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RECOVERY AND INCREASE OF THE PRODUCTIVITY OF WELLS OF KASHIRSKIY AND PODOLSKIY RESERVOIRS OF THE CERTAIN PERM REGION OIL FIELD

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ВОССТАНОВЛЕНИЕ И ПОВЫШЕНИЕ ПРОДУКТИВНОСТИ ДОБЫВАЮЩИХ СКВАЖИН КАШИРСКОГО И ПОДОЛЬСКОГО ОБЪЕКТОВ НА ОДНОМ ИЗ НЕФТЯНЫХ МЕСТОРОЖДЕНИЙ ПЕРМСКОГО КРАЯ

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hydraulic fracturing, oil saturation of formations, productivity index, fracture-pore-type carbonate reservoir, water cut of wells, horizontal stresses, bottomhole pressure, optimization of hydraulic fracturing design.

The paper presents the results of the analysis of the efficiency of improved oil recovery (IOR) methods designed to restore and increase the productivity of wells of Kashirskiy and Podolskiy reservoirs of the certain Perm region oil field. Indirect evidences prove that the carbonate reservoir of the formations exhibits fracture-pore-type reservoir properties, which affects the productivity of wells and results of IOR methods.
Comparative analysis of the efficiency of IOR methods implemented on production wells poined out on higher values for proppant hydraulic fracturing (HF). The increment in well production oil rate after HF increases with an increase in the specific consumption of proppant.
The calculations are performed according to the wave acoustic cross-dipole logging (cross-dipole sonic). According to the results of studies and calculations, the profile of horizontal stresses in the reservoir was constructed, the values of bottomhole pressure at which the closure of the fracture occurs in individual layers are substantiated. A retrospective design of the main HF was performed for a certain well. It is showed that the height of fracture development is limited by dense barriers above and below the perforation interval, while the part of the fracture formed is not packed with proppant.
Proppant HF is accompanied by a significant increase in well water-cut after IOR methods implementation, the nature of which changes in subsequent periods indicates a high probability of involvment of formation drainage through a fractured interbeds with low natural oil saturation to the process.
The analysis of the results of IOR methods, well logging data, taking into account the built retrospective design of the main HF, leads to the conclusion that it is necessary to optimize the technological parameters while designing the HF for production wells of the Kashirskiy and Podolskiy reservoirs of the certain Perm region oil fields That is controlled by increasing the specific consumption of proppant, reducing the polymer load and the share of the buffer stage of the main HF.

Ключевые слова:
гидроразрыв пласта, нефтенасыщенность пластов, коэффициент продуктивности, трещинно-поровый карбонатный коллектор, обводненность скважин, горизонтальные напряжения, забойное давление, оптимизация дизайна гидроразрыва пласта.

Представлены результаты анализа технологической эффективности геолого-технических мероприятий (ГТМ) по восстановлению и увеличению продуктивности добывающих скважин каширского и подольского объектов разработки на одном из нефтяных месторождений (Пермский край). По косвенным признакам карбонатный коллектор на указанных объектах проявляет свойства коллектора трещинно-порового типа, что отражается на продуктивности скважин и результатах ГТМ.
Сравнительный анализ показателей эффективности проведенных геолого-технических мероприятий по фонду добывающих скважин указывает на более высокие значения показателей при пропантном гидроразрыве пласта (ГРП). Прирост дебита скважин по нефти после ГРП возрастает с увеличением удельного расхода пропанта.
Выполнены расчеты по данным волнового акустического кросс-дипольного каротажа (ВАК-Д). По результатам выполненных исследований и расчетов построен профиль горизонтальных напряжений в пласте, обоснованы значения забойного давления, при которых происходит смыкание трещины в отдельных пропластках. Для одной из скважин выполнен ретроспективный дизайн основного ГРП, который показал, что высота развития трещины ограничена плотными барьерами выше и ниже интервала перфорации, при этом часть образовавшейся трещины не упакована пропантом.
Проведение пропантного ГРП сопровождается значительным увеличением обводненности скважин после ГТМ, характер изменения которой в последующие периоды указывает на высокую вероятность подключения к процессу дренирования пласта через образованную трещину пропластков с низкой естественной нефтенасыщенностью.
Анализ результатов выполненных ГТМ, данных геофизических исследований скважин с учетом построенного ретроспективного дизайна основного ГРП приводит к выводу о необходимости оптимизации технологических параметров при построении дизайна пропантного ГРП для добывающих скважин каширского и подольского объектов на одном из нефтяных месторождений Пермского края путем увеличения удельного расхода пропанта, уменьшения загрузки полимера и доли буферной стадии основного ГРП.

