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Effect Assesment of Geological and Physical Characteristics of Reservoirs with a Complex Geological Structure on the Conditions of Hydrocarbons Inflow

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Оценка влияния геолого-физических характеристик залежей со сложным геологическим строением на условия притока углеводородов

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The relevance of research was due to the predominance of deposits with a complex geological structure in the total volume of hydrocarbon assets put into commercial development. The use of standard approaches in such conditions often does not allow to reliably describe the fluid inflow to wells and, as a result, to choose effective tools to control their productivity. The complexity of the implementation of technological processes for the development of reserves determined the expediency of using probabilistic-statistical methods for their modeling. It should be noted that the construction of multidimensional statistical models was supplemented by studies on the dimensionless assessment of the impact of each of the indicators on the well flow rate and subsequent comparison of these effects. Mathematically substantiated the differences in the patterns of fluid inflow to wells with different wellbore designs (conditionally vertical and horizontal), identified factors that affect the formation of flow rates. It was established that one of the key factors determining the value of the flow rate of both horizontal and vertical wells was the radius of the drainage zone. To determine it, it was advisable to use the van Pullen formula, as the permeability in determining the radius of the drainage zone, it was necessary to use the value obtained by processing the pressure recovery curve using the tangent method. Individual (linear) probabilistic models were obtained for each of the indicators used, characterizing the probability of classifying a well as a high- or low-rate well. A series of multivariate statistical models were built that allow determining the flow rates of horizontal and vertical wells in difficult geological and technological conditions with a high degree of reliability.

Ключевые слова:
дебит жидкости, уравнения притока, горизонтальные скважины, наклонно направленные скважины, радиус зоны дренирования, регрессионный анализ, многомерные статистические модели, вероятностный подход, карбонатный коллектор, нефтегазоконденсатная залежь.

Актуальность исследований обусловлена преобладанием залежей со сложным геологическим строением в общем объеме вводимых в промышленную разработку активов углеводородного сырья. Использование стандартных подходов в таких условиях зачастую не позволяет достоверно описать приток флюида к скважинам и, как следствие, выбирать эффективные инструменты по управлению их производительностью. Сложность реализации технологических процессов выработки запасов обусловливает целесообразность применения вероятностно-статистических методов для их моделирования. Стоить отметить, что построение многомерных статистических моделей дополнено исследованиями по безразмерной оценке влияния каждого из показателей на дебит скважины и последующим сравнением этих влияний. Математически обоснованы различия в закономерностях притока флюидов к скважинам с различной конструкцией ствола (условно вертикальным и горизонтальным), выделены факторы, влияющие на формирование дебитов. Установлено, что одним из ключевых факторов, определяющих значение дебита как горизонтальных, так и вертикальных скважин, является радиус зоны дренирования. Для его определения целесообразно использовать формулу ван Пуллена, в качестве проницаемости при определении радиуса зоны дренирования необходимо применять значение, полученное при обработке кривой восстановления давления методом касательной. Получены индивидуальные (линейные) вероятностные модели по каждому из используемых показателей, характеризующие вероятность отнесения скважины к категории высоко- или низкодебитных. Построена серия многомерных статистических моделей, позволяющих с высокой степенью достоверности определять дебиты горизонтальных и вертикальных скважин в сложных геолого-технологических условиях.

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Introduction

A constant reserves deterioration of the developed sites influences the technological processes in hydrocarbon production. Thus, the deposits with complex reservoirs full of multiphase hydrocarbon systems are brought into commercial development. The Tournaisian-Famennian reservoir of the Zhilinskoye field could be considered as an example. The field is a complex reservoir with hard-to-recover reserves due to several factors. Firstly, the deposit is represented by spherical grumous limestones, which groundmass consists of irregularly recrystallised multigrain calcite with micrograin clots and lumps of algal or shell origin, cattered spheres and rare ostracod detritus. Rock porosity is due to leaching and recrystallisation, pores are intraformed (in spheres) and interformed, intergrain, angular, irregular, cavernous, and irregularly distributed. There are rare subvertical and inclined cracks, fading cracks, multiple layering and variously inclined intersecting cracks in some parts [1, 2]. The site is referred to the category of oil-gas-condensate in terms of phase state. At the same time, mark setting of the gas-oil contact (GOC) had some difficulties: its position was initially accepted due to the test data of two wells and corresponded to the depth of the first oil-saturated sublayer. A complex of MDT tests carried out in several wells to solve other field problems allowed to clarify and correct the position of the GOC, and the difference between the marks was 8 metres. Formation gas-oil factor was 230 m^3/t, viscosity in reservoir is 0.72 mPa-s. The initial period of well operation is characterised by different dynamics of the gas factor. According to the first instrumental measurements data its value varies in the range from 14 to 1700 m^3/t, averaging at 690 m^3/t.

