Perm Journal of Petroleum and Mining Engineering. 2024. Vol.24, no.4. P.204-211. DOI: 10.15593/2712-8008/2024.4.4

ISSN 2712-8008
Volume / Том 24 №4 2024
Journal Homepage: http://vestnik.pstu.ru/geo/

Perm Journal of Petroleum and Mining Engineering

UDC 622.276
Article / Статья
© PNRPU / ПНИПУ, 2024

# Comprehensive Analysis of Methods for Assessing the Bottomhole Zone of Wells Operating Complex Carbonate Reservoirs

**Vasily I. Chernykh, Vladislav I. Galkin, Inna N. Ponomareva, Dmitriy A. Martyushev**

Perm National Research Polytechnic University (29 Komsomolskiy av., Perm, 614990, Russian Federation)

# Комплексный анализ методов оценки гидродинамического состояния призабойной зоны скважин, эксплуатирующих сложнопостроенные карбонатные коллекторы

**В.И. Черных, В.И. Галкин, И.Н. Пономарева, Д.А. Мартюшев**

Пермский национальный исследовательский политехнический университет (Российская Федерация, 614990, г. Пермь, Комсомольский пр., 29)

Received / Получена: 29.03.2024. Accepted / Принята: 30.09.2024. Published / Опубликована: 31.10.2024

*Keywords:*
carbonate reservoir, bottomhole zone, skin factor, dimensionless diagnostic feature, well testing, pressure recovery curve, method of deterministic pressure moments, tangent method, regression analysis, statistical analysis, multivariate statistical model.

Assessing the hydrodynamic state of bottomhole zones is a key task to be solved when conducting and interpreting hydrodynamic well studies. The most widely used indicator of the condition of bottomhole zones in practice is the skin factor. However, its definition for the conditions of complex carbonate reservoirs is often accompanied by difficulties. Under conditions of incomplete pressure recovery, typical for the conditions under consideration, the value of the skin factor often takes on an unreliable value, in some cases leading to an incorrect interpretation of the state of the bottomhole zone, regardless of the approaches used to interpretation. Using actual data as an example, the article demonstrates that a reduction in the pressure recovery curve leads to false negative skin factor values both when implementing the tangent graph-analytical method and when processing in accordance with Bourdais's theory. In such conditions, it is recommended to use fundamentally different indicators of the state of the bottomhole zones, for example, a dimensionless diagnostic feature determined when implementing the method of deterministic moments of pressure. However, the lack of experience in the widespread practical application of this method necessitates an assessment of its reliability. For this purpose, this article uses an effective tool of mathematical statistics – multiple regression analysis, which, in this case, was reduced to the construction of multidimensional models of well flow rates. The geological and technological indicators of well operation were used as independent variables, including parameters characterizing the bottomhole formation zone (skin factor determined in the KAPPA Workstation software product (Saphir module), skin factor calculated using the tangent method, as well as a dimensionless diagnostic feature). According to the theory of regression analysis, the parameter that is included in the constructed model at the earliest possible step is reliable. The procedure for constructing and analyzing multidimensional statistical models performed in this work demonstrated the reliability of a dimensionless diagnostic feature in assessing the state of bottomhole zones of productive formations represented by complex carbonate reservoirs.

*Ключевые слова:*
карбонатный коллектор, призабойная зона, скин-фактор, безразмерный диагностический признак, гидродинамические исследования скважин, кривая восстановления давления, метод детерминированных моментов давления, метод касательной, регрессионный анализ, статистический анализ, многомерная статистическая модель.

Оценка гидродинамического состояния призабойных зон является ключевой задачей, решаемой при проведении и интерпретации гидродинамических исследований скважин. Наиболее распространенным на практике показателем состояния призабойных зон является скин-фактор. Однако его определение для условий сложнопостроенных карбонатных коллекторов зачастую сопровождается затруднениями. В условиях неполного восстановления давления, характерного для рассматриваемых условий, величина скин-фактора нередко принимает недостоверное значение, в некоторых случаях приводящее к некорректной трактовке состояния призабойной зоны, независимо от используемых подходов к интерпретации. На примере фактических данных продемонстрировано, что сокращение кривой восстановление давления приводит к ложноотрицательным значениям скин-фактора как при реализации графоаналитического метода касательной, так и при обработке в соответствии с теорией Бурдэ. В таких условиях рекомендуется использовать принципиально другие показатели состояния призабойных зон, например, безразмерный диагностический признак, определяемый при реализации метода детерминированных моментов давления. Однако отсутствие опыта широкого практического применения данного метода обусловливает необходимость оценки его достоверности. С этой целью в данном исследовании использован эффективный инструмент математической статистики – множественный регрессионный анализ, который в данном случае сводился к построению многомерных моделей дебитов скважин. В качестве независимых переменных использовались геолого-технологические показатели эксплуатации скважин, в том числе параметры, характеризующие призабойную зону пласта (скин-фактор, определенный в ПК Saphir, скин-фактор, вычисленный методом касательной, а также безразмерный диагностический признак). В соответствии с теорией регрессионного анализа достоверным является тот параметр, который включается в построенную модель на максимально раннем шаге. Выполненная в настоящей работе процедура построения и анализа многомерных статистических моделей продемонстрировала достоверность безразмерного диагностического признака при оценке состояния призабойных зон продуктивных пластов, представленных сложнопостроенными карбонатными коллекторами.

---

© **Vasily I. Chernykh** (Author ID in Scopus: 57739954500, ORCID: 0000-0001-8152-0048) – PhD Student at the Department of Oil and Gas Technologies (tel.: +007 (342) 219 82 50, e-mail: chernykh.perm@gmail.com).
© **Vladislav I. Galkin** (Author ID in Scopus: 55418067700, ORCID: 0000-0003-4867-2298) – Doctor in Geology and Mineralogy, Professor, Head of the Department of Oil and Gas Geology (tel.: +007 (342) 219 82 50, e-mail: vgalkin@pstu.ru).
© **Inna N. Ponomareva** (Author ID in Scopus: 36242312300, ORCID: 0000-0003-0546-2506) – Doctor in Engineering, Associate Professor, Professor at the Department of Oil and Gas Technologies (tel.: +007 (342) 219 82 50, e-mail: pin79@yandex.ru). The contact person for correspondence.
© **Dmitriy A. Martyushev** (Author ID in Scopus: 56308102400, ORCID: 0000-0002-5745-4375) – Doctor in Engineering, Associate Professor, Professor at the Department of Oil and Gas Technologies (tel.: +007 (342) 219 82 50, e-mail: martyushevd@inbox.ru).

© **Черных Василий Игоревич** – аспирант кафедры нефтегазовых технологий (тел.: +007 (342) 219 82 50, e-mail: chernykh.perm@gmail.com).
© **Галкин Владислав Игнатьевич** – доктор геолого-минералогических наук, профессор, заведующий кафедрой геологии нефти и газа (тел.: +007 (342) 219 82 50, e-mail: vgalkin@pstu.ru).
© **Пономарева Инна Николаевна** – доктор технических наук, доцент, профессор кафедры нефтегазовых технологий (тел.: +007 (342) 219 82 50, e-mail: pin79@yandex.ru). Контактное лицо для переписки.
© **Мартюшев Дмитрий Александрович** – доктор технических наук, доцент, профессор кафедры нефтегазовых технологий (тел.: +007 (342) 219 82 50, e-mail: martyushevd@inbox.ru).