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Introduction

Productive carbonate formations with moderate thickness and not very high oil saturation which contain oil with high or higher than average viscosity are characterized by low productivity ratios of oil-producing wells. When the formation pressure and bottom hole pressure start declining in the process of reservoir development, the effective tension in the formation increases and that affects the expansion of natural fractures that often complicate the rocks' structure in carbonate collectors and causes significant reduction of the formation permeability and well productivity [1]. Geological and technical actions aimed at recovering and boosting the productivity of producing wells is one of the means for managing oilfield development [2, 3].

In the last decade, the technology of hydraulic fracturing (hydrofracturing) has been widely used in the oilfields located in Perm region. This method is cost-intensive and its effectiveness depends on many factors. The evaluation of hydrofracturing results in the given geological and physical conditions and the optimization of technical parameters for carrying out well operations is a critical task.

Main Body

The productive formations of Kashirskian and Podolskian horizons of mid-Carboniferous period located in one of the oilfields in the south of Perm region are characterized by low natural oil saturation and productivity (see Table 1).

A carbonate reservoir of Kashirskian (Ksk) and Podolskian (Pod) formations manifests the features typical of fractured-porous type of reservoirs, which is confirmed by the information provided in Table 2 [4, 5].

Well No. 1 was commissioned into operation in Kashirskian deposit in 1989 and at first had a productivity ratio (K_{prod}) of 3.4 m^3/(days·MPa) with the bottom hole pressure (P_{BHP}) of 7.8 MPa and formation pressure (ΔP_{res}) of 2.2 MPa. After the reduction of P_{BHP} in 1990 to 3.5 MPa and increase of drawdown pressure to 6.7 MPa, K_{prod} was reduced 5.7 times (Table 2).

Table 1

Geological and Physical Characteristics of Production Targets

Description	Ksk	Pod
Average depth of occurrence, m	1,103	1,027
Type of deposit	Anticline	Anticline
Type of collector	Porous, carbonate	Porous, carbonate
Absolute oil-water contact point, m	–890	–812
Average net oil thickness, m	3	4
Initial formation temperature, ºC	26.5	25
Initial formation pressure, MPa	11.7	11.2
Average oil saturation, unit fractions	0.63	0.63
Porosity, unit fractions	0.16	0.19
Permeability, μm^2	0.19	0.073
Sand content ratio, unit fractions	0.66	0.48
Average number of permeable intervals, unit fractions	3	5
Oil viscosity in reservoir conditions, mPa·s	45.7	18.6
Oil density in reservoir conditions, kg/m^3	891	880
Oil density in aboveground conditions, kg/m^3	911	890
Formation volume factor, unit fractions	1.033	1.026
Bubble point pressure, MPa	5.3	7.52
Gas/oil ratio, m^3/g	8.5	12.6

Table 2

Technical Parameters of Wells No. 1-3

Well No.	Target	Switch on production / after hydrofracturing			After the P_{BHP} drop (rise)		
		P_{BHP}, MPa	ΔP_{res}, MPa	K_{prod}, m^3/(days·MPa)	P_{BHP}, MPa	ΔP_{res}, MPa	K_{prod}, m^3/(days·MPa)
1	Ksk	7.8	2.2	3.4	3.5	6.7	0.6
	Pod	2.8	8.4	0.2	4.7	6.5	0.8
2	Ksk	5.6	5.4	0.3	2.5	8.5	0.2
	Pod	5.0	6.0	0.4	1.9	9.1	0.1
3	Ksk	7.4	4.0	3.9	2.4	4.6	2.2

Podolskian horizon was completed in 1990 with P_{BHP} = 2.8 MPa and ΔP_{res} = 8.4 MPa and productivity ratio of 0.2 m^3/(days·MPa). After the increase of P_{BHP} to 4.7 MPa and the reduction of draw-down pressure to 6.5 MPa, K_{prod} grew 4 times.

