PERM JOURNAL OF PETROLEUM AND MINING ENGINEERING
ВЕСТНИК ПНИПУ. ГЕОЛОГИЯ. НЕФТЕГАЗОВОЕ И ГОРНОЕ ДЕЛО
ISSN 2224-9923
Volume / Том 17 №2 2018
http://vestnik.pstu.ru/geo/

УДК 622.276:532.5.013

Article / Статья

OPTIMIZATION OF CARBONATE RESERVOIR WELL TESTING

Anastasiya E. Davydova, Aleksandr A. Shchurenko, Nikita M. Dadakin,
Artyom D. Shutalev, Bronislav B. Kvesco

Siberian Federal University (79 Svobodny av., Krasnoyarsk, 660041, Russian Federation)

ОПТИМИЗАЦИЯ ПРОВЕДЕНИЯ ГИДРОДИНАМИЧЕСКИХ ИССЛЕДОВАНИЙ СКВАЖИН В УСЛОВИЯХ КАРБОНАТНОГО КОЛЛЕКТОРА

А.Е. Давыдова, А.А. Щуренко, Н.М. Дадакин, А.Д. Шуталев, Б.Б. Квеско

Сибирский федеральный университет (660041, Россия, г. Красноярск, пр. Свободный, 79)

Received / Получена: 06.06.2018. Accepted / Принята: 09.06.2018. Published / Опубликована: 29.06.2018

Key words:
well test, pressure recovery curve, workflow, well test time, well operation mode, carbonate reservoir, oil and gas field.

The purpose of the paper is to design a workflow for well testing to optimize the time of study and reduce the switch-off period of wells in a pilot test. Another puprose is to confirm the economic efficiency of the presented workflow. Wells T-23, T-361, T-388 of the A-field were used as objects of study. Deposits of A-field are predominantly represented by cavernous-fractured carbonate rocks of the Riphean age.

During the study an analysis of publications on the problem was performed. Field tests of wells located in low permeability carbonate reservoir were carried out. Modeling of well tests was carried out. Comparative calculations on the processing of results with help of Saphir software of KAPPA Engineering were made.

Results on development of the well test workflow are given. The data of hydrodynamic investigations for 12 wells operating Riphean carbonate deposits for the period 2005–2008 are analyzed and results for wells T-23, T-361, T-388 are presented. An example of calculation of stabilization time for wells by the method of steady-state sampling as well as estimation of the optimal time of recording the pressure recovery curve are given. In addition, a comparison of the standard workflow) used in the well test (RD 153-39.0-109-01) is performed. Methodical instructions on complexing and stage of implementation of geophysical, hydrodynamic and geochemical studies of oil and oil and gas deposits (with the method) are presented in the paper. Based on the comparison economic efficiency was established.

Ключевые слова:
гидродинамические исследования скважин, кривая восстановления давления, дизайн, длительность исследования скважины, режим работы скважины, карбонатный коллектор, нефтегазовое месторождение.

В статье была поставлена цель разработать дизайн гидродинамических исследований скважин для оптимизации времени проведения исследований и сокращения периода их остановки на этапе опытно-промышленной эксплуатации; подтвердить экономическую эффективность представленной методики. Объектом исследования выступили скважины Т-23, Т-361, Т-388 месторождения А, продуктивные отложения которого преимущественно представлены кавернозно-трещиноватыми карбонатными породами рифейского возраста.

В ходе работы был выполнен анализ публикаций по исследуемой проблеме; проведены промысловые гидродинамические исследования скважин, вскрывающих низкопроницаемый карбонатный коллектор; выполнено моделирование гидродинамических исследований, проведены сравнительные расчёты по обработке результатов с помощью программного комплекса Saphir компании KAPPA Engineering.

Приведены результаты разработки дизайна гидродинамических исследований в условиях карбонатного коллектора. Проанализированы данные гидродинамических исследований для 12 скважин, эксплуатирующих рифейские карбонатные отложения, за период 2005–2008 гг., представлены результаты по трем скважинам: Т-23, Т-361, Т-388. Приведены пример расчета времени стабилизации при исследовании скважины методом установившихся отборов, а также оценка оптимального времени регистрации кривой восстановления давления. Кроме того, выполнено сравнение стандартной методики, которой руководствуются при испытании скважины – «РД 153-39.0-109-01. Методические указания по комплексированию и этапность выполнения геофизических, гидродинамических и геохимических исследований нефтяных и нефтегазовых месторождений», – с методикой, представленной в статье. На основе данного сравнения была установлена экономическая эффективность.

Anastasiya E. Davydova – PhD student at the Department of Reservoir Engineering (tel.: +007 391 244 86 25, e-mail: DavydovaAE@knipi.rosneft.ru). The contact person for correspondence.
Aleksandr A. Shchurenko – PhD student at the Department of Reservoir Engineering (tel.: +007 391 244 86 25, e-mail: ShchurenkoAA@knipi.rosneft.ru).
Nikita M. Dadakin – PhD student at the Department of Reservoir Engineering (tel.: +007 391 244 86 25, e-mail: DadakinNM@knipi.rosneft.ru).
Artyom D. Shutalev – PhD student at the Department of Reservoir Engineering (tel.: +007 391 244 86 25, e-mail: ShutalevAD@knipi.rosneft.ru).
Bronislav B. Kvesco (Author ID in Scopus: 57201123338) – PhD in Physics and Mathematics, Professor at the Department of Reservoir Engineering of the Institute of Oil and Gas (tel.: +007 391 244 86 25, e-mail: kveskobb@gmail.com).

Давыдова Анастасия Евгеньевна – аспирант кафедры разработки и эксплуатации нефтяных и газовых месторождений (тел.: +007 391 244 86 25, e-mail: DavydovaAE@knipi.rosneft.ru). Контактное лицо для переписки.
Щуренко Александр Александрович – аспирант кафедры разработки и эксплуатации нефтяных и газовых месторождений (тел.: +007 391 244 86 25, e-mail: ShchurenkoAA@knipi.rosneft.ru).
Дадакин Никита Михайлович – аспирант кафедры разработки и эксплуатации нефтяных и газовых месторождений (тел.: +007 391 244 86 25, e-mail: DadakinNM@knipi.rosneft.ru).
Шуталев Артем Дмитриевич – аспирант кафедры разработки и эксплуатации нефтяных и газовых месторождений (тел.: +007 391 244 86 25, e-mail: ShutalevAD@knipi.rosneft.ru).
Квеско Бронислав Брониславович – кандидат физико-математических наук, профессор кафедры разработки и эксплуатации нефтяных и газовых месторождений Института нефти и газа (тел.: +007 391 244 86 25, e-mail: kveskobb@gmail.com).

Introduction

Hydrocarbons located in carbonate reservoirs progressively play an important role in world energy resources. Today, oil reserves containing heavy and super heavy oil associated with carbonate reservoirs compose 30 % of all explored world reserves [1-4]. Oil reserves located in such reservoirs in Russia represent more than 50 % of all reserves. The largest assets with such deposits are as follows: an Eastern section of the Orenburg field, Kuyumbinskoe and Zapadno-Chonskoye deposits in Eastern Siberia, Badra project in Iraq, Prirazlomnoye field offshore the Pechora Sea [5-6].