Thus, the geological structure of the studied site is complicated both by the phase state of the saturating fluid and the void space structure. Such a complex geological structure along with the territorial overlap of the Zhilinskoye deposit with the unique Verkhnekamskoye potassium salt deposit makes it appropriate to take the most detailed approach to the study and management of filtration processes and sustainable reserves recovery [3].

The deposit commissioning using vertical and horizontal wells is characterised by significant differentiation of their initial flow rates, despite the relatively small deposit size (0.7-2.8 × 5.3 km) and similarity of geological and physical conditions in the drainage zones. The values of initial fluid flow rates vary in the range from 15 to 76 m^3/d, averaging 44 m^3/d. The range of effective thicknesses changes is not so significant, and all wells commissioning within a short time allows to consider the energy in the zones of sampling as equal. It should also be noted that irregular well water cut (from 1 to 30 %) was recorded at the initial stages of development.

Thereby surveying the individual conditions of fluid intrusion to production wells of the complex Tournaisian-Famennian reservoir on Zhilinskoye field is of scientific and practical interest.

Currently, there are no analytical solutions (as flow equations) for fractured-porous-cavernous reservoirs saturated with oil and gas condensate and irregularly watered. The known equations [4–7], which take into account at least some of the mentioned factors, are very complicated, and their practical application is very difficult.

This paper presents a method of describing fluid inflow based on the construction and analysis of multidimensional statistical models (multiple regression equations). The advantage of the probabilistic-statistical method is fairly simple and reliable description of processes occurring in complex systems, which include hydrocarbon production fields. In contrast to analytical solutions based on "imposing" researchers' conceptions to the studied object and its following "fitting" to the conceptions by means of clarifying coefficients, which are often insufficiently substantiated. Probabilistic-statistical methods work on a different principle. Their task is to describe real processes by accurate mathematical treatment of the facts [8].

Thus, the solution of the task is the construction and analysis of multidimensional models for determining well flow rates, based on the use of field data – actual geological and technological parameters of well operation at the considered site. For maximum reliability of the developed inflow models, the parameters of the first hydrodynamic studies (HDS) for the wells are taken as input data. Using the parameters determined by the first hydrodynamic studies will allow describing filtration processes in conditions close to the initial natural state of the site, undisturbed by technogenic effect.

The construction of multidimensional statistical models of flow rates for solving various problems of oil and gas engineering has been studied in many papers [8–10]. Classical multidimensional statistical models of flow rate forecast, constructed in these works, are statistically significant, but with notable calculation error. At the same time, the effect of parameters on the process of flow rates is determined only by the order of inclusion in the resulting model.

Individual probabilistic models based on geological and technological parameters of well operation

