determining reservoir pressure without shut-in the well for research.

It is worth noting that a decreasing sample was used in the construction of models. All the initial data were ranked by the magnitude of reservoir pressure from maximum to minimum in order to reproduce its behavior during the production of reserves.

For each of the constructed models, statistical characteristics were calculated, which can be used to assess its reliability: the coefficient of multiple correlation (determination) R and the level of its significance *p*, as well as the standard error of calculations S_0. The step-by-step method of building models allows to analyzing the effectiveness of modeling on all ranges of reservoir pressure. For this purpose, the coefficient R was calculated for each of the intermediate models, after which graphs were built, reflecting its behavior depending on the magnitude of the reservoir pressure. The presence on the graph of any prominent areas with their characteristic behavior R indicates a special regularity in the behavior of reservoir pressure in this range and is the mathematical basis for dividing the entire study sample into separate parts.

Also, for each model, an analysis was made of what parameters are used in it and what is the ordinal number of their inclusion. It should be noted that the factors that are in the first places have a prevailing influence on the forecast value. This analysis will make it possible to establish factors having the greatest influence and controlling the magnitude of reservoir pressure in the conditions of the considered field. It is also possible to build a model that will include not all used parameters as input data, but only those that have the greatest impact on the reservoir pressure. Obviously, this model will have a much simpler form. Simpler equations are easier to use for rapid assessment of the predicted parameter (reservoir pressure).

The construction of models is carried out using a multi-level approach, according to which different differentiation of research objects is used:

- first level – all deposits are generalized;
- second level – differentiated for each deposit;
- the third level is the integrated use of previously developed models.

It is assumed that it is the multilevel approach that will allow the most detailed analysis of the individual patterns of reservoir pressure behavior for the oilfield and obtain the most workable mathematical models for its determination (prediction).

To demonstrate the practical application of the developed methodology based on the use of multidimensional models, as well as to assess the reliability of its results, a control sample was used. For this purpose, all materials on wells have been collected, on which hydrodynamic studies were carried out to determine the actual reservoir pressures in the period after the construction of multidimensional models. These materials were not used as source data. Based on the complex of field data, the values of reservoir pressures were calculated according to the developed method, which were then compared with the actual reservoir pressures obtained during hydrodynamic studies at the wells.

Results of the study of correlations

The results of the study of correlations between the studied parameters are presented in the form of a correlation matrix (Table 2).

Below are the results of building and analyzing models for the three levels identified earlier.

First level of modeling

Within the framework of the first level (L1) of modeling, a multidimensional model was built, which has the following form:

$$P_{ResL1} = 3.858 + 0.4977 \cdot P_{Res0} - 0.0037 \cdot T + 0.3096 \cdot P_{bh} + 0.0001 \cdot Q_{Wcum} - 0.0006 \cdot K_C + 0.0216 \cdot S + 0.00001 \cdot Q_{Ocum}; \quad (1)$$

at R = 0.892, $p < 0.0000$, standard error S_0 = 1.38 MPa.