Well No. 2 was commissioned into operation in formations Ksk and Pod in 1993. It can be seen from Table 2 that upon significant reduction of P_{BHP} and increase of ΔP_{res}, the productivity ratios for each target, especially Podolskian, declined materially.

Well No. 3 was completed in Kashirskian horizon with a transfer from Bashkirian horizon (Bsh) in 2017 and carrying out a proppant hydrofracturing. With the formation pressure of 11.4 MPa, bottom hole pressure of 7.4 MPa and ΔP_{res} = 4 MPa, the productivity ratio totaled 3.9 m^3/(days·MPa). In a year, P_{res} went down to 7 MPa with the draw-down pressure at 4.6 MPa and the reduction of P_{BHP} to 2.4 MPa. Provided that, K_{prod} went down to 2.2 m^3/(days·MPa), i.e. 1.8 times.

Taking into account low water cut in wells No. 1 and 2 and the same level of this indicator during the periods under review, the information about the reduction of K_{prod} alongside the decline of P_{res} and P_{BHP}, and the increase of drawdown pressure, and the information about the increase of K_{prod} with the growth of P_{BHP} and reduction of ΔP_{res} (Well No. 1, Pod) indicate the manifestation of characteristics of a fractured-porous type of reservoir and its deformation [6-12].

In order to recover and enhance well productivity and increase oil production rates at an oilfield, production enhancement operations are performed in respect of the formation and the bottom hole area [13-15]. In the period from 2008 to 2017, 19 acid treatments were performed with the average specific incremental oil output per treatment of 0.6 tonnes/day/m and a 3-month effect and 29 production enhancement operations with the average specific oil output of 1.7 tonnes/day/m. By 2015, two acid hydrofractures had been performed, one at each target. In 2015, one operation was performed, followed by 10 in 2016 and 16 in 2017 (Table 3).

Two operations of acid hydrofracturing (2008) showed low efficiency (specific incremental output of 0.3 tonnes/day/m with the plan of 2.4 tonnes/day/m and the length of effect of 108 days), possibly, due to incomplete removal of reaction products [16-18]. The specific incremental oil output achieved in connection with nitrogen and foam and proppant hydrofractures slightly exceeded the plan and amounted to 2.1 and 1.9 tonnes/day/m, respectively (Fig. 1). No nitrogen and foam or proppant hydrofractures were performed in 2017 due to organizational and technical reasons.

Table 3

Hydrofracturing in 2015-2017

Type of hydrofracture	Number of operations				
	2015	2016		2017	
	Pod	Ksk	Pod	Ksk	Pod
Nitrogen and foam	1	2	2	–	–
Proppant	–	4	2	10	6

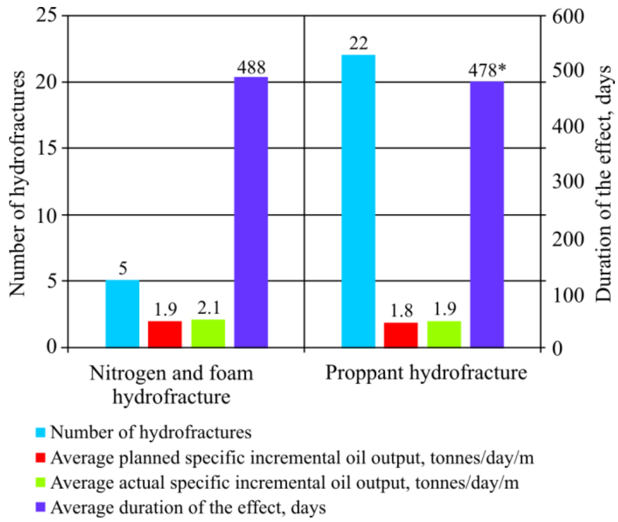

Fig. 1. Efficiency of hydrofractures performed in respect of Ksk and Pod targets of the oilfield under review (* - the values are taken for the wells with complete effect)

The key parameters of proppant hydrofractures are set out in Table 4.