The paper considers the A-field with pay zone represented mainly by strong naturally fractured carbonate rocks of Riphean age. Riphean deposits are composed by terrigenous deposits in the lower part (Zelidukonskaya and Vedrashevskaya strata) overlapped by clay and carbonate deposits of the Madrinian strata. There are about 2.500 m of deposits of predominantly carbonate composition consisting of alternating carbonate packs that have thickness of about 500 m each and clay-carbonate packs, each of that has thickness around 100-200 m. Carbonate packs consist of dolomite for 90-95 % and interbeds of mudstone for 10-5 %. Argillite interlayers occupy 30 to 70 % of total thickness in argillaceous-carbonate packs. Thickness of interlayers of argillites varies from millimeters to several meters [7].

When carbonate reservoir rocks are formed both conditions for formation of sediments and secondary post-sedimentation transformations of carbonate rocks are crucial. According to the total amount of geochemical indications of sedimentation conditions, it is assumed that formation of the A-field occurred in marine desalinated conditions with significant local influences of freshwater masses. Voids in carbonate rocks have been forming at all the stages of lithogenesis. The primary sedimentation structure of carbonate sediments determines further development of post-sedimentation processes, which in aggregate finally forms the reservoir properties of carbonate rocks. Primary porosity in organogenic structures is much higher than in fine-grained sludge. That is caused by void space in stromatolite and algal dolomites. Dense packing of primary sedimentation sludges and absence of organic residues define their low porosity. A matrix is almost impermeable. Its porosity is in the range of 0.1-1 % [8-11].

It should be noted that fracturing significantly influences conditions of fluid flow in carbonate rocks of Vendian and Riphean age. That causes development of complex type reservoirs such as fracture-pore, pore-fracture and fracture-vug ones [12-13]. Fracturing is one of the factors contributing to both flow of hydrocarbons and formation of secondary porosity [14-15]. Numerous studies conducted in the All-Russian Petroleum Research Geological Exploration Institute (VNIGRI), established that density of fractures does not increase with depth, but its role in the formation of reservoir properties increases. Significance of cracks as the main ways of fluid flow increases with depth. Results of the study show the fracture volume is extremely low and does not exceed 0.03-0.05 % in much fractured rocks [16]. Therefore, cracks serve mainly as filtration ways of hydrocarbons and indirectly participate in the formation of secondary leaching pores. Secondary pores of leaching, developed along the open fractures are 0.5-2.5 % and reach 5-6 % in highly fractured rocks [17].

Design of well test

The main geological characteristics of the A-field are given in Table 1.

The A-field refers to deposits of a very complex geological structure with the following characteristics:

- high lithological and facies heterogeneity;
- significant disintegration;
- isotropy of fluid flow properties;
- intensive exchange fluid flow between fractures and matrix.

Table 1

Geological parameters of the A-field

Parameter		Description
Phase state		Oil and gas condensate
Field type		Massive, tectonically shielded
Reservoir type	Lithological composition	Carbonate
	By the type of void space	Vug-fracture

Such the parameters are the reason for radial fluid flow mode not to be reached. On the one hand, the radial flow can be “hidden” by the effect of wellbore influence or by a linear flow in the case of a well and fracture. On the other hand, the radial inflow regime can be distorted by the appearance of the following boundary conditions:

– interference with surrounding wells;

– geological fault, facies substitution (presence of an impenetrable boundary);

– processes occurre in the wellbore;

– gas cap (constant pressure boundary).

Since the movement of fluid flow is complex, interpretation of well test results in a carbonate reservoir is not an easy task. In order to eliminate the ambiguity of the information gathering, the paper proposes the development of an integrated approach to modeling the process of conducting research and forecasting the data obtained by design.

The method allows to:

– predict the duration of work in a certain mode;

– predict the duration of the stop on the pressure build-up (PBU) curve while the total duration of well test is determined taking into account the least loss of operating time and production of hydrocarbons;

– take into account the technical and technological conditions of work;

– identify the most frequently pop-up factors and take actions to reduce their negative impact on well test;

– assess the possibility of obtaining reservoir properties and well parameters using PBU curves;

– estimate oil production losses.

The paper presents the results of an analysis of data from three production wells that have revealed a pay zone represented by Riphean carbonate sediments. It is planned to re-test the Wells T-23, T-361, T-388 at the A-field in 2018 using multi-rate flow testing and pressure transient testing (recording of bottomhole pressure after shutdown of the well). It is planned to shut-in the well for trial operation after well testing.

Design of well tests was developed in the software Saphir of the Ecrin package of KAPPA Engineering [18]. The following data are used as initial information:

1. Characteristics of candidate wells

The first tests of Wells T-23, T-361, T-388 were carried out in 2007. Well completion is done for them by cumulative perforation PKO-89C with hole density of 14 holes/meter for the Well T-23 and 20 holes/meter for Wells T-361 and T-388. Several cycles of swabbing were conducted to trigger the inflow with depression of up to 35 % of reservoir pressure, after which the well started to gush.

Real well performance was used to make the research design. The main parameters of candidate wells are shown in Table 2.

Table 2

Description of wells

Parameter	Description		
Well	T-23	T-361	T-388
Value	Exploration	Exploration	Exploration
Type	Vertical	Vertical	Vertical
Rate, m^3/day	182.8	309.0	136.0

2. PVT fluid properties, reservoir parameters

Tables 3 and 4 show the properties of fluids and parameters of the reservoir.

Table 3

Properties of fluids

Parameter	Units	T-23	T-361	T-388
Initial formation pressure	kgf/cm^2	216	200,6	200,6
Viscosity of reservoir oil μ_o	cPs	1.332	1.06	1.06
Volume factor of oil B_o	fr.unit	1.288	1.465	1.465
Density of oil (reservoir conditions) $\rho_{o\ r.c}$	g/cm^3	0.714	0.7	0.7
Density of oil (standard conditions) $\rho_{o\ s.c}$	g/cm^3	0.822	0.825	0.825
Total compressibility Ct	1/MPa·10^{-4}	18.3	18.3	18.3

Table 4

Parameters of the reservoir

Parameter	Units	Value
Net pay thickness $H_{n.p}$	M	93.2
Mean reservoir porosity φ	fr.unit	0.01

3. Screening for equipment

The device SAMT-02 is proposed to run well test. That depth gauge-thermometer is designed to record pressure and temperature values along the wellbore and change them over the time at any point, for example, at the bottom when the pressure recovery curve is recorded [19]. The main advantages of the device are:

– speed measuring mode to ensure a quick study;

– tuning the operating mode and data transfer without disassembling the housing.

Characteristics of equipment given in Table 5 were used as initial data for design of the research.

Table 5

Some technical features of SAMT-02

Parameter	Units	Value
Pressure measuring range	MPa	0-60
Maximum permissible operating conditions	°C	–40...+125
Minimum measurement resolution	s	1/128
Continuous operation time from a new battery	Units	Up to 1 year
Pressure resolution by pressure	MPa	0.0001
Maximum recording speed	s	1
Accuracy of pressure measurements from full scale	%	0.15

4. Creating of a research program

The paper deals with design of an indicator diagram (ID) having forward and reverse stroke by the method of monotonically-step change in production rate.

Multi-rate flow testing underly all the modifications of research options using the ID. Full pressure recovery during shutdown of a well and complete stabilization at regime are mandatory requirements for conducting studies using the multi-rate flow testing [20]. It is known, that in case of low-permeability reservoirs, this process requires a longer time.