	P_{ResT}, MPa	P_{Res0}, MPa	T, days	Q_L, m^3/day	Q_O, m^3/day	P_{bh}, MPa	K_0, mD	K_C, mD	S	Q_{Ocum}, t	Q_{Lcum}, m^3	Q_{Wcum}, t	GOR, m^3/t
P_{ResT}, MPa	1.00** 1.00 1.00 1.00	0.64* 0.67* 0.55* 0.41*	-0.32* -0.39* -0.44* -0.27	0.46* 0.72* 0.15 0.01	0.53* 0.64* 0.15 -0.05	0.62* 0.74* 0.27* 0.12	-0.24* 0.07 -0.33* -0.40*	-0.08 0.08 -0.29 -0.52*	0.17 0.37* 0.18 -0.04	-0.08 -0.05 0.16 -0.24	-0.05 -0.03 0.15 -0.22	0.12 0.10 0.05 0.10	0.07 0.30* -0.39* -0.41*
P_{Res0}, MPa		1.00 1.00 1.00 1.00	0.31* 0.28* 0.19 0.39*	0.35* 0.62* -0.22 0.75*	0.40* 0.56* -0.22 0.71*	0.19 0.27* -0.19 0.29*	-0.45* -0.20 -0.49* -0.60*	-0.23* -0.08 -0.29* -0.31	0.20* 0.17 0.52* -0.07	0.51* 0.60* 0.16 0.58*	0.51* 0.59* 0.15 0.57*	0.22* 0.23* 0.05 -0.09	0.19 0.46* -0.29* -0.11
T, days			1.00 1.00 1.00 1.00	-0.17* -0.26* -0.17 0.22	-0.16* -0.28* -0.17 0.22	-0.46* -0.65* -0.26* -0.16	-0.13 -0.19 0.04 -0.30	-0.13 -0.18 -0.01 0.01	-0.05 -0.27* 0.20 -0.19	0.90* 0.87* 0.94* 0.91*	0.90* 0.87* 0.94* 0.94*	0.36* 0.36* 0.82* 0.42*	0.25* 0.05 0.40* 0.33*
Q_L, m^3/day				1.00 1.00 1.00 1.00	0.96* 0.95* 0.99* 0.99*	0.59* 0.62* 0.56* 0.42*	0.08 0.06 0.44* -0.40*	0.16 0.11 0.40* 0.02	-0.01 0.15 -0.10 -0.21	0.16 0.11 0.04 0.54*	0.15 0.10 0.04 0.47*	-0.02 0.01 0.09 -0.56*	0.24* 0.55* 0.03 0.09
Q_O, m^3/day					1.00 1.00 1.00 1.00	0.57* 0.59* 0.57* 0.49*	0.10 -0.01 0.44* -0.30	0.18 0.11 0.41* 0.08	0.02 0.15 -0.09 -0.21	0.14 0.08 0.04 0.54*	0.10 0.04 0.04 0.46*	-0.21* -0.22* 0.09 -0.57*	0.22* 0.50* 0.03 0.11
P_{bh}, MPa						1.00 1.00 1.00 1.00	0.21* 0.26* 0.53* 0.30	0.31* 0.30* 0.54* 0.33*	-0.03 0.11 -0.16 -0.06	-0.27* -0.38 -0.18 0.01	-0.26* -0.37 -0.17 -0.04	-0.08 -0.09 -0.04 -0.40	0.20* 0.43* -0.01 -0.06
K_0, mD							1.00 1.00 1.00 1.00	0.63* 0.63* 0.71* 0.65*	0.04 0.08 -0.25* 0.01	-0.13 -0.20 0.10 -0.32	-0.13 -0.16 0.10 -0.35*	-0.06 0.19 0.09 -0.27	0.12 0.19 0.23 0.05
K_C, mD								1.00 1.00 1.00 1.00	0.17 0.08 0.06 0.21	-0.09 -0.14 0.08 0.05	-0.10 -0.14 0.08 -0.01	-0.09 -0.03 0.07 -0.34	0.19* 0.32* 0.13 0.41*
S									1.00 1.00 1.00 1.00	-0.03 -0.16 0.21 -0.23	-0.03 -0.16 0.20 -0.22	-0.07 -0.01 0.10 0.07	0.12 -0.14 -0.10 0.00
Q_{Ocum}, t										1.00 1.00 1.00 1.00	0.99* 0.99* 0.99* 0.99*	0.34* 0.34* 0.91* 0.04	0.31* 0.26* 0.39* 0.29
Q_{Lcum}, m^3											1.00 1.00 1.00 1.00	0.46* 0.48* 0.91* 0.16	0.31* 0.25* 0.39* 0.28
Q_{Wcum}, t												1.00 1.00 1.00 1.00	0.05 0.06 0.41* -0.01
GOR, m^3/t													1.00 1.00 1.00 1.00

*Tab. 2. Correlation matrix. Note: * – significant correlation coefficients. ** 1.00 – all data; 1.00 – target D_3 fm; 1.00 – target C_2v; 1.00 – target C_2b.*

The ranges of applicability of this model are shown in Table 3.

Information on the list of indicators used in all, including intermediate, models and on the order of their inclusion in the model is presented in the form of diagrams (Fig. 1).

The behavior of the coefficient of determination R at different ranges of reservoir pressure is shown in the diagram (Fig. 2).

To assess the reliability of the first level modeling, reservoir pressures were calculated using formula (1), which were compared with actual data (Fig. 3).

Used parameters	Range of applicability
P_{Res0}, MPa	8.5 - 21.8
T, day	0.0 - 1842
P_{bh}, MPa	2.8 - 18.4
Q_{Wcum}, t	0.00 - 38952.6
K_C, mD	0.8 - 4020,0
S	-8.0 - 46.5
Q_{Ocum}, t	0.0 - 115835.1

Tab. 3. Ranges of applicability of the first level model

Since more often than others, when constructing models, such parameters were used as the duration of the well flowing (T) and the initial reservoir pressure P_{Res0}, for the express assessment of the predicted value, a model was built in which only these two parameters are used as initial data:

$$P_{ResL1\_1} = 1.824 + 0.9591 \cdot P_{Res0} - 0.0016 \cdot T + 0.005 \cdot (P_{Res0})^2 - 0.0003 \cdot (P_{Res0} \cdot T) + 0.00000189 \cdot (T)^2; \quad (2)$$

at $R = 0.861$, $p < 0.0000$, $S_0 = 1.45$ MPa.

The presented formula is used for values of P_{Res0} from 8.5 to 15.291 MPa; T – from 0 to 1842.2 days.

Modeling of the second and third levels is described using the example of the largest oil producing horizon – D_3fm carbonate reservoir.

Results of the second level of modeling

A model for rapid assessment of reservoir pressure by the most informative indicators, similar to equation (2), but built specifically for the D_3fm reservoir, has the form:

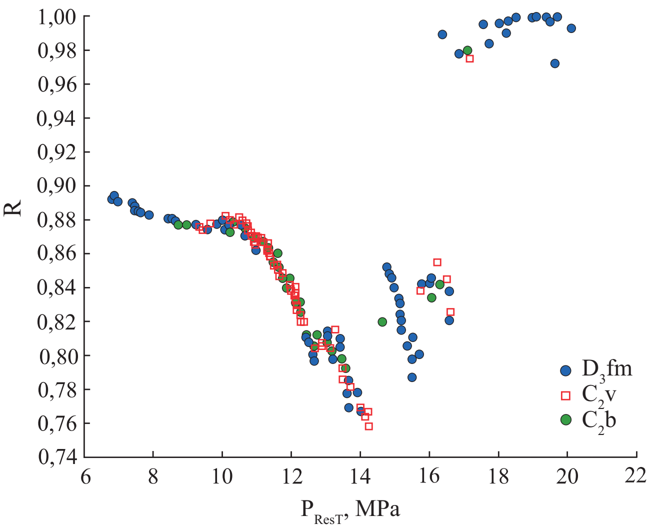

Fig. 2. Graphical chart of the change in the coefficient of models determination at different ranges of reservoir pressure (the first level of modeling)

$$P_{ResL2} = 9.437 - 0.2312 \cdot P_{Res0} - 0.0032 \cdot T + 0.0398 \cdot (P_{Res0})^2 - 0.0003 \cdot (P_{Res0} \cdot T) + 0.0000017654 \cdot (T)^2; \quad (3)$$

at $R = 0.925$, $p < 0.0000$, $S_0 = 1.39$ MPa.

The presented formula is used for values of P_{Res0} from 8.5 to 21.281 MPa; T – from 0 to 1842.2 days. If the values are not included in the specified ranges, then the formula is subject to correction. To assess the reliability of the first level modeling, reservoir pressures were calculated using formula (3), which are then compared with the actual values in the form of a correlation field

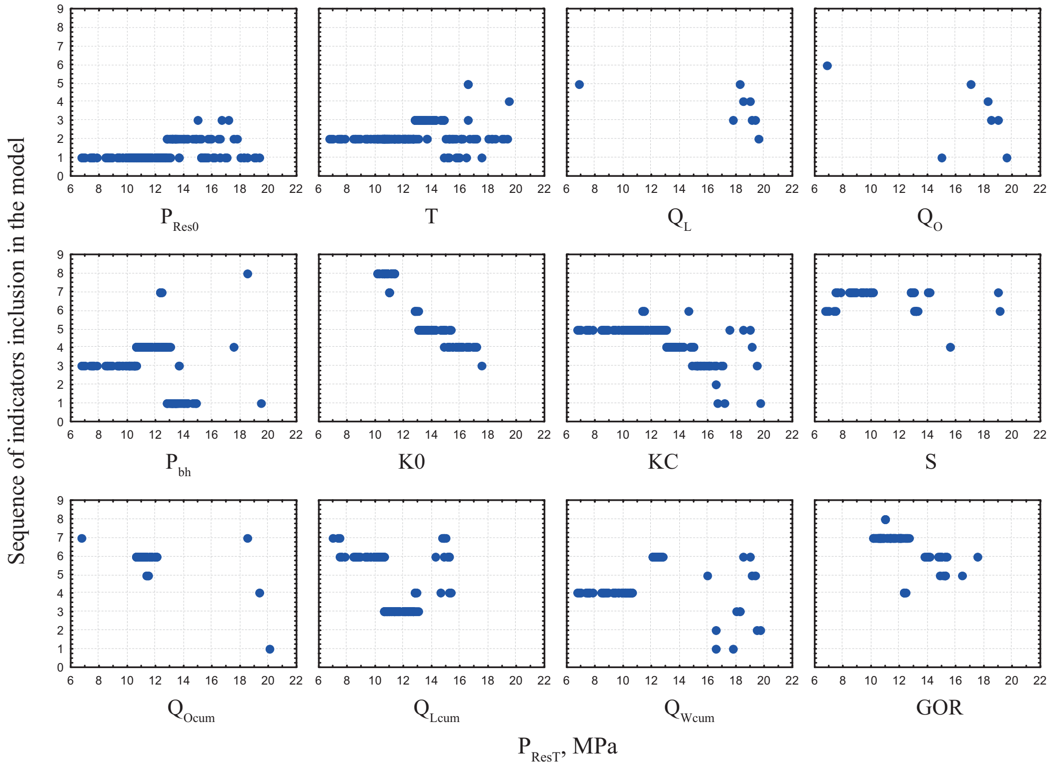

Fig. 1. Graphical chart of changes in the sequence of indicators inclusion in the model at different ranges of reservoir pressure (the first level of modeling)

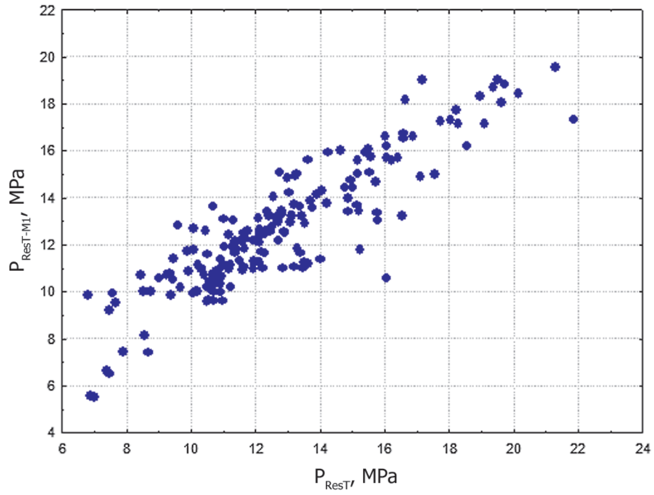

Fig. 3. Correlation field between calculated and actual reservoir pressures (first level of modeling)

(Fig. 4). The behavior of the coefficient of determination R is shown in Figure 5.