Table 4

Key parameters of proppant hydrofractures

Parameter		Value
Consumption of blend, m^3/min		3.5
Loading of gallant, kg/m^3		3
Maximum concentration of proppant, kg/m^3		800
Proppant size, mesh		16/20
Specific consumption of proppant, tons/m	Ksk	6.2
	Pod	9.2
Share of buffer stage, %	Ksk	27
	Pod	29
Average wellhead pressure of injection, MPa	Ksk	19.2
	Pod	17.5
Average effective pressure in case of mini hydrofracturing, MPa	Ksk	5.9
	Pod	5.4
Effectiveness of fracture fluid in case of mini hydrofracturing, %	Ksk	82
	Pod	72
Closure gradient, MPa/m	Ksk	0.0161
	Pod	0.0155
Bottom hole closure pressure, MPa	Ksk	16.8
	Pod	14.7

A close-to-linear dependence of specific incremental oil output on specific proppant spending was detected (Fig. 2).

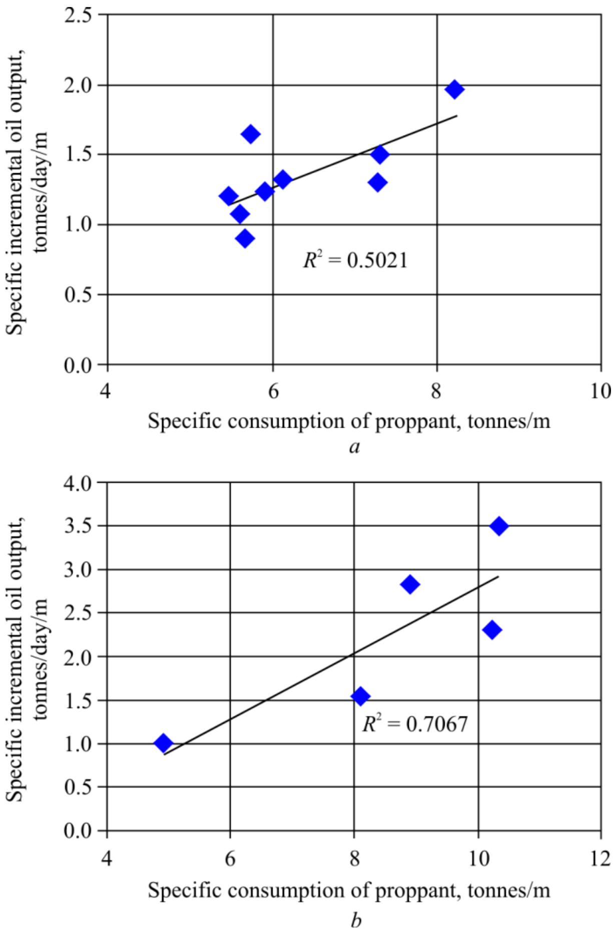

Fig. 2. The dependence of specific incremental oil output on the consumption of proppant in relation to formations K (*a*) and Pod (*b*) of the oilfield under review

A significant increase of water cut after hydrofracturing (Fig. 3) that exceeds 2-4 times the same indicator for the wells with a proppant hydrofracturing is noted in the south group of oilfields developed by LLC LUKOIL-Perm (Kashirskian and Vereiskian formations). No correlation has been found between the increase of water cut and the increase of proppant consumption by the wells of the oilfield under review.

In order to identify the source and reason of water cut and to optimize the technology of proppant hydrofracturing, the results of researches (hydrodynamic, flow measurement, cross dipole variable density logging – VDL-D) performed in respect of the wells with hydrofractures and information about the natural oil saturation of stringers involved in the fluid inflow into the well were analyzed.