---

Please cite this article in English as:
Chernykh V.I., Galkin V.I., Ponomareva I.N., Martyushev D.A. Comprehensive analysis of methods for assessing the bottomhole zone of wells operating complex carbonate reservoirs. *Perm Journal of Petroleum and Mining Engineering*, 2024, vol.24, no.4, pp.204-211. DOI: 10.15593/2712-8008/2024.4.4

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Комплексный анализ методов оценки гидродинамического состояния призабойной зоны скважин, эксплуатирующих сложнопостроенные карбонатные коллектора / В.И. Черных, В.И. Галкин, И.Н. Пономарева, Д.А. Мартюшев // Недропользование. – 2024. – Т.24, №4. – С.204–211. DOI: 10.15593/2712-8008/2024.4.4

## Introduction

The hydrodynamic state of the near-wellbore (bottomhole) zones of productive formations (BZP) is a criterion that largely determines successful oil recovery within the well drainage zone. As a result, the impact on the bottomhole zone is the main element of the well productivity management system [1–3]. Accordingly, a reliable assessing the state of this formation part is the most important task of oil field engineering which is solved in practice by interpreting pressure recovery curves (PRC). In work [4] the authors emphasize the importance of having the results of interpreting well hydrodynamic studies including the skin factor value while modeling processes in three-dimensional models of complex oil deposits. In the overwhelming majority of cases the skin factor is used as a criterion describing the state of the bottomhole zones [5]. In work [6] the authors present the results of studies on numerical modeling the skin factor value in order to study the efficiency of the applied technologies for primary and secondary opening of a gas formation. The authors of work [7] call the skin factor a parameter characterizing the reservoir properties of the bottomhole zones. However, they point out the difficulty of determining the permeability of the bottomhole zone based on the known skin factor value. In work [8] the authors show data that determining the skin factor value is one of the main tasks of hydrodynamic well studies and present the results of studies on the development of algorithms for its determination in multi-wellbore conditions. The work [9] is devoted to the problems of interpreting negative skin factor values. The author points out the complexity of the very concept of "skin factor" and the large number of processes that determine its value.

The author of work [10] points out a more complex shape of the pressure recovery curves of wells in carbonate reservoirs of the fractured-pore type. A similar conclusion about the pronounced influence of a complex type of porosity, namely the presence of cracks, on the shapes of pressure recovery curves and the results of their interpretation, was obtained by the authors in papers [11–14]. In the article [15] the authors point out one of the main problems of hydrodynamic well testing – the non-uniqueness of solutions that accompanies the manual interpretation of pressure recovery curves.

A large number of uncertainties also accompanies the practical implementation of the algorithm for diagnosing fractures taking into account the data of hydrodynamic well testing which the authors of the algorithm point out in the article [16].

The problem of assessing the state of the BZP based on the data of well testing in carbonate reservoirs is aggravated by the complexity of the structure of their void space [17]. As a rule, the process of pressure recovery continues for a longer period of time and the shape of the graphs of the pressure recovery curve (PRC) differs from the standards. A frequent situation is while during well testing in carbonate reservoirs the pressure is not restored to the reservoir value which is accompanied by an underestimation of the resulting values of the determined filtration parameters (permeability, skin factor) [18, 19]. As an example, Figure 1 and Table 1 show a comparison of two pressure build-up curves and the results of their interpretation: in the first case, a fully reconstructed curve was processed, in the second case, a specially truncated one. The presented graphs were processed using the tangent method, one of the common methods for processing well study materials [20].

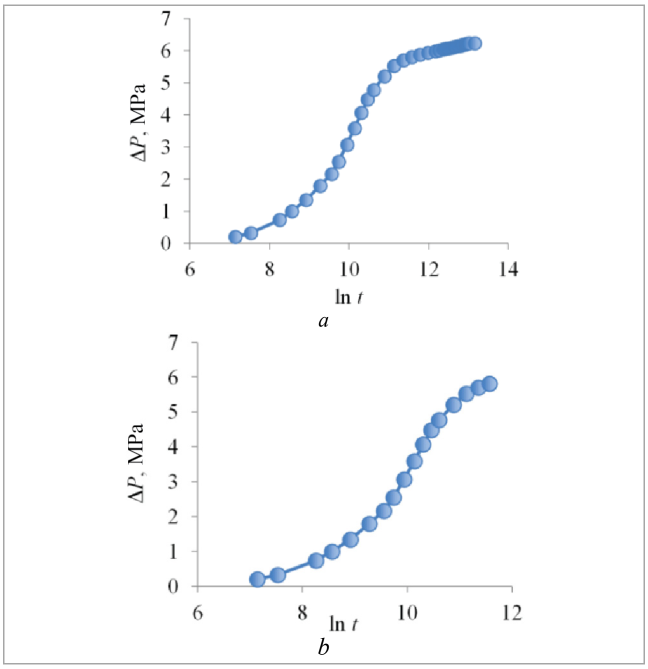


Fig. 1. Graphs of the pressure recovery curve:
*a* – fully recovered curve; *b* – truncated

Table 1

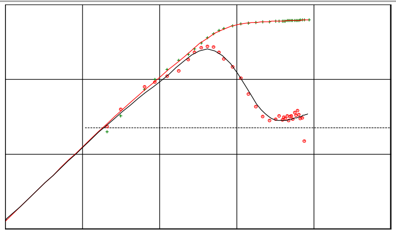
Comparison of the results of interpretation of the full and abbreviated PRC by the tangent method

| PRC graphs (Fig. 1) | Fully recovered curve | Truncated curve |
|---|---|---|
| Time of studying, min | 7459 | 1770 |
| Rate of recovering, % | 99.7 | 96.7 |
| Permeability of the remote formation zone, □m2 | 0.044 | 0.018 |
| Skin-factor b/r | 3.1 | –2.3 |

It follows from the data presented in Table 1 that a reduction in the duration of the study and a decrease in the degree of pressure recovery by only 3% leads to a significant underestimation of the parameters being determined. Thus, the skin factor value takes a false negative value which indicates its pronounced sensitivity to the duration of the well shutdown for the study and the degree of pressure recovery [21].

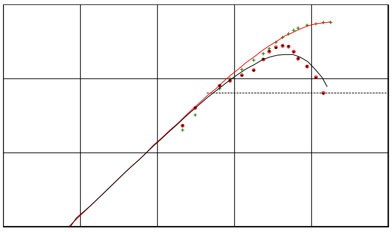
Interpretation of the full and shortened pressure recovery curves, performed in modern software products based on the analysis of the pressure derivative graph in bilogarithmic coordinates, also often leads to different results which is demonstrated using the same data as an example (Fig. 2, Table 2).