When analyzing the graph of the coefficient R behavior, characteristic areas of the of reservoir pressure behavior were identified – these are ranges of more and less than 14 MPa. This boundary was taken into account when building third-level models.

Models of the second level for two other reservoirs of the considered oilfield were constructed in a similar way. In both cases, it was also found that the reservoir pressure behaves differently in the two ranges, that is, there are two separate stages in the reservoir pressure behavior. Reservoir pressure values set as boundary when separating two stages for all reservoirs of the Sukharev field are shown in Table 4. This table also shows the initial reservoir pressure values for the oilfield as a whole, and the ratio of boundary and initial reservoir pressures.

For the mathematical confirmation of the correctness of the selection of stages, a linear discriminant function Z was constructed:

$$Z = -0.0019 \cdot T - 0.0084 \cdot Q_O + 0.1159 \cdot P_{bh} + 0.3408 \cdot P_{Res0} + 0.00005 \cdot Q_{Wcum} - 0.0167 \cdot GOR - 4.097; \quad (4)$$

at $R = 0.755$, $\chi^2 = 60.47$, $p = 0.0000$. Recognition for this function was 90.34 %. Using the function, the values of Z and P (Z) are calculated (Fig. 6).

The average Z value for the first stage is +1.203, for the second it is 1.039. For the first stage, the following model was obtained (a characteristic feature is the positive value of the discriminant function):

$$P_{ResL2\_1} = 0.721 + 0.9611 \cdot P_{Res0} - 0.0053 \cdot T + 0.0001 \cdot Q_{Wcum}; \quad (5)$$

at $R = 0.958$, $p < 0.0000$, the standard error is 0.55 MPa.

This formula can be used for the values given in Table 5. It should be noted that formula (5) needs to be corrected if the values are not within these ranges (Table 5).

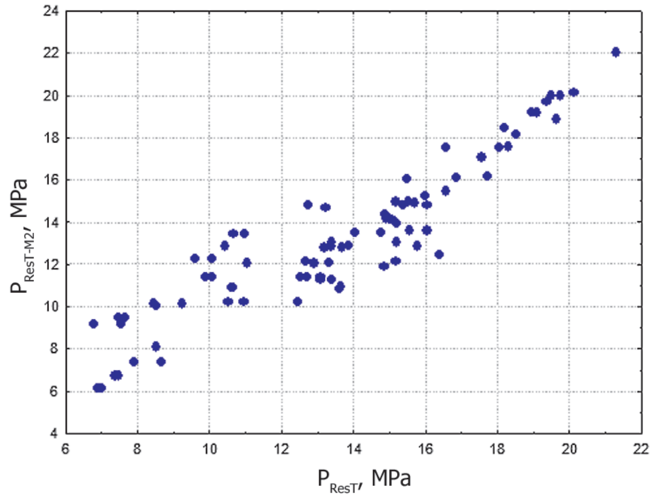

Fig. 4. Correlation field between calculated and actual reservoir pressures (second level of modeling, reservoir D_3fm)

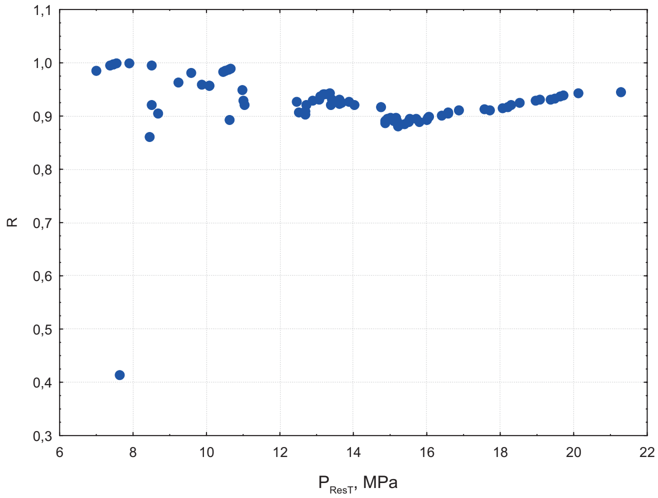

Fig. 5. Graphical chart of the change in the coefficient of multidimensional models determination at different ranges of reservoir pressure (second level of modeling, reservoir D_3fm)

Item	Object	P_{ResBd}, MPa	P_{ResO}, MPa	P_{ResBd}/P_{ResO}
1	D_3fm	14.0	21.5	**0.65**
2	C_2v	12.0	19.8	**0.61**
3	C_2b	11.5	18.5	**0.62**

Tab. 4. Boundary values of reservoir pressures for development objects

For the second stage, the following model is obtained (the characteristic feature is the negative value of the discriminant function):

$$P_{ResL2\_2} = 2.903 + 0.4528P_{bh} + 0.4343P_{Res0} + 0.1514S - 0.0280GOR + 0.0025K_0^H; \quad (6)$$

at $R = 0.924$, $p < 0.0000$, $S_0 = 0.95$ MPa.

Table 6 shows the ranges of change in indicators, at which it is possible to use formula (6). Figure 7 shows the field of correlations between the calculated and actual values of reservoir pressure.