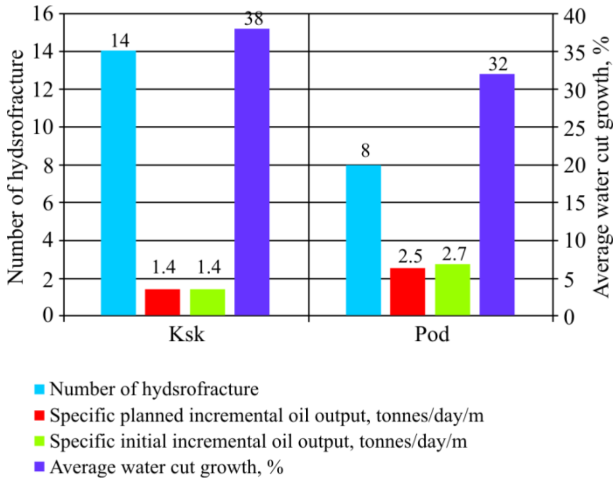

Fig. 3. Efficiency of hydrofractures in performed Ksk and Pod targets of the oilfield under review

For the well No. 4 (Ksk) of the reviewed oilfield a profile of horizontal tensions was defined based on VDL-D results on the hydrofracture interval prior to its performance (Fig. 4) [19-21].

The calculated values of tensions in the expected interval of hydrofracture development interval are fully compliant with the interval from the actual bottom hole closure ($P_{\text{closure BHP 5}}$) to the bottom hole initial shut-in pressure (ISIP), indicating the reliability of the obtained results (Fig. 5) [21-25].

Taking into account the effect of circular compressive stress in the rock, the closure of fractures close to the wells is detected if the pressure is twice as low as double lateral rock pressure $P_{\text{lat.r}}$ [5], which is defined through horizontal stress ratio K_{lat}: $P_{\text{lat.r}} = K_{\text{lat}} \cdot P_{\text{vert.r}}$, were $P_{\text{vert.r}}$ is vertical rock pressure. The ratio $K_{\text{lat}} = \frac{\upsilon}{1-\upsilon}$, where υ is Poisson ratio [26-29].

For the conditions of Kashkirian target $P_{\text{vert.r}} =$ = 26 MPa, Poisson ratio for the rocks completed by Well No. 4 amounts to 0.24-0.25 in the hydrofracture interval (see Fig. 4). Doubled lateral rock pressure $2P_{\text{lat.r}} = \frac{2\upsilon \cdot P_{\text{vert.r}}}{1-\upsilon} = 16.4...17.2$ MPa. The minimal bottom hole pressure of fracture closure $P_{\text{closure BHP 5}}$ is equal to 16.2 MPa (see Fig. 5), i.e. the condition $P_{\text{closure BHP}} < 2P_{\text{lat.r.}}$ is fulfilled.

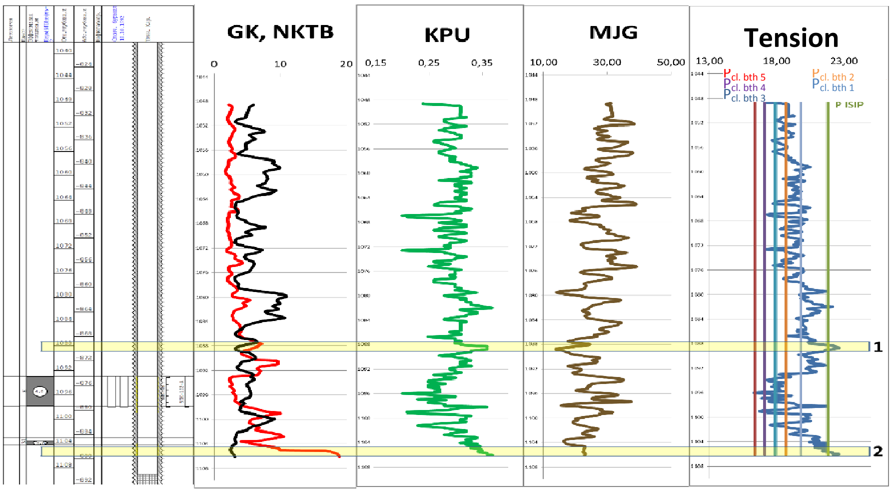

Fig. 4. Profile of horizontal pressures in the target interval for hydrofracturing performance on the Well No. 4