Regression equation	Range of application / probability range	Regression equation	Range of application / probability range
$P(W) = 0.423 + 0.0123W$	0.5–27.0 % 0.435–0.761	$P(d) = 0.164 + 0.14874d$	1.88–2.96 % 0.443–0.604
$P(\mu) = 1.305 + 1.4352\mu$	0.34–0.72 mPa·s 0.271–0.817	$P(P_{dr}^{T}) = 0.317 + 0.0002P_{dr}^{T}$	312.0–13861.0 m 0.379–0.967
$P(b) = -2.086 + 1.623b$	1.42–1.87 0.218–0.949	$P(P_{dr}^{T\text{-}Sob}) = 0.455 + 0.00002P_{dr}^{T\text{-}Sob}$	48.3–13861.0 m 0.456–0.829
$P(h) = 0.565 - 0.0224h$	0.6–6.0 m 0.430–0.552	$P(P_{dr}^{T\text{-}P}) = 0.455 + 0.00002P_{dr}^{T\text{-}P}$	42.3–8102.9 0.429–0.894
$P(G_f) = 0.565 - 0.0224G_f$	14.2–1698.8 m^3/t 0.482–0.525	$P(k_{rzr}^{S}) = 0.420 + 0.00232k_{rzr}^{S}$	4.19–208.5 μM^2 0.429–0.904
$P(P_f) = 0.565 - 0.0224P_f$	9.99–22.35 mPa 0.035–0.820	$P(S^S) = 0.726 + 0.06084S^S$	–7.62 – –0.002 FU 0.262–0.726
$P(P_b) = 0.565 - 0.0224P_b$	5.97–19.65 mPa 0.043–0.921	$P(P_{dr}^{S\text{-}Ch}) = 0.226 + 0.00044P_{dr}^{S\text{-}Ch}$	316–1656 0.365–0.955
$P(m) = 1.854 - 0.1507m$	6.7–12.3 % 0.001–0.844	$P(P_{dr}^{S\text{-}S}) = 0.456 + 0.0001P_{dr}^{Sob\text{-}S}$	49.7–3597.9 m 0.460–0.816
$P(F_r) = 0.487 - 0.026F_r$	0–1 0.487–0.517	$P(P_{dr}^{S\text{-}P}) = 0.372 + 0.00029P_{dr}^{Sob\text{-}P}$	37.0–2103.3 0.382–0.982
$P(k_{rzr}^{T}) = 0.418 + 0.00062k_{rzr}^{T}$	0.0047–0.8 μM^2 0.420–0.916	$P(P_{dr}^{S}) = 0.372 + 0.00029P_{dr}^{Sob}$	1150.0–9081.0 m 0.442–0.855
$P(S^T) = 0.273 - 0.0513S^T$	–7.24 – –2.29 FU 0.390–0.644	–	–

In this paper, the construction of multidimensional statistical models is completed with studies on the dimensionless assessment of each parameter effect on the well flow rate and the following comparison of these effects. For this purpose, individual (linear) probabilistic models were constructed for each parameter, characterising the probability of relating the well to the category of high or low flow rates according to this parameter.

The wells with productivity exceeding the average for the deposit (44 m^3/d) are considered as high-yield wells, while low-yield wells are those with lower than average flow rate. Accordingly, the whole sample is divided into two classes by the flow rate: class 1 includes high-yield wells, class 2 – low-yield wells. It should be noted, that despite the significant differentiation of flow rates, the average values of other geological and technological parameters used for the two selected classes are not statistically different, which was determined with Student's *t*-criterion. Significant differences between the average values for the two classes are determined only for the bottomhole pressure parameter. It means that statistical non-different values of geological and technological parameters form such different values of flow rates. This fact testifies using detailed research of liquid inflow conditions to wells of the considered site. It is introduced in the present article with application of probabilistic-technological parameters.

Classification of initial data

For constructing models, liquid flow rate Q (m^3/d) is used as a dependent (forecasted parameter), and viscosity of reservoir oil μ (mPa s), water cut of production W (%), Formation Volume Factor b, gas factor G_f (m^3/t), formation and bottomhole pressures P_f, P_b (MPa), porosity m (%) and permeability k (mD) of the reservoir, efficient oil saturated thickness of the reservoir h (m), bottomhole zone condition parameters (S, d) and drainage zone radius values (R_{dr}) are used as independent factors. Reservoir fracturing, diagnosed by pressure recovery curve (PRC) data, is taken into account by introducing an appropriate index F_r. The value $F_r = 1$ corresponds to the presence of natural reservoir fracturing in the drainage zone, $F_r = 0$ – its absence. Similarly, the bottomhole design is taken into account. The value of $I_e = 1$ indicates the horizontal end of the wellbore, the zero value of this index is introduced for vertical wells].

The filtration parameters of productive reservoirs for each well were determined by a specially performed interpretation of the first Pressure Recovery Curve (PRC) by using different methods. The permeability characterises the remote zone of the reservoir and is determined with tangent method and the Kappa Workstation software package (Saphir module) [11]. The bottomhole zone condition is taken into account by the skin factor value found by the tangent method and in Saphir module, as well as by dimensionless diagnostic d feature found by the method of deterministic pressure moments [12–15].