Four modes of the direct stroke (with a minimum choke) are studied, a stop at the PBU and two reversal modes. Reverse run modes are used to control well cleaning and deterioration of bottomhole zone properties. Recording the PBU curve after the end of the direct stroke is suitable, since in the last mode of the direct stroke, the work with the maximum production rate takes place, which determines the maximum value of the derivative pressure at the PBU curve. Thus, the most favorable conditions are created for cleaning the bottomhole from liquid and mechanical particles, which ensures good quality of a PBU curve [21-26].

Stabilization time for wells under consideration in research at the A-filed is calculated by the multi-rate flow testing using the formula

$$t_y = \frac{R_k^2}{4 \cdot \chi},$$

where R_k – radius of a source bounder or half a distance to neighboring wells, m; χ – piezoconductivity of the formation, m^2/s.

Duration of well performance in each mode is measured based on well switch-on to the steady state. The coefficient of piezoconductivity of the reservoir is calculated by the formula

$$\chi = \frac{k}{\mu \cdot \beta^*},$$

where k – formation permeability, m^2; μ – dynamic viscosity of formation fluid, Pa·s; β^* – reservoir elasticity, Pa^{-1}.

Table 6

Recommended well operating modes

Technology	Choke, mm	Duration, h	Estimated production rate, m^3/day
Well T-23			
Cleaning of the bottomhole formation zone	10	24	149.8
PBU curve			
Straight run	6	42	64.9
	8	42	113.2
	10	42	149.8
	12	42	182.8
PBU curve			
Reverse run	10	42	149.8
	8	42	113.2
Well T-361			
Cleaning of the bottomhole formation zone	10	24	216
PBU curve			
Straight run	6	17	121.9
	8	17	166.1
	10	17	216
	12	17	309
PBU curve			
Reverse run	10	17	216
	8	17	166.1
Well T-388			
Cleaning of the bottomhole formation zone	10	24	123
PBU curve			
Straight run	6	19	70
	8	19	93
	10	19	123
	12	19	136
PBU curve			
Reverse run	10	19	123
	8	19	93

Well test data taken in 2007 (permeability, wellbore storage, flow rate) was used as initial data to create the design [27]. Neutral value of the mechanical skin factor equal to 0 was used during the modelling. Table 6 shows the initial data and estimated time required to operate the well in each mode.

Models of well test design for Wells T-23, T-361, T-388 are given in Fig. 1. According to results of the modelling conducted noted that in order to obtain a high-quality ID it is necessary to operate the well in each mode (without taking into account the time required to change the regime), not less than:

– 42 h for Well T-23;

– 17 h for Well T-361;

– 19 h for Well T-388.

Diagnostic PBU curves were obtained as a result of numerical modeling. Fig. 2 shows a detailed curve for Well T-23.

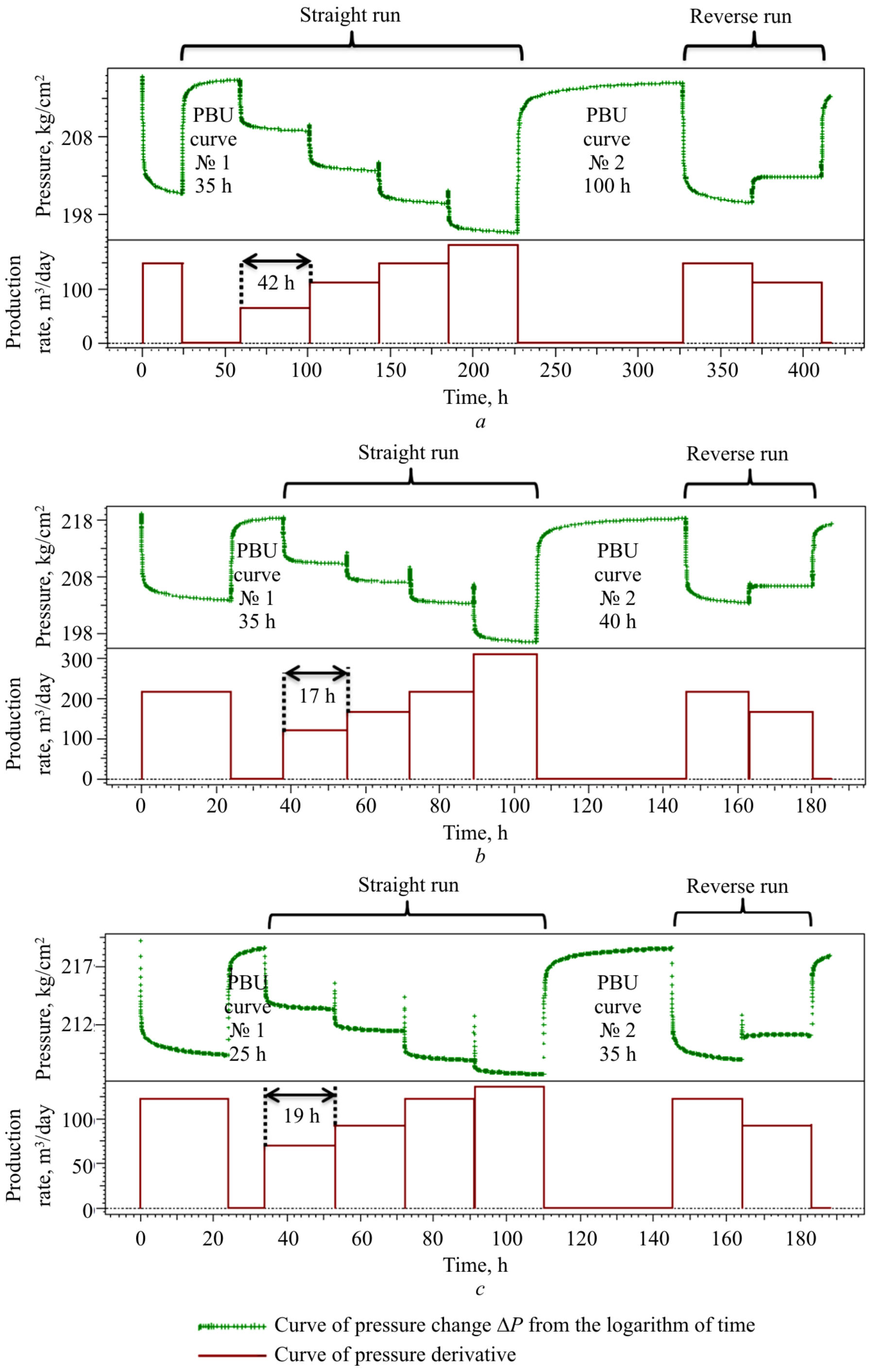

Fig. 1. Well test design: *a* – T-23; *b* – T-361; *c* – T-388

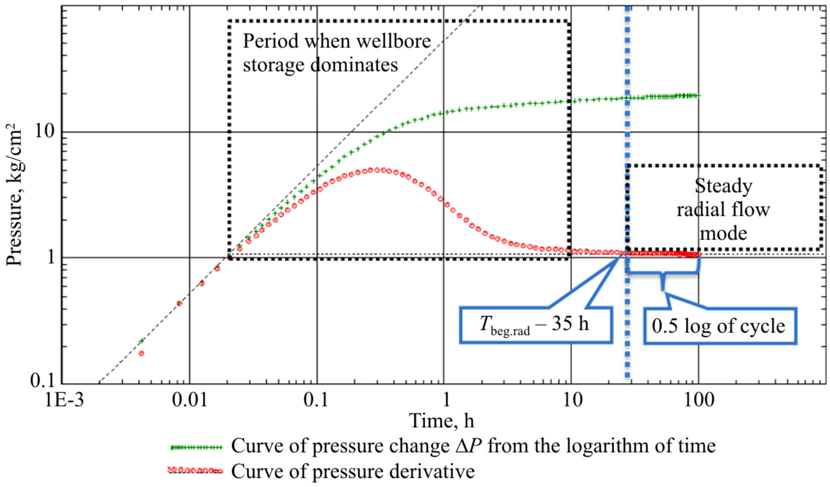

Fig. 2. Design of the graph to diagnose the PBU curve of the Well T-23 in bilogarithmic coordinates