Processing of shortened pressure recovery curves in the KAPPA Workstation software (Saphir module) leads to an even greater number of uncertainties. Exclusion of the last section on the graph from the analysis causes difficulties in choosing interpretation models which is the basis of this approach to processing hydrodynamic research materials. Thus, while processing reduced data, visually identical combination of the calculated and actual pressure build-up is achieved using different interpretation models, which, in turn, lead to obtaining very different results, especially in the value of the skin



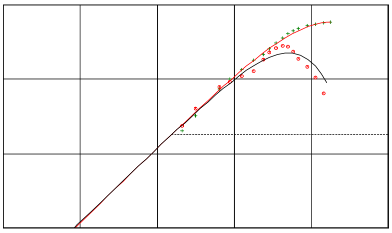
Log-Log plot: dp and dp' [MPa] vs dt [min]

*a*



Log-Log plot: dp and dp' [MPa] vs dt [min]

*b*



Log-Log plot: dp and dp' [MPa] vs dt [min]

*c*

Fig. 2. Interpretation of the full and truncated pressure recovery curves: *a* – original curve; *b* – truncated curve (model 1); *c* – truncated curve (model 2)

Table 2

Comparing the results of interpreting the full and abbreviated PRC in the KAPPA Workstation software (Saphir module)

| PRC graph | original curve | truncated curve (model 1) | truncated curve (model 2)) |
|---|---|---|---|
| Studying duration, min | 7459 | 1770 | 1770 |
| Pressure recovery rate, % | 99.7 | 96.7 | 96.7 |
| Permeability of the remote zone of the formation, μm2 | 0.052 | 0.019 | 0.065 |
| Skin factor | 4.6 | –3.1 | 12.3 |

Table 3

Definition of a dimensionless diagnostic feature

| PRC characteristic | Original curve | Truncated curve |
|---|---|---|
| Studying duration, min | 7459 | 1770 |
| Pressure recovery rate, % | 99.7 | 96.7 |
| Dimensionless diagnostic feature, *d* | 2.82 | 2.64 |

factor. That is, reducing the duration of the study, leading to the exclusion of the final informative sections on the pressure build-up graph, contributes to significant uncertainties in the choice of interpretation models and errors in determining the resulting parameters, especially the value of the skin factor.

In this regard, it is advisable to use fundamentally different criteria characterizing the hydrodynamic state of the near-wellbore formation zones, for example, the dimensionless diagnostic feature *d* determined while processing pressure recovery curves using the method of deterministic pressure moments. In accordance with the algorithms [22] of the method, the state of the near-wellbore zone is considered to be deteriorated if the value of the dimensionless diagnostic feature $d > 2.5$.

In works [23, 24] it is shown that even while processing under-recovered pressure build-up curves, the value of *d* is determined quite stably. This conclusion is demonstrated using the example of the results of data processing used earlier in this article for a comparative analysis of skin factors. It should be noted that, in contrast to the tangent method and the algorithms of the KAPPA Workstation software (Saphir module), the method of deterministic moments does not allow directly assessing the permeability of a remote formation zone, in connection with which only the values of the dimensionless diagnostic feature *d* characterizing the state of the near-wellbore zone (Table 3) are accepted for analysis. As follows from the data presented in Table 3 the values of *d* determined during processing of the full and shortened pressure build-up curves correspond to the same range characterizing the state of the BZP as deteriorated. Thus, with regard to the data under consideration, it can be concluded that a significant reduction in the duration of well testing will not lead to errors in assessing the state of the BZP if the method of deterministic moments of pressure is used as the appropriate tool.

It should be noted that the algorithm of the deterministic moments method does not imply the use of a large number of initial data: to determine the numerical value of the parameter *d*, no additional information is required, except for the direct data of well measurements (time and pressure). At the same time, while determining the value of the skin factor, it is also necessary to use a large number of geological and technological parameters, such as well flow rate, thickness of the working part of the formation (forming the pressure build-up curve), oil viscosity, etc., which increases the likelihood of obtaining unreliable estimates of the BZP state. The disadvantage of the method of deterministic pressure moments should be considered its low testing and an insignificant number of studies devoted to assessing the reliability of its results. It should also be noted that the algorithm for applying the method is quite labor-intensive; its mass application requires special software implementation.

Taking into account the above, this study is devoted to assessing the reliability of applying the method of deterministic pressure moments in assessing the hydrodynamic state of the BZP in carbonate reservoirs. At the same time, it is advisable to solve the problem in comparison with proven approaches to assessing the state of near-wellbore zones based on determining the skin factor value using the tangent method in the KAPPA Workstation software (Saphir module).

## Methods and methologies

To achieve the main objective of the study, multiple regression analysis which is a mathematical tool that has been repeatedly tested in verifying different geological and production data is used [25–30]. The study consists of constructing a series of multivariate statistical models where the well flow rate acts as the predicted parameter (dependent feature), and the independent features are a set of geological and technological indicators including the verified parameters that probably form the predicted value. A conclusion on the reliability of the verified parameter is obtained based on the fact of its inclusion in the multivariate statistical model at the earliest possible step. This verification principle is discussed in detail in papers [31, 32].

Within the framework of this study, three multivariate statistical models were constructed using such BZP characteristics as the skin factor determined during the PRC processing in the Kappa Workstation software (Saphir module) – $S^S$; the skin factor determined during the PRC processing using the tangent graph-analytical method – $S^{MK}$, as well as using the dimensionless diagnostic feature *d*. In addition to the specified parameters, the following set of indicators was also used as initial data:

- formation thickness $h$ (m);
- formation pressure $P_b$ (MPa);
- bottomhole pressure $P_{bh}$ (MPa);
- water cut $W$ (%);
- permeability coefficient $k$ (mD);
- gas factor $G$ ($m^3$/t).

The specified parameters were selected based on the assumption of their probable influence on the well flow rate in combination with the characteristics of the bottomhole formation zone, as well as the availability of their quantities verified values for the period corresponding to the date of well shutdown for research.

The initial data were adopted based on the results of hydrodynamic studies of wells at one of the fields in the north of the Perm Territory (an oil deposit in complex carbonates of the Tournaisian-Famennian age), and the amount of data corresponds to the volume of research performed at the site and is $n = 83$.

The first multidimensional model was built using geological and field indicators and the $S^S$ value; the second one is the same with the value of $S^{MK}$, when constructing the third model, the indicator $d$ is used. For each model, the ranges of applicability are given and statistical estimates are calculated, on which basis their predictive abilities are compared. For a numerical assessment of the contribution of each indicator to the resulting performance of the model, the current value of the determination coefficient is calculated at each step of its formation. It is proposed to consider the indicator of the state of the BZP used in the model with the highest statistical estimates as reliable. With equal estimates the most reliable is the indicator that is included in the model at an early step.

## Results

A series of multivariate statistical models of liquid flow rates constructed for the purpose of comparative assessing the reliability of parameters characterizing bottomhole zones is given below.

The model constructed using geological and technological indicators and the parameter $S^S$ has the form:

$$Q_l^{M1} = 3.218P_{bh} + 0.028k + \\ + 0.218W - 6.724h + 2.487. \qquad (1)$$

Table 4

Ranges of applying the model (1)

| Parameter | Range of application | Parameter | Range of application |
|---|---|---|---|
| $P_{bh}$, MPa | 1.92–18.05 | $W$, % | 11.0–60.0 |
| $k$, mD | 0.631–2883.5 | $h$, м | 2.8–31 |

Table 5

Ranges of applying the model (2)

| Parameter | Range of application | Parameter | Range of application |
|---|---|---|---|
| $P_{bh}$, MPa | 1.92–18.05 | $B$, % | 11.0–60.0 |
| $k$, mD | 0.631–2883.5 | $S^{MK}$ | –7.39… +38.8 |

Table 6

Ranges of applying the model (3)

| Parameter | Range of application | Parameter | Range of application |
|---|---|---|---|
| $P_{bh}$, MPa | 1.92–18.05 | $W$, % | 11.0–60.0 |
| $k$, mD | 0.631–2883.5 | $h$, m | 2.8–31 |
| $d$, b/r | 1.77–4.0 | | |

The statistical estimates of the model have the following values: determination coefficient $R = 0.802$, significance level $p < 0.0001$, standard calculation error 14.8 $m^3$/day. Model (1) was formed in the sequence given in the regression equation. The values of the $R$ coefficients describing the strength of statistical relationships changed as follows: 0.745; 0.784; 0.796; 0.802. Model (1) is characterized by the applicability limits presented in Table 4.