It is worth noting that in the research the effect of such an important parameter as the size (radius) of the drainage zone on flow rates was studied [16-20]. In fact, all analytical inflow equations include this parameter, but little attention is paid to the study of its actual values. In this paper, the values of the drainage zone radius are determined with the Chekalyuk formula $\left(P_{\text{dr}}^{\text{Ch}}\right)$, Van Pullen formula $\left(P_{\text{dr}}^{\text{P}}\right)$ [21, 22], Sobbie formula $\left(P_{\text{dr}}^{\text{Sob}}\right)$ [23, 24] and in Saphir module [25-32]. Radius by Chekalyuk, van Pullen and Sobbie were calculated twice: using permeabilities determined by the tangent method (T) and in Saphir module (S).

Methodology of the probabilistic-statistical studies

The first stage of problem solving was to construct individual probabilistic models of flow rates dependence on each of the geological and technological parameters accepted as initial data [33–35].

The algorithm of model construction can be briefly described as following. The preliminary stage included comparison of the distribution densities of each parameter (noted as x) for the two defined classes, with the optimal ranges (intervals) calculated using the Sturge's formula. At the next stage in each interval the probabilities of compliance of the given parameter value to the class of high-yield wells $P(x)$ were calculated. Matching correlation coefficients r were calculated for the values of $P(x)$ and x and regression equations were constructed. All linear probability models constructed in this way are given in the table.

The linear probability models presented in the table allow to assess individual informativeness of each parameter in formation of increased fluid flow rate. It should be noted that all constructed models perform correctly, as in all cases probability values are in the range of 0.0–1.0. The minimum value of probabilities is obtained from $P(m)$, the maximum from – $P\left(P_{\text{dr}}^{\text{S-P}}\right)$. It means that the factor with the greatest effect is the size of the drainage zone, determined by van Pullen formula, and with the least the porosity coefficient is. This conclusion is quite feasible and corresponds to the concepts of underground hydromechanics: almost all known analytical formulas of flow rate include the drainage zone size and do not use the porosity coefficient [36-40]. Accordingly, the constructed individual probabilistic models do not contradict the physics of the described process.

To account for the combined effect of parameters on the probability of increased flow rate values, it is proposed to use a complex parameter $P_{\text{комп}}$, which is calculated by the formula:

$$P_{\text{comp}} = \frac{\prod_{j=1}^{m} P(W_1 \mid X_j)}{\prod_{j=1}^{m} P(W_1 \mid X_j) + \prod_{j=1}^{m} (1 - P(W_1 \mid X_j))}, \quad (1)$$

where $P(W_1 \mid X_j)$ – individual probabilities of belonging to the class of wells with increased flow rates.

The approach based on the calculation of a dimensionless parameter that integrates effect of several parameters on the forecasted value is described in the following papers [8, 10].

For practical determination of the complex parameter, multidimensional statistical models were constructed, using geological and technological parameters as initial data. The models were constructed in combination for all wells, and differentiated for wells with horizontal wellbore and vertical wells. To assess statistical significance of the constructed models such parameters as multiple correlation coefficient (R), significance level (p) and standard error (S_0) were used.

The general model is as follows:

$$\begin{aligned} P_{\text{comp}}^{\text{M}} &= 0,026156 P_b + 0,001649 P_{\text{dr}}^{\text{S-Ch}} + 0,878614 b - \\ &- 0,114047 m - 0,047996 W - 0,156458 T_{\text{p}} - \\ &- 0,000115 P_{\text{dr}}^{\text{T-Ch}} - 0,015831 S^{\text{T}} - 0,8851, \end{aligned} \quad (2)$$

at $R = 0.999$, $p < 0.00404$, $S_0 = 0.0028$ unit fraction.

For vertical wells, the model has the following form:

$$P_{\text{comp}}^{\text{MB}} = 2\text{б}17112b + 0,071114T_{\text{p}} - 3,147, \qquad (3)$$

at $R = 0.999$, $p < 0.00036$, $S_0 = 0.014$ unit fraction.

For horizontal wells, the model has the following form:

$$P_{\text{comp}}^{\text{MH}} = -0,173078m + 0,000283k_{\text{rzr}}^{\text{T}} - \\ - 0,007419T_{\text{p}} + 2,1223. \qquad (4)$$

at $R = 0.999$, $p < 0.00022$, $S_0 = 0.00016$ unit fraction.