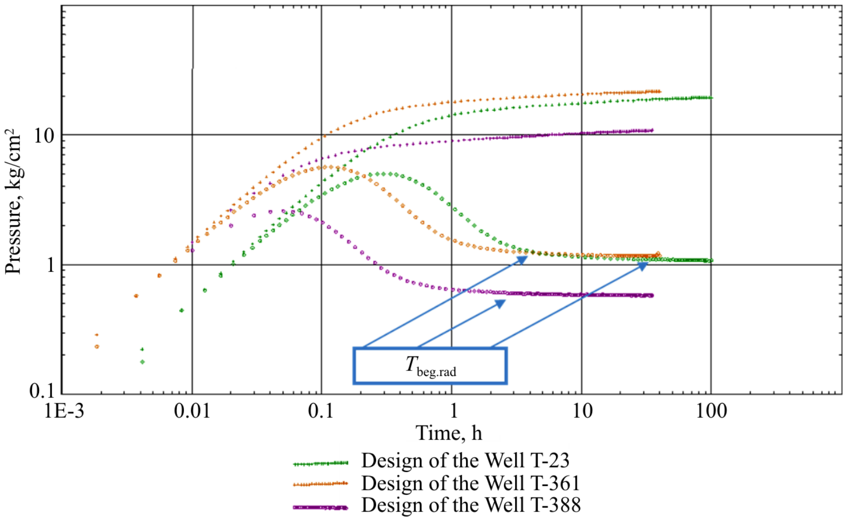

Fig. 3. Design of the graph to diagnose the PBU curve of the Well T-23, T-361, T-388 in bilogarithmic coordinates: $T_{\text{beg.rad}}$ – beginning of radial flow mode

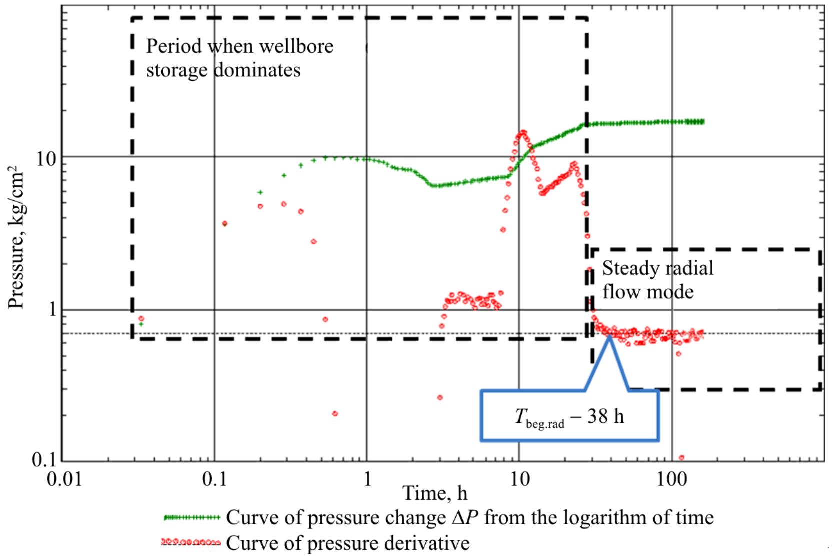

Fig. 4. Real chart to diagnose the PBU curve of the Well T-23 in bicoordinates

According to the modelling done wellbore storage time was 12 hours and radial flow started after 35 hours.

In order to obtain correct results when interpreting the PBU curves of the Well T-23, radial flow regime should be at least 1/2 of logarithmic cycle. Taking into account such the condition the time of recording the PBU curve is around 100 hours (4 days).

As a result of the design made, a thorough analysis of the initial data was performed and bottomhole pressure behavior for Wells T-23, T-361, T-388 was numerically modelled (Fig. 3). Based on results of modelling, the recommended study time is:

– 100 h for Well T-23;
– 40 h for Well T-361;
– 35 h for Well T-388.

Besides, it was possible to compare results of the study design with real test results for the Well T-23.

It should be noted that the PBU curve have been recording for 144 hours as stated in recommendations specified in RD 153-39.0-109-01.

There is in the obtained diagnostic chart of PBU curve mathematical modeling a long period of influence of wellbore storage observed in bilogarithmic coordinates. That is complicated by phase redistributions lasting for 35 h. The time to radial flow is about 38 h.

Analysis of the Fig. 6 shows that radial flow mode of the real well test starts to be stable after $T_{\text{beg.rad}}$ which is equal to 38 hours, while the $T_{\text{beg.rad}}$, obtained as a result of study design modeling was 35 h. The data above confirm the high efficiency of the application of the methodology for developing an integrated approach to modeling the research-based design process.

Economic impact

During the planning of well testing at the stage of pilot operation of wells testing time is the factor for the economic evaluation. The smaller the period of well testing and, as a consequence, shut-in period, the more profitable the project is.

A comparative analysis was performed in order to assess the economic impact of the approach presented, Recommendations specified in RD 153-39.0-109-01 were used in accordance with geological conditions as well as data obtained as a result of modeling the design of the study. Based on recommendations specified in the RD, the required operating time for the well in one mode for a reservoir with a permeability of 0.05-0.01 μm^2 is 96 hours, and the time for PBU curve recording is 144 hours [28-32].

Initial data for calculation are given in Table 7.

Table 7

Initial data for economic analysis

Parameter	Value		
Technical characteristics			
Well	TT-23	T-361	T-388
Production rate Q_{oil}, tonnes/day	150.3	254.0	111.8
The time of recording the PBU curve, day:			
– standard procedure RD 153-39.0-109-01 T_1	6	6	6
– test design methodology T_2	4.2	1.7	1.5
Economic macro parameters			
Oil price S_{barr} (average for the year, as of February 2018), USD/bbl			68.95
Barrel coefficient K_{barr} (according to the analytical agency ARGUS), barrel/tonne			7.43

As it was mentioned above, when considering the standard approach, the minimum time to record the PBU curve of T_1 = 144 hours (6 days) is accepted for wells with high stable rates and reservoirs with a permeability below 0.05-0.01 μm^2.

Oil price S_o, doll/tonne [33-34]:

$$S_o = S_{\text{barr}} \cdot K_{\text{barr}} = \\ = 68.95 \cdot 7.43 = 512.30.$$

Taking into account the dollar exchange rate (for February 2018) S_{doll} = 57.66 rub/doll, cost of oil S, thousand rubles/tonne:

$$S = S_o \cdot S_{\text{doll}} = \\ = 512.30 \cdot 57.66 = 29.54.$$

Mass of oil obtained during well testing, depending on the methodology used for well test forecast, tonne:

$$M_o = Q_{\text{oil}} \cdot T.$$

The economic impact I when applying the design development method in comparison with the standard approach was calculated by the formula [34-38]

$$I = (M_{o_1} - M_{o_2})S,$$

The Table 8 presents the results of economic calculations.