The constructed model using geological and technological indicators and the $S^{MK}$ parameter has the following form:

$$Q_l^{M2} = 6.005P_{bh} + 0.016k + \\ + 0.012B - 0.684S^{MK} + 8.597, \qquad (2)$$

where $R = 0.805$, $p < 0.0001$, standard error – 16.6 $m^3$/day.

The model was formed in the sequence given in the regression equation. The values of the $R$ coefficients describing the strength of statistical relationships changed as follows: 0.722; 0.777, 0.794; 0.805. The ranges of indicator values when model (1) can be applied are presented in Table 5.

The model constructed using geological and technological indicators and the parameter d has the form:

$$Q_l^{M3} = 1.745P_{bh} + 0.076k + 20.438d + \\ + 0.101W - 1.612h + 1.761, \qquad (3)$$

where $R = 0.882$, $p < 0.0001$, standard error – 6.6 $m^3$/day.

The model was formed in the sequence given in the regression equation. The values of the R coefficients describing the strength of statistical relationships changed as follows: 0.714, 0.820; 0.840; 0.858; 0.882. This formula can be used with the values of the indicators given in Table 6.

High statistical estimates of model (3), as well as the fact that the $d$ indicator is included in its composition at the third step, allow us to conclude that it can be used to assess the state of the BZP in the considered conditions of complex carbonate reservoirs. An additional study of the constructed statistical models was carried out by analyzing the correlation fields that compare the actual and calculated flow rates using models (1)–(3) (Fig. 3).

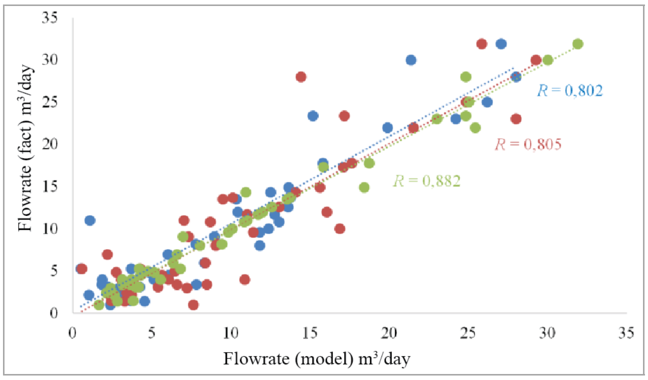


Fig. 3. Correlation fields between actual and calculated flow rates

## Descussion

The main objective of the present research is a comparative assessing the reliable characteristics of the near-wellbore zones of productive formations represented by low-permeability complex carbonate reservoirs. The considered conditions are characterized by a long duration of the pressure recovery process during well testing [33–37]. As a result, it is not uncommon for the pressure at the well bottom to unfully recover till the reservoir value during testing. The example of one well demonstrates the validity of the conclusion noted in the scientific literature that the processing of under-recovered pressure build-ups leads to significant errors in determining the filtration characteristics of drainage zones including the bottomhole formation zone. It should be noted that errors in determining the skin factor during the processing of under-recovered pressure build-ups are characteristic of both the widespread tangent graph-analytical method and the modern approach which consists of analyzing the pressure derivative graph in bilogarithmic coordinates [38–42]. To interpret pressure buildup curves of wells operating in low-permeability carbonate reservoirs, alternative methods should be used to obtain numerical characteristics of the near-wellbore zones, such as the method of deterministic pressure moments [43–45]. In addition to the possibility of using the method for processing under-recovered pressure buildup curves, the method of deterministic moments has a number of additional advantages, such as the absence of any other geological and technological indicators (well flow rate, formation thickness, oil viscosity, etc.) in the list of initial data. However, recommendations for the practical application of the method should be based on a detailed study of its reliability in individual geological and physical conditions. In this study, an approach that has been successfully tested for solving similar problems in petroleum engineering, namely, multiple regression analysis, was used for this purpose. All pressure buildup curves of the producing wells were interpreted using the tangent method with skin factor determination in the Saphir software package, as well as the method of deterministic pressure moments including obtaining characteristics of the near-wellbore zone state. The results of the interpretation are supplemented by a set of geological and technological indicators and used as independent variables in the construction of multivariate statistical models. The predicted parameter is the well flow rate for liquid, since the selected independent variables probably affect its value.

As a result, multivariate statistical models of the flow rate were built for three options.

The first option used the results of the pressure build-up interpretation in the KAPPA Workstation software (Saphir module), the second is the tangent method, the third one is the method of deterministic pressure moments. A number of important conclusions were obtained during the analysis of the constructed models.

Firstly, all the constructed models are characterized by high statistical estimates which allows us to recommend them for use not only for the purpose of verifying geological and technological indicators but also directly for forecasting tasks.

Secondly, the inclusion of bottomhole pressure in each model at the first step indicates a pronounced influence of this indicator on the fluid flow rate and the importance of its control while monitoring well operation.

The multivariate statistical model (1) built using the results of the pressure build-up interpretation in the KAPPA Workstation software (Saphir module) is characterized by high estimates but none of its steps includes the skin factor value. Accordingly, for the conditions of the field under consideration this parameter does not control the fluid inflow to the wells. It is advisable to study the reasons for this phenomenon in a separate study.

The skin factor determined by the tangent method, together with a set of other parameters, affects the formation of well flow rates, as evidenced by the fact that it is included in the model at the fourth step. However, it should be noted that the flow rate is indirectly involved in determining the skin factor while processing the pressure build-up curve using the tangent method so the parameters are not completely independent and the inclusion of the skin factor in the statistical model can also be explained by this fact.

The dimensionless diagnostic feature $d$ is determined without the participation of the well flow rate and any other additional parameters so it is a completely independent feature of statistical modeling. Accordingly, its inclusion in the third step in the model (3) indicates the presence of a relationship between the parameters and emphasizes the feasibility of using the indicator to assess the state of the bottomhole zones of low-permeability carbonate reservoirs.

It should also be noted that all the constructed statistical models are characterized by high statistical estimates. This conclusion is confirmed by the analysis of correlation fields where the points are grouped quite closely and uniformly throughout the range under consideration. As a result, the constructed models are recommended to be used not only while solving the verification problem, as in this article but also for direct prediction of fluid inflow into the well.

In general, the approach used to assess the reliable characteristics of the bottomhole formation zone allows us to take into account their influence on filtration processes in combination with other factors which makes it possible to reasonably recommend it for replication to solve similar problems when it is impossible to verify a parameter by comparing it with an actually determined (measured) value.

## Conclusion

In conditions of low-permeability carbonate reservoirs, well testing data are often characterized by an insufficient degree of bottomhole pressure recovery to the reservoir value.