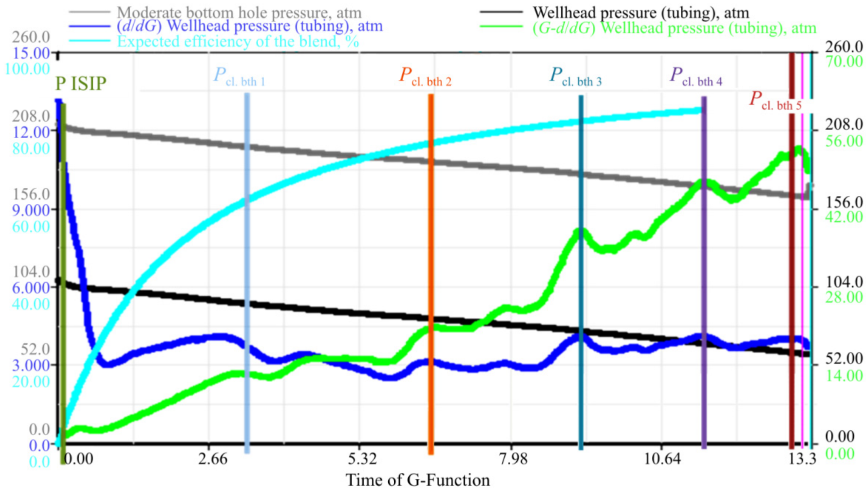

Fig. 5. The graph of *G*-function of mini hydrofracture on the Well No. 4; bottom hole closure pressure – 164.1 atm; closure pressure gradient– 0.1556 atm/m; wellhead closure pressure– 59.7 atm; time of closure – 306.5 min; injection time – 9.2 min; implied blend efficiency– 86.9 %; calculated effective pressure – 48.3 atm

The obtained profile of horizontal tensions allowed evaluating the hydrofracture of the formation in its productive part and in the tight barrier stringers [30, 31]. The following findings were made as a result of researches' analysis:

1. The height of hydrofracture is limited by right barriers *1* and *2* (see Fig. 4).

2. The bottom hole pressure P_{BHP} is a minimal horizontal component of the rock pressure for the productive part of the formation close to the well walls; this pressure defined the condition for full closure of the hydrofracture in the perforation interval.

3. The calculated tensions in the fracture development interval correlate to the actual pressure values of its closure in the bottom hole, determined according to the graph of mini hydrofracture G-function (see Fig. 5).

The existence of several bottom hole values of fracture closure pressure in this graph can be explained by non-homogeneous distribution of formation permeability across section and, therefore, different volumes of crosslinked gel that penetrated into separate interlayers [32, 33].

A retrospective design of main hydrofracture for the Well No. 4 performed on the basis of obtained data has shown that a part of the fracture is not packed with proppant (Fig. 6), which is probably due to high efficiency of breakdown agent and its low filtration into the formation [34-36].

Similar information has been obtained for Kashkirian target for Wells No. 5-7. Researches and calculations using VDL-D data indicate the presence of highly tense barriers above and below the productive part of the formation and incomplete packing of hydrofractures with proppant.

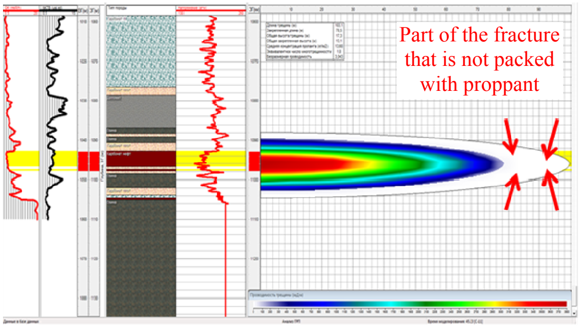

Fig. 6. Profile of the hydrofracture based on retrospective analysis for the Well No. 4

The Well No. 3 (Ksk) featured high water cut (73 %) after a proppant hydrofractrure with the specific incremental oil output of 1.3 tons/day/m with the plan of 1.7 tonnes/day/m. The assumption that the hydrofracture could have perforated the water stringer in the interval 1,151.4-1,152.2 m (with the perforation interval 26 m below) was not confirmed by the results of tension calculations or hydrofractures performed on neighbor wells, which indicate that hydrofractures are limited with tight layers (see Fig. 4) above and below the productive part and do not penetrate the water-saturated stringer.