Table 8

Results of economic comparison of methods

Well	Oil rate, tonne/day	Time, days		Oil loss, tonnes		Cost of oil, thousand rubles/tonne	Economic impact, thousand rubles
		RD	Test-design	RD	Test-design		
	Q	T_1	T_2	M_{o_1}	M_{o_2}	S	I
T-23	150.3	6	4.2	901.8	631.3	29.54	7 991.8
T-361	254.0	6	1.7	1 524.0	431.8		32 263.6
T-388	111.8	6	1.5	670.8	167.7		14 861.6

It follows from the data above that economic impact of the application of the proposed methodology for forecasting a well test based on design in comparison with the standard approach for RD 153-39.0-109-01 for the considered wells of an A-field will be as follows: I_1 = 7991.8 thousand rubles, I_2 = 32 263,6 thousand rubles, I_3 = 14 861.6 thousand rubles.

It can be concluded that the design methodology of the study allows shortening the period of well test at the stage of planning. Thus, the shut-in period of the well will decrease, which will allow reducing losses at the stage of pilot operation of wells and obtaining additional profit from the product sales (Fig. 5).

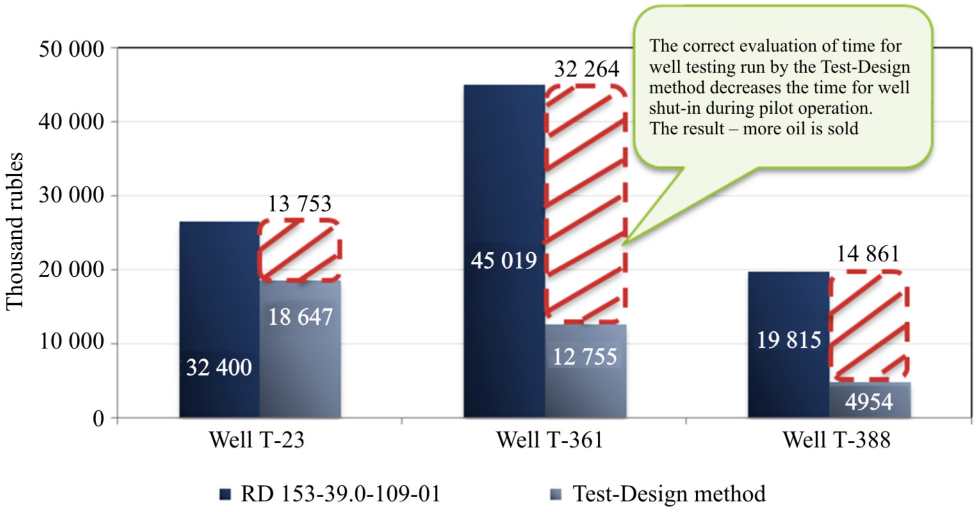

Fig. 5. Results of economic comparison of methodologies. Economic effect of applying the Test-Design methodology

Conclusions

As a result of the design, a thorough analysis of the initial data was made and bottomhole pressure bahaviour in wells T-23, T-361, T-388 was numerically simulated. Based on modelling results recommended duration of the test is:

- 100 h for Well T-23;
- 40 h for Well T-361;
- 35 h for Well T-388.

Oil losses for the well shut-in are:

- 631.3 tonnes for Well T-23;
- 431.8 tonnes for Well T-361;
- 167.7 tonnes foe Well T-388.

Data of the Well T-23 were also compared with real test data. It was established in the study that the design chosen of the study and calculations performed are fully confirmed.

Modelling of well testing based on the design of the study is econmically proved. Specification of the time for the test in comparison with the standard approach RD 153-39.0-109-01 allows shortening the well shut-in period and increasing the time of oil production at the stage of pilot operation. Based on data of three exploratory wells of the A-field the average economic impact was 20.292.7 thousand rubles.

In conditions of existing pattern of a field development system, in order to improve the quality of well testing it is necessary to accurately set the hydrodynamic study objectives in a target well with identification of capabilities of several methods of well testing, as well as obligatory observance of the research technology stated in the design. That will significantly improve the quality of well testing, optimize the cost of research and loss of oil, compensating their high accuracy of information received. The solutions proposed in the paper allows to assess the feasibility and cost-effectiveness of the work planned.

It is obvious, that in order to carry out qualitative research, it is necessary to plan well testing at the pre-measurement stage. In other words, before any testing it is necessary to execute the design of well testing either in a specialized software product or by empirical formulas [39-42].

It is important to note that, no matter how ideal the study was planned, it is necessary to provide technical (well preparation, selection of operable research equipment) and technological (observance of the test time) conditions in a target well of each of the responsible parties (oil company and service company). In addition, it is necessary to establish what exactly can prevent the obtaining of a clearly diagnosed area of radial flow. On the one hand, the radial flow can be "hidden" by the borehole storage or by a linear flow in case of a well with a fracture. On the other hand, the radial inflow regime can be destroyed by the boundary condition such as: 1) interference with surrounding wells; 2) geological fault (impermeable boundary); 3) gas cap (constant pressure boundary).

References

1. Deeva T.A., Kamartdinov M.R., Kulagina T.E., Mangazeev P.V. Gidrodinamicheskie issledovaniia skvazhin analiz i interpretatsiia dannykh [Well tests: analysis and interpretation of data]. Tomsk, Izdatelstvo Tomskogo politekhnicheskogo universiteta, 2009, 243 p.

2. Pokrepin B.V. Razrabotka neftianykh i gazovykh mestorozhdenii [Development of oil and gas fields]. Volgograd, In-Folio, 2008, 192 p.

3. Brand U., Veizer J. Chemical diagenesis of a multicomponent carbonate system – 1: trace elements. *Journal of Sedimentary Petrology*, 1980, vol.50, no.4, pp.1219-1236. DOI: 10.1306/212F7BB7-2B24-11D7-8648000102C1865D

4. Choquette Ph. W., James N.P. Diagenesis 12. Diagenesis in limestones – 3. The deep burial environment. *Geoscience Canada*, 1987, vol.14, no.1, pp.3-35.

5. Altunina L.K., Kuvshinov V.A., Kuvshinov I.V. Uvelichenie nefteotdachi v karbonatnykh kollektorakh [Increase of oil recovery in carbonate reservoirs]. *NEFTEGAZ.RU*, 2017, no.3, pp.99-103.

6. Barnaby R.J., Read J.F. Dolomitization of a carbonate platform during late burial: Lower to Middle Cambrian Shady dolomite, Virginia Appalachians. *Journal of Sedimentary Geology*, 1992, vol.62, no.6, pp.1023-1043. DOI: 10.1306/D4267A3C-2B26-11D7-8648000102C1865D

7. Vasileva K.Iu. Stadiinost postsedimentatsionnykh izmenenii karbonatnykh porod rifeia – venda Kuiumbinskogo mestorozhdeniia i ee sviaz s geologicheskoi evoliutsiei Baikitskoi anteklizy (iugozapad Sibirskoi platformy) [Stages of post-sedimentation changes of carbonate rocks of the Riphean-Vendian Kuyumbinsky deposit and its connection with the geological evolution of the Baikite anteclase (south-west of the Siberian platform)]. Saint Petersburg, 2017, 138 p.