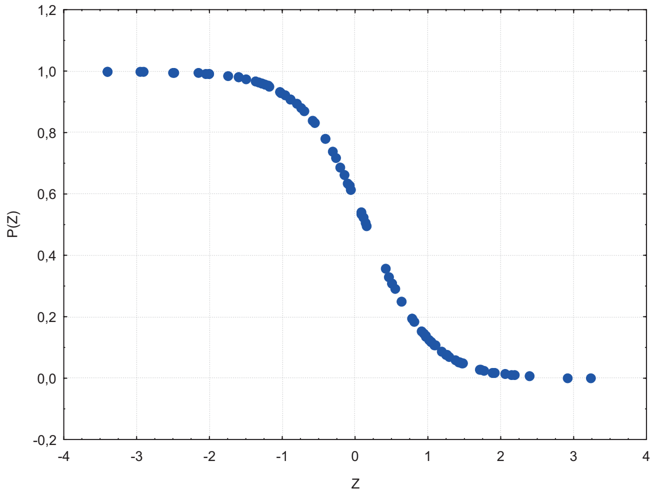

Fig. 6. Dependence of P(Z) on Z in justification of reservoir pressure sampling separation

Used parameters	Range of applicability
P_{Res0}, MPa	14.9 - 21.28
T, day	0.00 - 1335.00
Q_{Wcum}, t	0.0 - 1355.0

Tab. 5. Ranges of change of indicators

Used parameters	Range of applicability
P_{Res0}, MPa	8.5 - 21.281
P_{bh}, MPa	2.88 - 13.76
K_0, mD	31.7 - 779.4
S	-7.7 - 7.4
GOR, m^3/t	37.3 - 127.0

Tab. 6. Ranges of change of indicators

Results of the third level of modeling

For the purpose of the integrated use of models of all levels at the third level, the resulting multi-level multidimensional (MM) mathematical model was built:

$$P_{ResMM} = 0.214 - 0.3742 \cdot P_{ResL2} + 1.3476 \cdot (P_{ResL2\_1}, P_{ResL2\_2}) + (P_{ResL2})^2 + 0.0077 \cdot (P_{ResL2}) \cdot (P_{ResL2\_1}, P_{ResL2\_2}) - 0.0162 \cdot (P_{ResL2\_1}, P_{ResL2\_2})^2; \quad (7)$$

at R = 0.979, p < 0.0000, the standard error is 0.74 MPa.

Practical example

The list of initial data for determining the reservoir pressure according to the developed method is shown in Table 7.

$$P_{ResT\text{-}M(Pres0,\ T)} = 9.437 - 0.2312 \cdot P_{Res0} - 0.0032 \cdot T + 0.0398 \cdot (P_{Res0})^2 - 0.0003 \cdot (P_{Res0} \cdot T) + 0.0000017654 \cdot (T)^2 = 10.704\ \text{МПа};$$

$$Z = -0.00193 \cdot T - 0.00844 \cdot Q_O + 0.1159 \cdot P_{bh} + 0.34079 \cdot P_{Res0} + 0.00005 \cdot Q_{Wcum} - 0.01666 \cdot GOR - 4.09775 = -1.1;$$

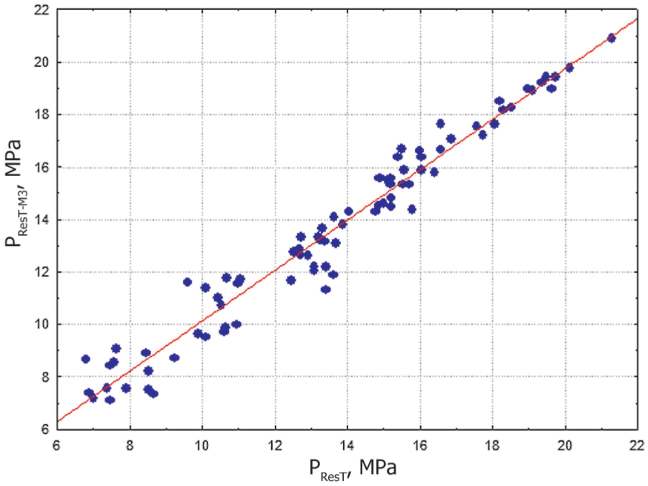

Fig. 7. Correlation field between calculated and actual reservoir pressures (third level)

$$P_{ResT\text{-}M2} = 2.903 + 0.452763 \cdot P_{bh} + 0.434338 \cdot P_{Res0} + 0.151458 \cdot S - 0.027958 \cdot GOR + 0.002506 \cdot К_0 = 11.824\ \text{МПа};$$

$$P_{ResT\text{-}MM} = 0.214 - 0.3742 \cdot P_{ResT\text{-}M(Pres0,\ T)} + 1.3476 \cdot (P_{ResT\text{-}M1}, P_{ResT\text{-}M2}) + 0.0093 \cdot (P_{ResT\text{-}M(Pres0,\ T)})^2 + 0{,}0077 \cdot (P_{ResT\text{-}M(Pres0,\ T)}) \cdot (P_{ResT\text{-}M1}, P_{ResT\text{-}M2}) - 0.0162 \cdot (P_{ResT\text{-}M1}, P_{ResT\text{-}M2})^2 = 11.918\ \text{МПа}.$$

Thus, as a result of calculations using the developed methodology, the value of reservoir pressure in the selection zone of well No. 2 as of January 14, 2019 is 11.918 MPa. The actual reservoir pressure, determined in the same period of time, is 12.15 MPa. The discrepancy between the calculated and actual reservoir pressures is 0.232 MPa.