The increase of wells' water cut after hydrofracturing with account to this indicator's changes in subsequent periods of their operation can be explained by high water saturation of the stringers involved in the production process after the fracturing [37]. For example, for the Well No. 3 the average natural oil-saturation of the layers identified with flow-metering amounted to 38 %. Gradual reduction of water cut in this and other wells during several months after the hydrofracture by 10-20 % with its further stabilization indirectly indicates that the fracture does not penetrate to the water-saturated layers and to the displacement front and oil-water contact [38-40]. In the Well No. 3 the water cut went down from 73 to 56 % during 11 months after the hydrofracture and in the Well No. 1 (Pod) – from 72 to 64 % during 5 months.

In connection with incomplete filling of hydrofractures with proppant, a new design for wells No. 4 and No. 1 was performed with the new technological parameters (Table 5).

The calculations related to the new design have shown that with the increase of specific spending of proppant and reduction of polymer consumption and the share of buffer unit, the technological efficiency of hydrofracturing may be enhanced.

The optimization of technological parameters was carried out in connection with performing a proppant hydrofracture on Pod target in Wells No. 8 and No. 9. In the Well No. 8 the hydrofracture was performed in December, 2017.

As a result of mini hydrofracture, polymer consumption was reduced from 3.0 (basic design) to 2.8 kg/m^3 and the specific consumption of proppant was increased from 7.7 to 10.4 tonnes/m. The hydrofracturing on the Well No. 9 was performed in May, 2018. The basic design included polymer consumption reduced to 2.8 kg/m^3 and specific proppant consumption increased to 10.6 tonnes/m. As a result of mini hydrofracture, the share of buffer was additionally reduced from basic 27 to 22 %. The information about the wells operation are provided in Table 6.

Table 5

Technological Parameters of Proppant Hydrofracture

Parameter	Well No. 4 (Ksk)		Well No. 1 (Pod)	
	Actual hydrofracture	New design	Actual hydrofracture	New design
Specific consumption of proppant, tonnes/m	4.9	6.8	9.2	11.0
Polymer consumption, kg/m^3	3.0	2.8	3.0	2.8
Share of buffer volume, %	24	22	27	22
Specific oil output, tonnes/day/m	1.3	1.5	1.9	3.3

Table 6

Indicators of the performance of Wells No. 8 and 9

Indicator	Well No. 8			Well No. 9		
	Prior to hydro-fracturing	Plan	After hydro-fracturing, Jan. 2018	Prior to hydro-fracturing	Plan	After hydro-fracturing, June 2018
Specific fluid output, m^3/day/m	1.1	11.5	11.9	2.5	11.6	15.2
Specific oil output, tonnes/day/m	0.7	4.6	4.9	1.5	5.0	7.2
Water cut, %	34.0	55	53.4	36.0	50	47.0
Specific oil output increment, tonnes, day/m	–	3.9	4.3	–	3.5	5.7

Conclusions

A dependence of specific growth of oil output on proppant consumption during the hydrofractures performed on the wells of Ksk and Pod targets of the oilfield under review was established.

As a result of calculating horizontal tensions, the boundaries of hydrofractures development were determined (by height).

The productive formations with low natural oil-saturation involved in the draining process are the main source of water cut growth in the well produce after hydrofracturing.

The evaluation of proppant hydrofracturing results with account of geophysical well research indicates the necessity to optimize technological parameters of hydrofracturing design development for Kashkirian and Podolskian targets. Taking into account retrospective hydrofracture design for the Well No. 4 and the hydrofracrtures performed in Wells No. 8 and 9, it is proposed to optimize technological parameters with an increase of specific proppant consumption to 9 (Ksk target) and 11 tonnes/m (Pod target), and reduction of polymer consumption to 2.8 kg/m^3 and the share of buffer volume to 21–22 %.

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