In conditions of incomplete pressure recovery, the assessing the state of the bottomhole zone by the skin factor value is often characterized by insufficient reliability. In such conditions, it is advisable to use other interpretation methods, for example, deterministic pressure moments, which is reduced to determining the dimensionless diagnostic feature *d*.

The insufficient prevalence of the deterministic pressure moments method in the practice of well testing interpretation determines the need to conduct studies to assess its reliability for the individual conditions of individual fields.

The approach used in this paper based on the use of multiple regression analysis demonstrated the reliability of the deterministic pressure moments method for assessing the state of bottomhole zones of productive formations for the geological and physical conditions of the Tournaisian-Famennian deposit of one of the fields in the north of the Perm Territory.

## References

1. Gasanov R.A., Gasymova Dzh.R. Sposoby uluchsheniia fil'tratsionnykh svoistv prizaboinoi zony skvazhiny [Methods for improving the filtration properties of the well bottomhole zone]. *Gornyi zhurnal*, 2021, no. 10, pp. 76-80. DOI: 10.17580/gzh.2021.10.09
2. Dong Y., Song L., Zhao Q., Ding Z., Qiu L., Lu C., Chen G. A physics-guided eXtreme gradient boosting model for predicting the initial productivity of oil wells. *Geoenergy Science and Engineering*, 2023, vol. 231, Article 212402. DOI: 10.1016/j.geoen.2023.212402
3. Galkin V.I., Martyushev D.A., Ponomareva I.N., Chernykh I.A. Developing features of the near-bottomhole zones in productive formations at fields with high gas saturation of formation oil. *Journal of Mining Institute*, 2021, vol. 249, pp. 386-392. DOI: 10.31897/PMI.2021.3.7
4. Kumar A., Liang L., Ojha K. Simultaneous inversion of permeability, skin and boundary from pressure transient test data in three-dimensional single well reservoir model. *Petroleum Research*, 2024, vol. 9, iss. 2, pp. 265-272. DOI: 10.1016/j.ptlrs.2024.01.004
5. Iktisanov V.A., Musabirova N.Kh., Baigushev A.V., Bilalov M.Kh., Akhmadishin F.F. Otsenka kachestva pervichnogo, vtorichnogo vskrytiia plastov i osvoeniia skvazhiny po rezul'tatam gidrodinamicheskikh issledovanii [Evaluation of well completion quality based on flow test result]. *Neftianoe khoziaistvo*, 2020, no. 7, pp. 33-35. DOI: 10.24887/0028-2448-2020-7-33-35
6. Zhang Z., Guo J., Liang H., Liu Y. Numerical simulation of skin factors for perforated wells with crushed zone and drilling-fluid damage in tight gas reservoirs. *Journal of Natural Gas Science and Engineering*, 2024, vol. 90, Article 103907. DOI: 10.1016/j.jngse.2021.103907
7. Silva T.M.D., Bela R.V., Pesco S., Barreto A. ES-MDA applied to estimate skin zone properties from injectivity tests data in multilayer reservoirs. *Computers & Geosciences*, 2021, vol. 146, Article 104635. DOI: 10.1016/j.cageo.2020.104635
8. Bela R.V., Pesco S., Barreto A.B., Onur M. Assisted history matching and graphical methods for estimating individual layer properties from well testing data in stratified reservoirs with multilateral wells. *Journal of Petroleum Science and Engineering*, 2022, vol. 208, Article 109326. DOI: 10.1016/j.petrol.2021.109326
9. Iktisanov V.A. K voprosu ob otritsatel'nom skin-faktore [On negative values of skin factor]. *Neftianoe khoziaistvo*, 2020, no. 12, pp. 101-105. DOI: 10.24887/0028-2448-2020-12-101-105
10. Svalov A.M. Osobennosti krivykh pritoka i vosstanovleniia davleniia v treshchinovato-poristykh kollektorakh [Features of inflow and pressure recovery curves in fractured-porous reservoirs]. *Inzhenerno-fizicheskii zhurnal*, 2021, vol. 94, no. 2, pp. 393-399.
11. Sun H., Ouyang W., Zhu S., Wan Y., Tang Y., Cao W. A new numerical well test method of multi-scale discrete fractured tight sandstone gas reservoirs and its application in the Kelasu Gas Field of the Tarim Basin. *Natural Gas Industry B*, 2023, vol. 10, iss. 2, pp. 103-113. DOI: 10.1016/j.ngib.2023.01.003
12. Wei C., Liu Y., Deng Y., Cheng S., Hassanzadeh H. Analytical well-test model for hydraulicly fractured wells with multiwell interference in double porosity gas reservoirs. *Journal of Natural Gas Science and Engineering*, 2022, vol. 103, Article 104624. DOI: 10.1016/j.jngse.2022.104624
13. Mohammed-Sajed O.K., Glover P.W.J., Alrashedi M.A., Collier R.E.Ll Quantification of the effect of fracturing on heterogeneity and reservoir quality of deep-water carbonate reservoirs. *Journal of African Earth Sciences*, 2024, vol. 218, Article 105383. DOI: 10.1016/j.jafrearsci.2024.105383
14. Martyushev D.A., Yang Y., Kazemzadeh Y., Wang D., Li Y. Understanding the Mechanism of Hydraulic Fracturing in Naturally Fractured Carbonate Reservoirs: Microseismic Monitoring and Well Testing. *Arabian Journal for Science and Engineering*, 2024, vol. 49 (6), pp. 8573-8586. DOI: 10.1007/s13369-023-08513-1
15. Dong P., Chen Z., Liao X., Yu W. Application of deep learning on well-test interpretation for identifying pressure behavior and characterizing reservoirs. *Journal of Petroleum Science and Engineering*, 2022, vol. 208, Article 109264. DOI: 10.1016/j.petrol.2021.109264
16. Chen Z., Liao X. A workflow of fracture geometry diagnostics of unconventional wells with complex fracture networks coupling fracture mapping and well testing. *Journal of Petroleum Science and Engineering*, 2022, vol. 208, Article 109310. DOI: 10.1016/j.petrol.2021.109310
17. Reznikov I., Abdrazakov D., Chuprakov D. Model-based interpretation of bottomhole pressure records during matrix treatments in layered formations. *Petroleum Science*, 2024. DOI: 10.1016/j.petsci.2024.05.027
18. Jia H., Li P., Lv W., Ren J., Cheng C., Zhang R., Zhou Z., Liang Y. Application of fuzzy comprehensive evaluation method to assess effect of conformance control treatments on water-injection wells. *Petroleum*, 2024, vol. 10, iss. 1, pp. 165-174. DOI: 10.1016/j.petlm.2022.04.006
19. Wang H., Ma J., Li L. Pore pressure prediction based on rock physics theory and its application in seismic inversion. *Journal of Applied Geophysics*, 2024, vol. 229, Article 105494. DOI: 10.1016/j.jappgeo.2024.105494
20. Soromotin, A.V., Martyushev D.A., Melekhin A.A. Prediction of Hydrodynamic Parameters of the State of the Bottomhole Zone of Wells Using Machine Learning Methods. *Georesursy*, 2024, vol. 26 (1), pp. 109-117. DOI: 10.18599/grs.2024.1.9
21. Yamkin M.A., Safiullina E.U., Yamkin A.V. Machine learning methods for selectingcandidate wells for bottomhole formation zone treatment. *Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering*, 2024, vol. 335, iss. 5, pp. 7-16. DOI: 10.18799/24131830/2024/5/4428
22. Ponomareva I.N. K obrabotke krivykh vosstanovleniia davleniia nizkoproduktivnykh skvazhin [For processing of recovery curves of pressure of low-productive wells]. *Neftianoe khoziaistvo*, 2010, no. 6, pp. 78-79.
23. Erofeev A.A., Ponomareva I.N., Turbakov M.S. Otsenka uslovii primeneniia metodov obrabotki krivykh vosstanovleniia davleniia skvazhin v karbonatnykh kollektorakh [Evaluation of the application conditions for methods of processing well pressure recovery curves in carbonate reservoirs]. *Inzhener-neftianik*, 2011, no. 3, pp. 12-15.
24. Erofeev A.A., Ponomareva I.N., Mordvinov V.A. Osobennosti obrabotki krivykh vosstanovleniia davleniia v skvazhinakh, ekspluatiruiushchikh zalezhi vysokoviazkikh neftei v karbonatnykh kollektorakh [Processing features of recovery curves of pressure in wells of the carbonate collector with high-viscosity oil]. *Neftianoe khoziaistvo*, 2010, no. 10, pp. 113-115.
25. Jha N., Tanneru H.K., Palla S., Mafat I.H. Multivariate analysis and forecasting of the crude oil prices: Part I – Classical machine learning approaches. *Energy*, 2024, vol. 296, Article 131185. DOI: 10.1016/j.energy.2024.131185
26. Wen S., Wei B., You J., He Y., Xin J., Varfolomeev M.A. Forecasting oil production in unconventional reservoirs using long short term memory network coupled support vector regression method: A case study. *Petroleum*, 2023, vol. 9, iss. 4, pp. 647-657. DOI: 10.1016/j.petlm.2023.05.004
27. Zang J., Wang J., Zhang K., E.-S. El-Alfy M., Mańdziuk J. Expertise-informed Bayesian convolutional neural network for oil production forecasting. *Geoenergy Science and Engineering*, 2024, vol. 240, Article 213061. DOI: 10.1016/j.geoen.2024.213061
28. Ponomareva I.N., Martyushev D.A., Govindarajan S.K. A new approach to predict the formation pressure using multiple regression analysis: Case study from Sukharev oil field reservoir - Russia. *Journal of King University - Engineering Sciences*, 2022. DOI: 10.1016/j.jksues.2022.03.005
29. Zhang S., Guo K., Gao X., Yang H., Zhang J., Han X. Productivity Prediction Model of Perforated Horizontal Well Based on Permeability Calculation in Near-Well High Permeability Reservoir Area. *Energy Engineering*, 2023, vol. 121, iss. 1, pp. 59-75. DOI: 10.32604/ee.2023.041709
30. Chen G., Meng Y., Huan J., Wang Y., Xiao L., Zhang L., Feng D. A new predrilling reservoir permeability prediction model and its application. *Journal of Petroleum Science and Engineering*, 2022, vol. 210, Article 110086. DOI: 10.1016/j.petrol.2021.110086
31. Martyushev D.A., Ponomareva I.N., Shen W. Adaptation of transient well test results. *Journal of Mining Institute*, 2023, vol. 264, pp. 919-925.
32. Martyushev D.A., Ponomareva I.N., Galkin V.I. Conditions for effective application of the decline curve analysis method. *Energies*, 2021, vol. 14 (20), Article 6461. DOI: 10.3390/en14206461
33. Li Q., Yang X., Wang H. Fluid identification in fractured media with genetic algorithm. *Journal of Applied Geophysics*, 2024, vol. 227, Article 105409. DOI: 10.1016/j.jappgeo.2024.105409
34. Chen L., Jia C., Zhang R., Yue P., Jiang X., Wang J., Su Z., Xiao Y., Lv Y. High-pressure capacity expansion and water injection mechanism and indicator curve model for fractured-vuggy carbonate reservoirs. *Petroleum*, 2024, vol. 10, iss. 3, pp. 511-519. DOI: 10.1016/j.petlm.2024.01.001
35. Martyushev D.A., Ponomareva I.N., Davoodi S., Kadkhodaie A. Interporosity Flow Between Matrix and Fractures in Carbonates: A Study of its Impact on Oil Production. *Arabian Journal for Science and Engineering*, 2024. DOI: 10.1007/s13369-024-09533-1