8. Bathurst R.G.C. Carbonate sediments and their diagenesis. Amsterdam, Elsevier, 1975, 620 p.

9. Metodicheskie rekomendatsii po izucheniiu i prognozu kollektorov nefti i gaza slozhnogo tipa [Methodical recommendations for the study and forecasting of complex gas-oil reservoirs and gas]. Leningrad, Nedra, 1989, 103 p.

10. Varkasina I.V. Sidementatsionnye i postsidementatsionnye faktory formirovaniia rifeiskikh karbonatnykh kollektorov IuTZ neftegazonakopleniia (Vostochnaia sibir): kriterii otsenki neftegazonosnosti nizhe promyshlenno osvoennykh glubin i opredelenie prioritetnykh napravlenii geologo-razvedochnykh rabot [Sedimentation and post-sedimentation factors of formation of Riphean carbonate collectors of UTZ of oil and gas accumulation (East Siberia): Criteria for assessing oil and gas content lower than industrial depths and determining priority directions of geological prospecting works]. *Tezisy dokladov vserossiiskoi konferentsii*. Perm, 2000, 159 p.

11. Gutina O.V. Sovershenstvovanie skhemy raschleneniia i korreliatsii rifeiskikh otlozhenii iugo-zapadnoi chasti Sibirskoi platformy [Improvement of the scheme of dismemberment and correlation of the Riphean deposits of the southwestern part of the Siberian platform]. *Geologiia, stroenie, neftegazonosnost i perspektivy osvoeniia neftianykh i gazovykh mestorozhdenii nizhnego Priangaria. Sbornik dokladov Vserossiiskoi konferentsii*. Krasnoiarsk, 1996, pp.45-46.

12. Gmid L.P., Levi S.Sh. Atlas karbonatnykh porod-kollektorov [Atlas of carbonate rock-reservoirs]. Leningrad, Nedra, 1972, 200 p.

13. Korsakov S.P. et al. O vliianii epigeneticheskikh protsessov v karbonatnykh porodakh na vozniknovenie vtorichnoi emkosti (na primere mestorozhdenii Srednei Azii) [On the influence of epigenetic processes in carbonate rocks on the emergence of secondary capacities (on the example of deposits of Central Asia)]. *Karstovye kollektory nefti i gaza*. Perm, 1973, pp.148-149.

14. Kontorovich A.E., Izosimova A.N., Kontorovich A.A., Khabarov E.M., Timoshina I.D. Geologicheskoe stroenie i usloviia formirovaniia gigantskoi Iurubcheno-Tokhomsoki zony neftegazonakopleniia v verkhnem proterozoe Sibirskoi platformy [Geological structure and conditions for the formation of a giant Yurbchenko-Tohomoskoy oil and gas accumulation zone in the Upper Proterozoic of the Siberian Platform]. *Geologiia i geofizika*, 1996, vol.37, no.8, pp.166-195.

15. Sokolov D.S. Formirovanie poristosti i kavernoznosti rastvorimykh porod [Formation of porosity and cavity of soluble rocks]. *Izvestiia vysshikh uchebnykh zavedenii*, 1958, no.1, pp.54-66.

16. Belonovskaia L.G. Treshchinovatost karbonovykh porod i razrabotannye vo VNIGRI osnovy poiskov treshchinnykh kollektorov nefti i gaza [The fracture of carbonaceous rocks and the bases of the search for cracked oil and gas collectors developed in VNIGRI]. *Neftegazovaia geologiia. Teoriia i praktika*, 2006, pp.9-13.

17. Burdine N.T. Relative permeability calculations from pore size distribution data. *Transaction of AIME*, 1953, vol.5, no.3. DOI: 10.2118/225-G.

18. Houze O., Viturat D., Fjaere O.S. Dynamic data analysis v4.12.02. Kappa, 2011, 557 p.

19. Manometry-termometry glubinnye “CAMT-02-25-d32”, “CAMT-02-40-d32”, “CAMT-02-60-d32”. Rukovodstvo po ekspluatatsii [Manometers, thermometers deep “SAMT-02-25-d32”, “SAMT-02-40-d32”, “SAMT-02-60-d32”. Operating manual]. Moscow, 2010, 13 p.

20. Baikov V.A., Emchenko O.V., Zainulin A.V., Davletbaev A.Ia. Interpretatsiia i analiz rezultatov issledovanii kollektora treshchinno-kavernozno-porovogo tipa [Interpretation and analysis of the research results of the collector of the crack-cavernous-porous type]. *Nauchno-tekhnicheskii vestnik OAO NK “Rosneft”*, 2007, no.5, pp.30-34.

21. Brooks R.H., Corey A.T. Properties of porous media affecting fluid flow. *Journal of Irrigation and Drainage Engineering (ASCE)*, 1966, vol.92, no.2, pp.61-88.

22. Earlaugher R.C. Jr., Kerch K.M. Analysis of short-time transient test data by type-curve matching. *Journal of petroleum technologies*, 1974, vol.26, pp.793-800. DOI: 10.2118/4488-PA

23. Gringarten A.C. Well test analysis in practice. *The way ahead (TWA)*, 2012, p.10-15. DOI: 10.2118/0212-010-TWA

24. Horne R.N. Modern well test analysis. A computer Aided Approach. Petroway Inc. US, 1990, 185 p.

25. Zein Al-Abidin M.D., Sokhoshko S.K., Sarancha A.V. Razrabotka dizaina gidrodinamicheskogo issledovaniia neftianoi skvazhiny v neftegazokondensatnom kollektore s primeneniem metodov trekhmernogo chislennogo mo [Development of oil well test design in the oil-gas reservoir using the methods of 3d hydrodynamic simulation]. *Fundamentalnye issledovaniia*, 2016, no.4-1, pp.47-51.

26. Merkulov V.P., Krasnoshchekova L.A. Otsenka vliianiia filtratsionnoi anizotropii neftegazonosnykh kollektorov pri modelirovanii mestorozhdenii [An estimation of the influence of filtration anisotropy of oil and gas collectors in the field modeling]. *Gazovaia promyshlennost*, 2014, no.3, pp.22-27.

27. Olkhovskaia V.A., Zinovev A.M., Golovina Iu.A. Parametricheskaia interpretatsiia dannykh gidrodinamicheskikh issledovanii skvazhin i plasta kak reologicheskoi sistemy [Parametric interpretation of data of hydrodynamic investigations of wells and reservoirs as a rheological system]. *Geologiia, geofizika i razrabotka neftianykh i gazovykh mestorozhdenii*, 2012, no.8, pp.40-44.

28. Bo Gao, Zhao-Qin Huang, Jun Yao, Xin-Rui Lv, Yu-Shu Wu. Pressure transient analysis of a well penetrating a filled cavity in naturally fractured carbonate reservoirs. *Journal of Petroleum Science and Engineering*, 2016, pp.392-403. DOI: 10.1016/j.petrol.2016.05.037

29. RD 153-39.0-109-01. Metodicheskie ukazaniia po kompleksirovaniiu i etapnosti vypolneniia geofizicheskikh gidrodinamicheskikh i geokhimicheskikh issledovanii neftianykh i neftegazovykh mestorozhdenii [Methodical instructions on complexing and stage of execution of geophysical, hydrodynamic and geochemical studies of oil and oil and gas deposits]. Moscow, Nauka, 2002, 95 p.