Information on actual and calculated reservoir pressures for other wells from the control sample is given in Table 8.

On average, the error in determining the reservoir pressure according to the developed method does not exceed 1 MPa, which can be considered an acceptable value when using the calculated pressure for such tasks as assessing the energy state of the reservoir in the extraction zones, planning measures to regulate its development. The use of the calculated pressure to estimate the magnitude of the drawdown is also quite acceptable, since the actual values of the difference between the reservoir and bottomhole pressures are currently 7–8 MPa at the objects under consideration.

The study of correlations, which, according to the rules of multivariate regression analysis, is the main subject of the entire study, in this case demonstrated the complex nature of the mutual influence of geological and technological indicators on the magnitude of reservoir pressure in the zones of wells influence. The strongest influence on the studied value (reservoir pressure) is exerted by such indicators as the initial reservoir pressure, which is individual for each well, as well as

Item	Indicator name	Unit	Value
1	Well number		2
2	Geological index of the target reservoir		D_3fm
3	Test date		14.01.2019
4	Initial reservoir pressure in the production zone	MPa	21.28
5	Well in operation duration	Days	1900
6	Bottom hole pressure	MPa	4.34
7	Cumulative water production	m^3	5183
8	Cumulative oil production	t	117992
9	Oil production rate (current)	t / day	70.3
10	Liquid flow rate (current)	m^3/day	70.5
11	Gas / Oil Ratio	m^3/t	45.1
12	Initial permeability	mD	57.1
13	Current permeability	mD	22.0
14	Skin factor current		-6.6
15	Actual reservoir pressure determined during hydrodynamic studies	MPa	12.15

Tab. 7. Initial data for checking the proposed methodology

Well No.	Formation	Date	Reservoir pressure, MPa		Definition error, MPa
			actual	calculated	
2	D_3fm	14.01.2019	12.150	11.918	-0.232
5	C_2v	17.01.2020	10.987	10.209	0.778
117	C_2b	21.11.2019	11.335	10.460	0.875
125	C_2b	14.05.2019	8.750	9.576	-0.826
215	C_2v	03.12.2019	10.762	10.636	0.126
317	C_2v	15.09.2019	11.144	10.598	0.546
323	D_3fm	28.11.2019	11.626	12.512	0.886
327	C_2b	10.01.2020	12.060	12.042	0.018

Tab. 8. Comparison of actual and calculated reservoir pressures for wells of the control sample

the duration of its operation after commissioning from drilling. Also, the current bottomhole pressure, oil and liquid flow rates, and the initial permeability of the reservoir in the zone of influence of the well have a significant impact. It should be noted that the effect of the same indicators is different for various reservoirs. For example, the relationship between reservoir pressure and GOR for the D_3fm reservoir is positive, statistically significant. At the same time, the relationship between the same parameters for the C_2v and C_2b deposits is also statistically significant, but negative. The noted facts are proving of the complexity of the formation pressure formation process in the zones of influence of producing wells during the development of oilfields. The chosen tool – multivariate statistical modeling – is one of the options for describing complex processes.

The process of constructing multidimensional statistical models is carried out using an original approach, which consists in using a ranked (decreasing) sample and step-by-step model construction. This approach made it possible to both build models and establish some patterns of behavior of reservoir pressure in different periods of oil reservoir development. For each of the three oil reservoirs that are in commercial development at the Sukharev oil field, two stages of reservoir pressure behavior have been identified. In a multidimensional model describing the initial stage of reservoir pressure behavior (Formula 5), only individual initial reservoir pressure, well operation time after drilling input and cumulative water production are used as input parameters. It can be assumed that the inclusion of cumulative water production in the model makes it possible to take into account the influence of the water-pressure area on the energy state of the reservoir. It should be noted that in the initial period, the reservoir pressure is practically not affected by technological parameters (well performance indicators). The second stage of formation pressure formation is described by equation (6). As follows from the analysis of this equation, it includes the so-called technological indicators – bottomhole pressure, gas-oil ratio. That is, the implemented system for the development and operation of deposits begins to affect the magnitude of reservoir pressure only at this stage. These patterns are typical for all three deposits that are under development within the Sukharev field. It should be especially noted that there are significant differences in the geological and physical properties of these deposits. In the course of research, for each of the deposits, the boundary of each of the stages was substantiated. Justification of the boundaries is carried out using a well-known mathematical tool – discriminant analysis. Comparison of the boundary reservoir pressures with the initial reservoir pressures (Table 4) made it possible to obtain a very important conclusion. The first stage of reservoir pressure behavior at all deposits of the Sukharev field continues until the reservoir pressure drops to 60 % of the initial value.

Special attention should be paid to the analysis of the model (6). At the third step, the model includes a skin factor – an indicator characterizing the state of the bottomhole zone. It is proposed to take the skin factor value according to the data of the previous well survey. It is generally accepted that the third step of including the indicator is a sign of not so high sensitivity of the model to its value. It should also be noted that, for example, for carbonate reservoirs, the variability of the skin factor is not so significant as to have a significant impact on the calculated reservoir pressure.