36. Otchere D.A. Fundamental error in tree-based machine learning model selection for reservoir characterization. *Energy Geoscience*, 2024, vol. 5, iss. 2, Article 100229. DOI: 10.1016/j.engeos.2023.100229

37. Ji C., Dong S., Zeng L., Liu Y., Hao J., Yang Z. Fracture identification of carbonate reservoirs by deep forest model: An example from the D oilfield in Zagros Basin. *Energy Geoscience*, 2024, vol. 5, iss. 3, Article 100300. DOI: 10.1016/j.engeos.2024.100300

38. Ponomareva I.N., Savchik M.B., Erofeev A.A. Usloviia primeneniia skin-faktora dlia otsenki sostoianiia priskvazhinnykh zon produktivnykh plastov [Conditions of skin factor use when estimating the state of the critical area of formation]. *Neftianoe khoziaistvo*, 2011, no. 7, pp. 114-115.

39. Zhao L., Zhao Y., Yan D. Zhu, J., Cai J. Integrated rock physics characterization of unconventional shale reservoir: A multidisciplinary perspective. *Advances in Geo-Energy Research*, 2024, vol. 14 (2), pp. 86-89. DOI: 10.46690/ager.2024.11.02

40. H. Liu, Y. Ren, X. Li et al. Research status and application of artificial intelligence large models in the oil and gas industry. *Petroleum Exploration and Development*, 2024, vol. 51, iss. 4, pp. 1049-1065. DOI: 10.1016/S1876-3804(24)60524-0

41. Li Y., Li X., Guo M., Chen C., Ni P., Huang Z. Regression analysis and its application to oil and gas exploration: A case study of hydrocarbon loss recovery and porosity prediction, China. *Energy Geoscience*, 2024, vol. 5, iss. 4, Article 100333. DOI: 10.1016/j.engeos.2024.100333

42. Alencar M.L., de Miranda T.S., Filho O.J.C. et al. The effect of fracture networks on the vertical permeability of a tight carbonate reservoir analogue: laminites from the Crato Formation, NE Brazil. *Marine and Petroleum Geology*, 2024, vol. 162, Article 106735. DOI: 10.1016/j.marpetgeo.2024.106735

43. Kamali M.Z., Davoodi S., Ghorbani H. et al. Permeability prediction of heterogeneous carbonate gas condensate reservoirs applying group method of data handling. *Marine and Petroleum Geology*, 2022, vol. 139, Article 105597. DOI: 10.1016/j.marpetgeo.2022.105597

44. Rashid F., Hussein D., Lorinczi P., Glover P.W.J. The effect of fracturing on permeability in carbonate reservoir rocks. *Marine and Petroleum Geology*, 2023, vol. 152, Article 106240. DOI: 10.1016/j.marpetgeo.2023.106240

45. Gavidia J.C.R., Mohammadizadeh S.M., Chinelatto G.F. et al. Bridging the gap: Integrating static and dynamic data for improved permeability modeling and super k zone detection in vuggy reservoirs. *Geoenergy Science and Engineering*, 2024, vol. 241, Article 213152. DOI: 10.1016/j.geoen.2024.213152