30. Patrusheva E.G. Investitsionnyi menedzhment [Investment management]. Iaroslavl, Iaroslavskii gosudarstvennyi universitet imeni P.G. Demidova, 2017, 120 p.

31. Shpaikher E.D., Salikhov V.A. Geologo-razvedochnye raboty i geologo-ekonomicheskaia otsenka mestorozhdenii poleznykh iskopaemykh [Geological exploration and geological and economic evaluation of mineral deposits]. Novokuznetsk, Sibirskii gosudarstvennyi industrialnyi universitet, 2002, 311 p.

32. Astafeva M.P., Melekhin E.S., Porokhnia E.A. Otsenka mestorozhdenii poleznykh iskopaemykh kak obektov investirovaniia i biznesa [Assessment of mineral

deposits as investment and business objects]. Moscow, VNIILM, 2002, 142 p.

33. Khakimova A.S. Kompleks GIS v ekonomicheskikh raschetakh mestorozhdenii nefti i gaza [GIS complex in economic calculations of oil and gas deposits]. *Ekonomika i biznes: teoriia i praktika*, 2017, no.8, pp.79-81.

34. Kuzmin T.G., Molodykh P.V. Ekonomika investitsionnogo proekta v neftegazovoi otrasli [The economy of an investment project in the oil and gas industry]. Tomsk, Tomskii politekhnicheskii universitet, 2010, 181 p.

35. Kochetkov A.A. Ekonomicheskaia teoriia [Economic theory]. Moscow, Dashkov i K, 2016, 696 p.

36. Davydova A.E., Groo A.A. Razrabotka raschetnogo kompleksa poverkhnostnogo obustroistva 0-d urovnia [Development of the settlement complex of surface-level arrangement of 0-d]. *Sbornik dokladov VIII regionalnoi nauchno-tekhnicheskoi konferentsii molodykh spetsialistov OOO "RN-krasnoiarskNIPIneft"*. Krasnoyarsk, 2016, 108 p.

37. Babuk I.M., Korolko A.A., Adamenkova S.I., Kostiukevich E.N. Raschet ekonomicheskoi effektivnosti novykh tekhnologicheskikh protsessov [Calculation of economic efficiency of new technological processes]. Minsk, Belorusskii natsionalnyi tekhnicheskii universitet, 2010, 56 p.

38. Acka G., Mohammed A., Ampomah J., Oppong D., Sampah O. Impact of oil prices on nominal exchange rate: evidence from Ghana. *The International Journal Of Business & Management*, 2017, pp.269-281.

39. Bourde D. Well test analysis: the use of advanced interpretation Models. Amsterdam, Elsevier science, 2002, 461 p.

40. Economides M., Daniel H. Petroleum production systems. *Prentice Hall Inc, Upper Saddle River*, NJ 07458, 1994, 607 p.

41. Adedapo A., Ayham A.A Cohesive approach at estimating water saturation in a low-resistivity pay carbonate reservoir and its validation. *Journal of Petroleum Exploration and Production Technology*, 2017, pp.306-320.

42. Awolayo A., Ashqar A., Uchida M., Salahuddin A.A., Olayiwola S.O. A cohesive approach at estimating water saturation in a low-resistivity pay carbonate reservoir and its validation. *Journal of Petroleum Exploration and Production Technology*, 2017, vol.7, iss.3, pp.637-657 DOI: 10.1007/s13202-017-0318-2

43. Arbab B., Jahani D., Movahed B. Reservoir characterization of carbonate in low resistivity pays zones in the buwaib formation, Persian Gulf. *Open Journal of Geology*. 2017, pp.1441-1451. DOI: 10.4236/ojg.2017.79096

Библиографический список

1. Гидродинамические исследования скважин: анализ и интерпретация данных / Т.А. Деева, М.Р. Камартдинов, Т.Е. Кулагина, П.В. Мангазеев. – Томск: Изд-во Томск. политехн. ун-та, 2009. – 243 с.

2. Покрепин Б.В. Разработка нефтяных и газовых месторождений: учеб. пособие. – Волгоград: Ин-Фолио, 2008. – 192 с.

3. Brand U., Veizer J. Chemical diagenesis of a multicomponent carbonate system – 1: trace elements // Journal of Sedimentary Petrology. – 1980. – Vol. 50, № 4. – P. 1219–1236. DOI: 10.1306/212F7BB7-2B24-11D7-8648000102C1865D

4. Choquette Ph.W., James N.P. Diagenesis 12. Diagenesis in limestones – 3. The deep burial environment // Geoscience Canada. – 1987. – Vol. 14, № 1. – P. 3–35.

5. Алтунина Л.К., Кувшинов В.А., Кувшинов И.В. Увеличение нефтеотдачи в карбонатных коллекторах // NEFTEGAZ.RU. – 2017. – № 3. – С. 99–103.

6. Barnaby R.J., Read J.F. Dolomitization of a carbonate platform during late burial: Lower to Middle Cambrian Shady dolomite, Virginia Appalachians // Journal of Sedimentary Geology. – 1992. – Vol. 62, № 6. – P. 1023–1043. DOI: 10.1306/D4267A3C-2B26-11D7-8648000102C1865D

7. Васильева К.Ю. Стадийность постседиментационных изменений карбонатных пород рифея – венда Куюмбинского месторождения и ее связь с геологической эволюцией Байкитской антеклизы (юго-запад Сибирской платформы). – СПб., 2017. – 138 с.

8. Bathurst R.G.C. Carbonate sediments and their diagenesis. – Amsterdam: Elsevier, 1975. – 620 p.

9. Методические рекомендации по изучению и прогнозу коллекторов нефти и газа сложного типа. – Л.: Недра, 1989 – 103 с.

10. Варкасина И.В. Сидементационные и постсидементационные факторы формирования рифейских карбонатных коллекторов ЮТЗ нефтегазонакопления (Восточная Сибирь): Критерии оценки нефтегазоносности ниже промышленно освоенных глубин и определение приоритетных направлений геологоразведочных работ // Тезисы докладов Всероссийской конференции. – Пермь, 2000. – 159 с.

11. Гутина О.В. Совершенствование схемы расчленения и корреляции рифейских отложений юго-

западной части Сибирской платформы // Геология, строение, нефтегазоносность и перспективы освоения нефтяных и газовых месторождений нижнего Приангарья: сб. докл. Всерос. конф. – Красноярск, 1996. – С. 45–46.

12. Гмид Л.П., Леви С.Ш. Атлас карбонатных пород-коллекторов. – Л.: Недра, 1972. – 200 с.

13. О влиянии эпигенетических процессов в карбонатных породах на возникновение вторичной емкости (на примере месторождений Средней Азии) / С.П. Корсаков [и др.] // Карстовые коллекторы нефти и газа. – Пермь, 1973. – С. 148–149.

14. Геологическое строение и условия формирования гигантской Юрубчено-Тохомсокой зоны нефтегазонакопления в верхнем протерозое Сибирской платформы / А.Э. Конторович, А.Н. Изосимова, А.А. Конторович, Е.М. Хабаров, И.Д. Тимошина // Геология и геофизика. – 1996. – Т. 37, № 8. – С. 166–195.