In total, during the study, for the Sukharev field as a whole, 14 multidimensional models for forecasting reservoir pressure were built based on a set of geological and technological indicators. It should be noted that the indicators used in these models as input data are regularly and with sufficient accuracy determined (measured) at all oil fields. In addition, the very process of calculating the reservoir pressure is not complicated and does not require the use of special software products. These facts emphasize the simplicity of the practical application of the reservoir pressure determination technique, which is based on the constructed multivariate statistical models, which is demonstrated on the example of real data.

Of course, the limitations of the developed technique should also be noted. The above multidimensional models can only be used for the conditions of the Sukharev field. The initial data for the calculation must correspond to the given ranges. Otherwise, the calculation error will be more significant. However, the obvious advantages of the considered method for determining the reservoir pressure make it expedient to replicate the performed studies for the conditions of any other oil fields, where there is experience of multiple hydrodynamic studies with the determination of reservoir pressure.

Conclusion

The studies described in this article are devoted to the construction of multidimensional mathematical models of the current reservoir pressure in the selection zones of production wells of the oilfield named after I. Sukharev (two carbonate and one terrigenous reservoir).

When constructing the models, an original approach was used, which consists in preliminary ranking of the initial data. The initial data are ranged according to the current reservoir pressure from maximum to minimum values. This will make it possible to most accurately reproduce its behavior during the reservoir development.

During the analysis, it was found that in the initial period of development, the reservoir pressure is mainly influenced by two parameters: the initial reservoir pressure for a particular well and the duration of its operation. After the formation pressure drops to 60 % of the initial value, the so-called technological indicators begin to influence its value: skin factor, flow rate, gas factor and bottomhole pressure.

The constructed multilevel multidimensional statistical models are proposed to be used as a mathematical basis for the method for determining reservoir pressure without shutting in wells for research. The advantages of this technique are the simplicity of calculations and the use of only those parameters that are regularly and quite reliably determined (measured) in the field as input data.

The method for determining reservoir pressure based on the use of the developed models should not be considered as an alternative to hydrodynamic studies. Its use is advisable for express assessment of reservoir pressure, or when it is impossible to shut-in the well for research due to technological reasons.

References

Aaditya Khanal, Mohammad Khoshghadam, W. John Lee, Michael Nikolaou (2017). New forecasting method for liquid rich shale gas condensate reservoirs with data driven approach using principal component analysis. *Journal of Natural Gas Science and Engineering*, 38, pp. 621–637. https://doi.org/10.1016/j.jngse.2017.01.014

Abrosimov A.A., Shelyago E.V., Yazinina I.V. (2018). Substantiation of a representative volume of reservoir properties data to obtain statistically reliable petrophysical relationships. *Zapiski Gornogo instituta = Journal of Mining Institute*, 233, pp. 487–491. (In Russ.). https://doi.org/10.31897/pmi.2018.5.487

Ahmadi R., Pourfatemi S.M., Ghaffari S. (2017). Exergoeconomic optimization of hybrid system of GT, SOFC and MED implementing genetic algorithm. *Desalination*, 411, pp. 76–88. https://doi.org/10.1016/j.desal.2017.02.013

Akinbinu V.A. (2010). Prediction of fracture gradient from formation pressures and depth using correlation and stepwise multiple regression techniques. *Journal of Petroleum Science and Engineering*, 72(1–2), pp. 10–17. https://doi.org/10.1016/j.petrol.2010.02.003

Chernykh I.A., Galkin V.I., Ponomareva I.N. (2017). Comparative analysis of the methods for defining bottomhole pressure at well operation of Shershnevsky field. *Izvestiya Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov = Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*, 328(8), pp. 41–47. (In Russ.)

D. Childers P.E., X. Wu PhD (2020). Forecasting oil well performance in tight formation using the connected reservoir storage model. *Journal of Petroleum Science and Engineering*, 195, 107593. https://doi.org/10.1016/j.petrol.2020.107593

Davydova A.E., Shchurenko A.A., Dadakin N.M., Shutalev A.D., Kvesko B.B. (2019). Well testing design development in carbonate reservoir. *Izvestiya*

Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov = Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering, 330(6), pp. 68–79. (In Russ.). https://doi.org/10.18799/24131830/2019/6/2128

Davydova A.E., Shchurenko A.A., Dadakin N.M., Shutalev A.D., Rvesco B.B. Optimization of carbonate reservoir well testing. *Vestnik PNIPU. Geologiya. Neftegazovoe i gornoe delo = Bulletin of PNIPU. Geology. Oil and gas and mining*, 17(2), pp. 123–135. (In Russ.). DOI: 10.15593/2224-9923/2018.2.3

Dragunov A.A., Mukhamadiev R.S., Chernov S.V. (2017). Influence of geodynamic processes on reservoir properties of geological environment (on the example of the Romashkino field). *Georesources = Georesursy,* 19(4), pp. 319–322. (In Russ.). https://doi.org/10.18599/grs.19.4.3

Dyagilev V.F., Lazutin N.K., Baksheev V.N. (2019). Approbation of the assessing methodology for the impact nature of water injection on oil samples using the example of the North-Orekhovsky field. *SOCAR Proceedings*, 1, pp. 42–51. (In Russ.). DOI: 10.5510/OGP20190100378

Elesin A.V., Kadyrova A.Sh., Nikiforov A.I. (2018). Definition of the reservoir permeability field according to pressure measurements on wells with the use of spline function. *Georesources = Georesursy,* 20(2), pp. 102–107. https://doi.org/10.18599/grs.2018.2.102-107