## Библиографический список

1. Гасанов, Р.А. Способы улучшения фильтрационных свойств призабойной зоны скважины / Р.А. Гасанов, Дж.Р. Гасымова // Горный журнал. – 2021. – № 10. – С. 76–80. DOI: 10.17580/gzh.2021.10.09

2. A physics-guided eXtreme gradient boosting model for predicting the initial productivity of oil wells / Y. Dong, L. Song, Q. Zhao, Z. Ding, L. Qiu, C. Lu, G. Chen // Geoenergy Science and Engineering. – 2023. – Vol. 231. – Article 212402. DOI: 10.1016/j.geoen.2023.212402

3. Developing features of the near-bottomhole zones in productive formations at fields with high gas saturation of formation oil / V.I. Galkin, D.A. Martyushev, I.N. Ponomareva, I.A. Chernykh // Journal of Mining Institute. – 2021. – V. 249. – P. 386–392. DOI: 10.31897/PMI.2021.3.7

4. Kumar A. Simultaneous inversion of permeability, skin and boundary from pressure transient test data in three-dimensional single well reservoir model / A. Kumar, L. Liang, K. Ojha // Petroleum Research. – 2024. – Vol. 9, iss. 2. – P. 265–272. DOI: 10.1016/j.ptlrs.2024.01.004

5. Оценка качества первичного, вторичного вскрытия пластов и освоения скважины по результатам гидродинамических исследований / В.А. Иктисанов, Н.Х. Мусабирова, А.В. Байгушев, М.Х. Билалов, Ф.Ф. Ахмадишин // Нефтяное хозяйство. – 2020. – № 7. – С. 33–35. DOI: 10.24887/0028-2448-2020-7-33-35

6. Numerical simulation of skin factors for perforated wells with crushed zone and drilling-fluid damage in tight gas reservoirs / Z. Zhang, J. Guo, H. Liang, Y. Liu // Journal of Natural Gas Science and Engineering. – 2024. – Vol. 90. – Article 103907. DOI: 10.1016/j.jngse.2021.103907

7. ES-MDA applied to estimate skin zone properties from injectivity tests data in multilayer reservoirs / T.M.D. Silva, R.V. Bela, S. Pesco, A. Barreto // Computers & Geosciences. – 2021. – Vol. 146. – Article 104635. DOI: 10.1016/j.cageo.2020.104635

8. Assisted history matching and graphical methods for estimating individual layer properties from well testing data in stratified reservoirs with multilateral wells / R.V. Bela, S. Pesco, A.B. Barreto, M. Onur // Journal of Petroleum Science and Engineering. – 2022. – Vol. 208. – Article 109326. DOI: 10.1016/j.petrol.2021.109326

9. Иктисанов, В.А. К вопросу об отрицательном скин-факторе / В.А. Иктисанов // Нефтяное хозяйство. – 2020. – № 12. – С. 101–105. DOI: 10.24887/0028-2448-2020-12-101-105

10. Свалов, А.М. Особенности кривых притока и восстановления давления в трещиновато-пористых коллекторах / А.М. Свалов // Инженерно-физический журнал. – 2021. – Т. 94, № 2. – С. 393–399.

11. A new numerical well test method of multi-scale discrete fractured tight sandstone gas reservoirs and its application in the Kelasu Gas Field of the Tarim Basin / H. Sun, W. Ouyang, S. Zhu, Y. Wan, Y. Tang, W. Cao // Natural Gas Industry B. – 2023. – Vol. 10, iss. 2. – P. 103–113. DOI: 10.1016/j.ngib.2023.01.003

12. Analytical well-test model for hydraulicly fractured wells with multiwell interference in double porosity gas reservoirs / C. Wei, Y. Liu, Y. Deng, S. Cheng, H. Hassanzadeh // Journal of Natural Gas Science and Engineering. – 2022. – Vol. 103. – Article 104624. DOI: 10.1016/j.jngse.2022.104624

13. Quantification of the effect of fracturing on heterogeneity and reservoir quality of deep-water carbonate reservoirs / O.K. Mohammed-Sajed, P.W.J. Glover, M.A. Alrashedi, R.E.Ll Collier // Journal of African Earth Sciences. – 2024. – Vol. 218. – Article 105383. DOI: 10.1016/j.jafrearsci.2024.105383

14. Understanding the Mechanism of Hydraulic Fracturing in Naturally Fractured Carbonate Reservoirs: Microseismic Monitoring and Well Testing / D.A. Martyushev, Y. Yang, Y. Kazemzadeh, D. Wang, Y. Li // Arabian Journal for Science and Engineering. – 2024. – Vol. 49(6). – P. 8573–8586. DOI: 10.1007/s13369-023-08513-1

15. Application of deep learning on well-test interpretation for identifying pressure behavior and characterizing reservoirs / P. Dong, Z. Chen, X. Liao, W. Yu // Journal of Petroleum Science and Engineering. – 2022. – Vol. 208. – Article 109264. DOI: 10.1016/j.petrol.2021.109264

16. Chen, Z. A workflow of fracture geometry diagnostics of unconventional wells with complex fracture networks coupling fracture mapping and well testing / Z. Chen, X. Liao // Journal of Petroleum Science and Engineering. – 2022. – Vol. 208. – Article 109310. DOI: 10.1016/j.petrol.2021.109310

17. Reznikov, I. Model-based interpretation of bottomhole pressure records during matrix treatments in layered formations / I. Reznikov, D. Abdrazakov, D. Chuprakov // Petroleum Science. – 2024. DOI: 10.1016/j.petsci.2024.05.027

18. Application of fuzzy comprehensive evaluation method to assess effect of conformance control treatments on water-injection wells / H. Jia, P. Li, W. Lv, J. Ren, C. Cheng, R. Zhang, Z. Zhou, Y. Liang // Petroleum. – 2024. – Vol. 10, iss. 1. – P. 165–174. DOI: 10.1016/j.petlm.2022.04.006

19. Wang, H. Pore pressure prediction based on rock physics theory and its application in seismic inversion / H. Wang, J. Ma, L. Li // Journal of Applied Geophysics. – 2024. – Vol. 229. – Article 105494. DOI: 10.1016/j.jappgeo.2024.105494

20. Soromotin, A.V. Prediction of Hydrodynamic Parameters of the State of the Bottomhole Zone of Wells Using Machine Learning Methods / A.V. Soromotin, D.A. Martyushev, A.A. Melekhin // Georesursy. – 2024. – Vol. 26(1). – P. 109-117. DOI: 10.18599/grs.2024.1.9

21. Yamkin, M.A. Machine learning methods for selectingcandidate wells for bottomhole formation zone treatment / M.A. Yamkin, E.U. Safiullina, A.V. Yamkin // Bulletin of the Tomsk Polytechnic University. Geo Assets Engineering. – 2024. – Vol. 335. – Iss. 5. – P. 7–16. DOI: 10.18799/24131830/2024/5/4428

22. Пономарева, И.Н. К обработке кривых восстановления давления низкопродуктивных скважин / И.Н. Пономарева // Нефтяное хозяйство. – 2010. – № 6. – С. 78–79.