15. Соколов Д.С. Формирование пористости и кавернозности растворимых пород // Известия высших учебных заведений. – 1958. – № 1. – С. 54–66.

16. Белоновская Л.Г. Трещиноватость карбоновых пород и разработанные во ВНИГРИ основы поисков трещинных коллекторов нефти и газа // Нефтегазовая геология. Теория и практика. – 2006. – С. 9–13.

17. Burdine N.T. Relative permeability calculations from pore size distribution Data // Transaction of AIME. – 1953. – Vol. 5, № 3. DOI: 10.2118/225-G.

18. Houze O., Viturat D., Fjaere O.S. Dynamic data analysis v4.12.02. – Kappa, 2011. – 557 p.

19. Манометры-термометры глубинные «САМТ-02-25-d32», «САМТ-02-40-d32», «САМТ-02-60-d32»: Руководство по эксплуатации. – М., 2010 – 13 с.

20. Интерпретация и анализ результатов исследований коллектора трещинно-кавернозно-порового типа / В.А. Байков, О.В. Емченко, А.В. Зайнулин, А.Я. Давлетбаев // Научно-технический вестник ОАО «НК “Роснефть”». – 2007. – № 5. – С. 30–34.

21. Brooks R.H., Corey A.T. Properties of porous media affecting fluid flow // Journal of Irrigation and Drainage Engineering (ASCE). – 1966. – Vol. 92, № 2. – P. 61–88.

22. Earlaugher R.C. Jr., Kerch K.M. Analysis of short-time transient test data by type-curve matching // Journal of petroleum technologies – 1974. – Vol. 26. – P. 793–800. DOI: 10.2118/4488-PA

23. Gringarten A.C. Well test analysis in PRACTICE // The way ahead (TWA). – 2012. – P. 10–15. – SPE-0212-010-TWA. DOI: 10.2118/0212-010-TWA

24. Horne R.N. Modern well test analysis. A computer aided approach. – Petroway Inc. US, 1990. – 185 p.

25. Зейн Аль-Абидин М.Д., Сохошко С.К., Саранча А.В. Разработка дизайна гидродинамического исследования нефтяной скважины в нефтегазоконденсатном коллекторе с применением методов трехмерного численного моделирования // Фундаментальные исследования. – 2016. – № 4–1. – С. 47–51.

26. Меркулов В.П., Краснощекова Л.А. Оценка влияния фильтрационной анизотропии нефтегазоносных коллекторов при моделировании месторождений // Газовая промышленность. – 2014. – № 3. – С. 22–27.

27. Ольховская В.А., Зиновьев А.М., Головина Ю.А. Параметрическая интерпретация данных гидродинамических исследований скважин и пласта как реологической системы // Геология, геофизика и разработка нефтяных и газовых месторождений. – 2012. – № 8. – С. 40–44.

28. Pressure transient analysis of a well penetrating a filled cavity in naturally fractured carbonate reservoirs / Bo Gao, Zhao-Qin Huang, Jun Yao, Xin-Rui Lv, Yu-Shu Wu // Journal of Petroleum Science and Engineering. – 2016. – P. 392–403. DOI: 10.1016/j.petrol.2016.05.037

29. РД 153-39.0-109-01. Методические указания по комплексированию и этапности выполнения геофизических, гидродинамических и геохимических исследований нефтяных и нефтегазовых месторождений: утв. Приказом Минэнерго России от 5 февраля 2002 г. № 30. – М.: Наука, 2002. – 95 с.

30. Патрушева Е.Г. Инвестиционный менеджмент: учеб. пособие / Ярославский гос. ун-т им. П.Г. Демидова. – Ярославль, 2017. – 120 с.

31. Шпайхер Е.Д., Салихов В.А. Геологоразведочные работы и геолого-экономическая оценка месторождений полезных ископаемых: учеб. пособие / Сиб. гос. индустр. ун-т. – Новокузнецк, 2002. – 311 с.

32. Астафьева М.П., Мелехин Е.С., Порохня Е.А. Оценка месторождений полезных ископаемых как объектов инвестирования и бизнеса. – М.: ВНИИЛМ, 2002. – 142 с

33. Хакимова А.С. Комплекс ГИС в экономических расчетах месторождений нефти и газа // Экономика и бизнес: теория и практика – 2017. – № 8. – С. 79–81.

34. Кузьмин Т.Г., Молодых П.В. Экономика инвестиционного проекта в нефтегазовой отрасли: учеб. пособие / Томск. политехн. ун-т. – Томск, 2010. – 181 с.

35. Кочетков А.А. Экономическая теория: учеб. для бакалавров – М.: Дашков и К, 2016. – 696 с.

36. Давыдова А.Е., Гроо А.А. Разработка расчетного комплекса поверхностного обустройства 0-d уровня // Сб. докл. VIII Региональной научно-техн. конф. молодых специалистов ООО «РН-КрасноярскНИПИнефть». – Красноярск, 2016. – 108 с.

37. Расчет экономической эффективности новых технологических процессов / И.М. Бабук, А.А. Королько, С.И. Адаменкова, Е.Н. Костюкевич; Белорусский национальный технический университет. – Минск, 2010. – 56 с.

38. Impact of oil prices on nominal exchange rate: evidence from Ghana / G. Acka, A. Mohammed, J. Ampomah, D. Oppong, O. Sampah // The International Journal Of Business & Management. – 2017. – P. 269–281.

39. Bourde D. Well test analysis: the use of advanced interpretation models. – Amsterdam: Elsevier science, 2002. – 461 p.

40. Economides M., Daniel H. Petroleum production systems / Prentice Hall Inc, Upper Saddle River, NJ 07458. – 1994. – 607 p.

41. Adedapo A., Ayham A. A cohesive approach at estimating water saturation in a low-resistivity pay carbonate reservoir and its validation // Journal of Petroleum Exploration and Production Technology – 2017. – P. 306–320.

42. A cohesive approach at estimating water saturation in a low-resistivity pay carbonate reservoir and its validation / A. Awolayo, A. Ashqar, M. Uchida, A.A. Salahuddin, S.O. Olayiwola. // Journal of Petroleum Exploration and Production Technology. – 2017. – Vol. 7, iss. 3. – P. 637–657. DOI: 10.1007/s13202-017-0318-2

43. Arbab B., Jahani D., Movahed B. Reservoir characterization of carbonate in low resistivity pays zones in the buwaib formation, Persian gulf // Open Journal of Geology – 2017. – P. 1441–1451. DOI: 10.4236/ojg.2017.79096

Please cite this article in English as:
Davydova A.E., Shchurenko A.A., Dadakin N.M., Shutalev A.D., Kvesco B.B. Optimization of carbonate reservoir well testing. *Perm Journal of Petroleum and Mining Engineering*, 2018, vol.17, no.2, pp.123-135. DOI: 10.15593/2224-9923/2018.2.3

Просьба ссылаться на эту статью в русскоязычных источниках следующим образом:
Оптимизация проведения гидродинамических исследований скважин в условиях карбонатного коллектора / А.Е. Давыдова, А.А. Щуренко, Н.М. Дадакин, А.Д. Шуталев, Б.Б. Квеско // Вестник Пермского национального исследовательского политехнического университета. Геология. Нефтегазовое и горное дело. – 2018. – Т.17, №2. – С.123–135. DOI: 10.15593/2224-9923/2018.2.3