It should be noted that all the models are statistically significant. Applicability ranges of all constructed models fully correspond to actual conditions of fluid filtration on the considered field.

It is worth emphasising that the models constructed individually for wells of different designs show higher statistical estimates. Consequently, the different form of the constructed models confirms the fact of different flow conditions to horizontal and vertical wells. At the same time, the analysis of the constructed multidimensional equations allows to define the factors determining the flow to horizontal and vertical wells of the considered field. Thus, the probability of increased flow rates for vertical wells is determined by fluid properties and reservoir fracturing, for horizontal wells – only by its structure and properties.

The research allowed explaining a significant differentiation of well flow rates operating, at first sight, in similar geological and physical conditions.

The confirmed fact of different flow rates conditions requires separation of further research for vertical and horizontal wells, which is taken into account when solving the main task of the research – the construction of multidimensional statistical models for determining well flow rates.

The first model, constructed for all wells without considering their design, has the following form:

$$Q_{\text{liq}}^{\text{M}} = 1,2271P_b + 0,0803P_{\text{dr}}^{\text{S-Ch}} + 4,5206h - \\ - 2,9289W + 2,2592S^{\text{T}} + 19,3356d - \\ - 1,34m + 0,3796P_f - 48,2901, \qquad (5)$$

at $R = 0.999$, $p < 0.0522$, $S_0 = 1.32$ m^3/day.

For vertical wells, the model has the following form:

$$Q_{\text{liq}}^{\text{MV}} = 2,311688k_{\text{rzr}}^{S} + 0,012918P_{\text{dr}}^{\text{T-P}} + 6,992, \qquad (6)$$

at R $= 0.999$, $p < 0.00115$, $S_0 = 0.04$ m^3/day.

For horizontal wells, the model has the following form:

$$Q_{\text{liq}}^{\text{MH}} = -0,01837G_f + 0,00327P_{\text{dr}}^{\text{T-P}} - \\ - 2,45679d + 64,699, \qquad (7)$$

at $R = 0.999$, $p < 0.00118$, $S_0 = 0.02$ m^3/day.

Equation (5) is not statistically significant, despite the high value of the R coefficient, which confirms the unviability of using the same principles in describing the flow to vertical and horizontal wells on the considered field.

Models (6) and (7) are statistically significant and can be used to determine the well flow rates of different designs.

It should be noted that the radius of the drainage zone determined by van Pullen's formula takes the second place in both models. All known analytical inflow equations consider the size of the influence zone, but the corresponding parameter always takes the logarithm, which level up the effect of its variation on the well flow rate. The multidimensional statistical models presented in this paper demonstrate a significantly larger effect of the drainage area size on the amount of produced fluid.

The largest effect on the formation of the horizontal well flow rate is by the gas factor, it is the first to be included in the model with a negative sign. This conclusion indirectly indicates the differences in liberation of gas in the recovery zone of vertical and horizontal wells.

Model (7) at the last step includes the parameter d. It is a dimensionless diagnostic indicator that characterises the bottomhole zone properties, also defined by the method of deterministic pressure moments when processed with the pressure recovery curve. At the same time, the model did not include the values of skin factor determined by the tangent method and in the Saphir module. This conclusion indicates that the skin factor is a very complex parameter in the horizontal wells flow [41-45], and its feasibility in assessment of the bottomhole formation zone condition should be studied additionally.

Conclusion

The research is devoted to probabilistic-statistical assessment of fluid flow patterns in special geological and physical conditions of the developed site as a carbonate reservoir with a complex void volume and high formation of gas-oil factor.

The main tool is multidimensional statistical modelling, supplemented by a dimensionless (probabilistic) assessment of the specific effect of a wide range of geological and technological parameters on hydrocarbon flow patterns.

The original approach, as the construction of individual probabilistic linear equations, allowed to explain significant difference of well flow rates in similar, at first glance, geological and technological conditions.

The differences in the patterns of fluid flow to wells with various wellbore designs (vertical and horizontal) were statistically proven; the factors that can effect the flow rates were defined.

A series of multidimensional statistical models were constructed, which allowed to determine the flow rates of horizontal and vertical wells in complex geological and technological conditions with a high degree of reliability.

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