Escobar F.H., Hernandez Y.A., Hernandez C.M. (2007). Pressure transient analysis for long homogeneous reservoirs using TDS technique. *Journal of Petroleum Science and Engineering*, 58(1–2), pp. 68–82. https://doi.org/10.1016/j.petrol.2006.11.010

Galkin S.V., Kochnev A.A., Zotikov V.I. (2019). Estimate of radial drilling technology efficiency for the bashkir operational oilfields objects of Perm Krai. *Zapiski Gornogo instituta = Journal of Mining Institute*, 238, pp. 410–414. (In Russ.). https://doi.org/10.31897/pmi.2019.4.410

Galkin V.I., Ponomareva I.N., Chernykh I.A., Filippov E.V., Chumakov G.N. (2019). Methodology for estimating downhole pressure using multivariate model. *Neftyanoe Khozyaystvo = Oil industry*, 1, pp. 40–43. (In Russ.). DOI: 10.24887/0028-2448-2019-1-40-43

Karmanskiy D.A., Petrakov D.G. (2020). Laboratory modeling of changes in mechanical and flow properties of reservoir rocks at the stages of oil fields development. *Vestnik PNIPU. Geologiya. Neftegazovoe i gornoe delo = Bulletin of PNIPU. Geology. Oil and gas and mining*, 20(1), pp. 49–59. (In Russ.). DOI: 10.15593/2224-9923/2020.1.5

Kochnev A.A., Zotikov V.I., Galkin S.V. (2018). Analysis of the influence of geological technological parameters on the effectiveness of radial drilling technology on the example of operational objects in perm region. *Izvestiya Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov = Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*, 329(12), pp. 20–29. (In Russ.). https://doi.org/10.18799/24131830/2018/12/16

Martyushev D.A., Slushkina A.Yu. (2019). Assessment of informative value in determination of reservoir filtration parameters based on interpretation of pressure stabilization curves. *Izvestiya Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov = Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*, 330(10), pp. 26–32. (In Russ.). https://doi.org/10.18799/24131830/2019/10/2295

Nur Wijaya, James J. Sheng (2020). Probabilistic forecasting and economic evaluation of pressure-drawdown effect in unconventional oil reservoirs under uncertainty of water blockage severity. *Journal of Petroleum Science and Engineering*, 185, 106646. https://doi.org/10.1016/j.petrol.2019.106646

Olalere Oloruntobi, Stephen Butt (2019). Energy-based formation pressure prediction. *Journal of Petroleum Science and Engineering*, 173, pp. 955–964. https://doi.org/10.1016/j.petrol.2018.10.060

Ponomareva I.N., Martyushev D.A., Akhmetova M.I. (2016). Evaluation of the optimal duration of the hydrodynamic studies of low-productivity wells on the example of Ozernoye field. *Neftyanoe Khozyaystvo = Oil industry*, 1, pp. 60–63. (In Russ.)

Rastorguev M.N. (2019). Using discriminant analysis for the interpretation of gas logging data on the example of the Pavlov oil field. *Vestnik PNIPU. Geologiya. Neftegazovoe i gornoe delo = Bulletin of PNIPU. Geology. Oil and gas and mining*, 19(1), pp. 39–55. (In Russ.) DOI: 10.15593/2224-9923/2019.1.4

Saeed Rafieepour, Silvio Baldino, Stefan Z. Miska (2020). Determination of in-situ elastic properties and reservoir boundary conditions. *Journal of Natural Gas Science and Engineering*, 81, 103397. https://doi.org/10.1016/j.jngse.2020.103397

Salam Al-Rbeawi (2018). Integrated analysis of pressure response using pressure-rate convolution and deconvolution techniques for varied flow rate production in fractured formations. *Journal of Natural Gas Science and Engineering*, 51, pp. 195–209. https://doi.org/10.1016/j.jngse.2018.01.012

Valery B., Eslamloueyan R. (2015). Hydrocarbon reservoirs characterization by co-interpretation of pressure and flow rate data of the multi-rate well testing. *Journal of Petroleum Science and Engineering*, 135, pp. 59–72. https://doi.org/10.1016/j.petrol.2015.08.016

Virstyuk A.Yu., Mikshina V.S. (2020). Application of regression analysis to evaluate the efficiency of oil well operating with the paraffin oil. *Izvestiya Tomskogo politekhnicheskogo universiteta. Inzhiniring georesursov = Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*, 331(1), pp. 117–124. (In Russ.). https://doi.org/10.18799/24131830/2020/1/2453

About the Authors

Vladislav I. Galkin – DSc (Geology and Mineralogy), Professor, Head of the Department of Oil and Gas Geology

Perm National Research Polytechnic University
29 Komsomolskiy Av., Perm, 614990, Russian Federation

Inna N. Ponomareva – DSc (Engineering), Professor, Department of Oil and Gas Technologies

Perm National Research Polytechnic University
29 Komsomolskiy Av., Perm, 614990, Russian Federation

Dmitriy A. Martyushev – PhD (Engineering), Associate Professor, Department of Oil and Gas Technologies

Perm National Research Polytechnic University
29 Komsomolskiy Av., Perm, 614990, Russian Federation

Manuscript received 17 September 2020;
Accepted 23 March 2021; Published 30 September 2021