23. Ерофеев, А.А. Оценка условий применения методов обработки кривых восстановления давления скважин в карбонатных коллекторах / А.А. Ерофеев, И.Н. Пономарева, М.С. Турбаков // Инженер-нефтяник. – 2011. – № 3. – С. 12–15.

24. Ерофеев, А.А. Особенности обработки кривых восстановления давления в скважинах, эксплуатирующих залежи высоковязких нефтей в карбонатных коллекторах / А.А. Ерофеев, И.Н. Пономарева, В.А. Мордвинов // Нефтяное хозяйство. – 2010. – № 10. – С. 113–115.

25. Multivariate analysis and forecasting of the crude oil prices: Part I – Classical machine learning approaches / N. Jha, H.K. Tanneru, S. Palla, I.H. Mafat // Energy. – 2024. – Vol. 296. – Article 131185. DOI: 10.1016/j.energy.2024.131185

26. Forecasting oil production in unconventional reservoirs using long short term memory network coupled support vector regression method: A case study / S. Wen, B. Wei, J. You, Y. He, J. Xin, M.A. Varfolomeev // Petroleum. – 2023. – Vol. 9. – Iss. 4. – P. 647-657. DOI: 10.1016/j.petlm.2023.05.004

27. Expertise-informed Bayesian convolutional neural network for oil production forecasting / J. Zang, J. Wang, K. Zhang, E.-S. M. El-Alfy, J. Mańdziuk // Geoenergy Science and Engineering. – 2024. – Vol. 240. – Article 213061. DOI: 10.1016/j.geoen.2024.213061

28. Ponomareva, I.N. A new approach to predict the formation pressure using multiple regression analysis: Case study from Sukharev oil field reservoir – Russia. / I.N. Ponomareva, D.A. Martyushev, S.K. Govindarajan // Journal of King University – Engineering Sciences. – 2022. DOI: 10.1016/j.jksues.2022.03.005

29. Productivity Prediction Model of Perforated Horizontal Well Based on Permeability Calculation in Near-Well High Permeability Reservoir Area / S. Zhang, K. Guo, X. Gao, H. Yang, J. Zhang, X. Han // Energy Engineering. – 2023. – Vol. 121. – Iss. 1. – P. 59-75. DOI: 10.32604/ee.2023.041709

30. A new predrilling reservoir permeability prediction model and its application / G. Chen, Y. Meng, J. Huan, Y. Wang, L. Xiao, L. Zhang, D. Feng // Journal of Petroleum Science and Engineering. – 2022. – Vol. 210. – Article 110086. DOI: 10.1016/j.petrol.2021.110086

31. Martyushev, D.A. Adaptation of transient well test results / D.A. Martyushev, I.N. Ponomareva, W. Shen // Journal of Mining Institute. – 2023. – Vol. 264. – P. 919-925.

32. Martyushev, D.A. Conditions for effective application of the decline curve analysis method / D.A. Martyushev, I.N. Ponomareva, V.I. Galkin // Energies. – 2021. – Vol. 14(20). – Article 6461. DOI: 10.3390/en14206461

33. Li, Q. Fluid identification in fractured media with genetic algorithm / Q. Li, X. Yang, H. Wang // Journal of Applied Geophysics. – 2024. – Vol. 227. – Article 105409. DOI: 10.1016/j.jappgeo.2024.105409

34. High-pressure capacity expansion and water injection mechanism and indicator curve model for fractured-vuggy carbonate reservoirs / L. Chen, C. Jia, R. Zhang, P. Yue, X. Jiang, J. Wang, Z. Su, Y. Xiao, Y. Lv // Petroleum. – 2024. – Vol. 10. – Iss. 3. – P. 511-519. DOI: 10.1016/j.petlm.2024.01.001

35. Martyushev, D.A. Interporosity Flow Between Matrix and Fractures in Carbonates: A Study of its Impact on Oil Production / D.A. Martyushev, I.N. Ponomareva, S. Davoodi, A. Kadkhodaie // Arabian Journal for Science and Engineering. – 2024. DOI: 10.1007/s13369-024-09533-1

36. Otchere, D.A. Fundamental error in tree-based machine learning model selection for reservoir characterization / D.A. Otchere // Energy Geoscience. – 2024. – Vol. 5, iss. 2. – Article 100229. DOI: 10.1016/j.engeos.2023.100229

37. Fracture identification of carbonate reservoirs by deep forest model: An example from the D oilfield in Zagros Basin / C. Ji, S. Dong, L. Zeng, Y. Liu, J. Hao, Z. Yang // Energy Geoscience. – 2024. – Vol. 5, iss. 3. – Article 100300. DOI: 10.1016/j.engeos.2024.100300
38. Пономарева, И.Н. Условия применения скин-фактора для оценки состояния прискважинных зон продуктивных пластов / И.Н. Пономарева, М.Б. Савчик, А.А. Ерофеев // Нефтяное хозяйство. – 2011. – № 7. – С. 114–115.
39. Integrated rock physics characterization of unconventional shale reservoir: A multidisciplinary perspective / L. Zhao, Y. Zhao, D. Yan, J. Zhu, J. Cai // Advances in Geo-Energy Research. – 2024. – Vol. 14(2). – P. 86–89. DOI: 10.46690/ager.2024.11.02
40. Research status and application of artificial intelligence large models in the oil and gas industry / H. LIU, Y. REN, X. LI [et al.] // Petroleum Exploration and Development. – 2024. – Vol. 51, iss. 4. – P.1049–1065. DOI: 10.1016/S1876-3804(24)60524-0
41. Regression analysis and its application to oil and gas exploration: A case study of hydrocarbon loss recovery and porosity prediction, China / Y. Li, X. Li, M. Guo, C. Chen, P. Ni, Z. Huang // Energy Geoscience. – 2024. – Vol. 5, iss. 4. – Article 100333. DOI: 10.1016/j.engeos.2024.100333
42. The effect of fracture networks on the vertical permeability of a tight carbonate reservoir analogue: laminites from the Crato Formation, NE Brazil / M.L. Alencar, T.S. de Miranda, O.J.C. Filho [et al.] // Marine and Petroleum Geology. – 2024. – Vol. 162. – Article 106735. DOI: 10.1016/j.marpetgeo.2024.106735
43. Permeability prediction of heterogeneous carbonate gas condensate reservoirs applying group method of data handling / M. Z. Kamali, S. Davoodi, H. Ghorbani [et al.] // Marine and Petroleum Geology. – 2022. – Vol. 139. – Article 105597. DOI: 10.1016/j.marpetgeo.2022.105597
44. The effect of fracturing on permeability in carbonate reservoir rocks / F. Rashid, D. Hussein, P. Lorinczi, P.W.J. Glover // Marine and Petroleum Geology. – 2023. – Vol. 152. – Article 106240. DOI: 10.1016/j.marpetgeo.2023.106240
45. Bridging the gap: Integrating static and dynamic data for improved permeability modeling and super k zone detection in vuggy reservoirs / J.C.R. Gavidia, SM. Mohammadizadeh, G.F. Chinelatto [et al.] // Geoenergy Science and Engineering. – 2024. – Vol. 241. – Article 213152. DOI: 10.1016/j.geoen.2024.213152

Funding. The research was supported by the Ministry of Science and Higher Education of the Russian Federation (project No. FSNM-2024-0005).

Conflict of interest. The authors declare that there is no conflict of interest.

The authors' contribution is equivalent.