Study of the horizontal sidetracking efficiency using hydrodynamic modeling (on the example of a Kazakhstani field)

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ABSTRACT

One of the modern approaches for the effective development of small deposits is the construction and operation of wells with a complex architecture: horizontal wells (HW), sidetracks (BS, BGS), multilateral wells (MLW). Sidetracking makes it possible to reanimate an old well that is in an emergency state or inactivity for technological reasons, by opening layers that have not been previously developed, bypassing contamination zones, or watering the formation. This study examines the possibility of using horizontal sidetracks in the operating wells of the field of the Zhetybai group. To select the optimal length of the horizontal sidetrack of the wells, graphs of the dependences of the change in flow rate versus length of the horizontal well were built, taking into account the pressure losses due to friction. It can be seen from the dependence of NPV versus length of the horizontal wellbore that the maximum NPV is achieved with a horizontal wellbore length of 100 m. A further increase in the length of the horizontal wellbore leads to a decrease in NPV. This is due, firstly, to a decrease in oil prices, and secondly, interference of wells, a small number of residual reserves, and a small oil-bearing area. As a result of a comparison of technical and economic criteria, the optimal length of a horizontal wellbore is from 100-300 meters. Comparison of the flow rates of vertical wells and wells with horizontal sidetracks showed a clear advantage over the latter in all respects.

Keywords: horizontal sidetrack, hydrodynamic modeling, flow rate, friction pressure loss, Net present value – NPV.

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Introduction

One of the current approaches for the efficient development of small reservoirs is the drilling and operation of complex design wells - horizontal wells (HW), sidetracks (S, HS) and multilateral wells (MLW).

Sidetracking makes it possible to reanimate an old well that is in a breakdown state or inactivity for technological reasons, by penetrating layers that have not been previously developed and bypassing zones of contamination or water encroachment.

In the United States, multilateral drilling began in 1930. The first wells with two sidetracks each about 7 m long drilled in Texas at a depth of 900 m.

The oil flow rate of one of these wells increased from 0.25 to 9.6 tons/day (during the first ten days). Steady flow rates of sidetrack wells was 5-7 tons/day.

The first experimental work of drilling multilateral wells in the Soviet Union was carried out in 1952 at the Kartashovskoye field in wells 65-45. Almost 80% of the well length was drilled directly through the producing formation. The distance between the individual sidetracks bottomhole were increased to 300 m [1].

The works of the authors [[2], [3], [4], [5], [6], [7], [8], [9]] are devoted to the analysis of the horizontal sidetracks exploitation, determination of

well flow rates, drilling problems, planning and location of the horizontal sidetracks.

Differences in the horizontal wells production rate determination were defined as a result of statistical analysis in [[10], [11], [12]]. The main factor affecting the productivity of high-flow wells is reservoir pressure, for low-flow wells - the length of the horizontal section of the wellbore.

To enhance oil recovery and improve well productivity formation stimulation methods are considered in [[13], [14]].

This study is devoted to horizontal sidetracks application in the operating wells of the X oil field of the Zhetybai group.

Experimental part

Field X, related to the satellite of the Zhetybai field, is located in the steppe flat part of the Mangyshlak peninsula and is territorially included in the Mangistau region. This is one of the small fields in terms of oil reserves, which is part of the Production Office "Zhetybaimunaigaz". The oil-bearing capacity of the field was established in 1975, when a gush of oil was obtained from the J-IX horizon in exploration well 3.

One production zone the J-IX horizon was identified based on the analysis of geological field data and the results of the X oil field development analysis.

The initial geological and physical characteristics of the production zone are shown in Table 1.

Table 1 - Initial geological physical characteristic J-IX horizon of the X oil field of the Zhetybai group

Parameter	Horizon J-IX
Average depth, m	1861
Reservoir type	поровый
Oil Productive area, thous m²	3853
Gas Productive area, thous m²	-
Porosity, unit fraction	0.19
Average oil saturation, unit fraction	0.67
Absolute permeability, 10^{-3} mkm² (from core/from hydrodynamic study)	0.0215 (core) / 0.0615 (hydrodynamic)
Reservoir temperature, °C	85
Reservoir pressure, MPa	18.2
Reservoir oil viscosity, mPa*s	2.31
Reservoir oil density, ton/m³	0.783
Formation volume factor, unit fraction	1.166
Bubble point pressure, MPa	5.96
Gas-oil ratio, m³/ton	48

The production well stock includes six wells: 2 exploration and 4 production wells (108, 110, 114 and 120).

The hydrodynamic model uploaded a total of 11 wells placed according to depth, geological and physical characteristics and productive zone capabilities in accordance with development project production data (see Figure 1).
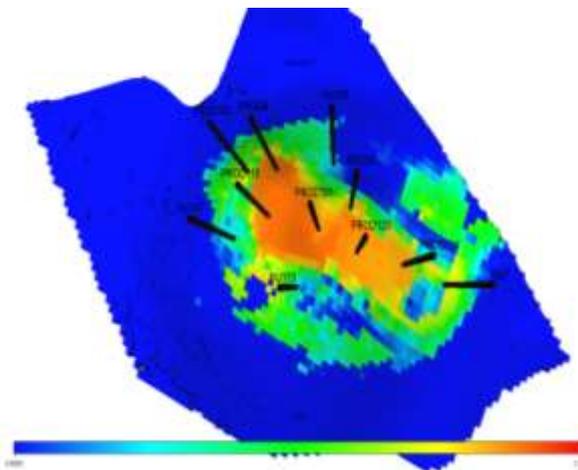

Figure 1 - Location of production and injection wells on the hydrodynamic model

At 2015, the remaining reserves of the X oil field of the Zhetybai group amounted to 3123.5 thousand tons of oil and it was the initial criteria for the selection of the candidate wells from the old stock. At the same time, when choosing wells for sidetracking operation, it is necessary to take into account the degree of formation waterflooding. In this regard, for each well it was necessary to carry out a detailed analysis of adjacent wells sections and the nature of the reservoir distribution in the formations that are the objects for sidetracking.

It was significant to determine the location of candidate wells, when designing the sidetrack wells. To determine the trajectory and justify the length of the horizontal sidetrack of the well, horizontal well (HW) production rates were calculated using various formulas. First, the areas of maximum residual oil reserves were determined using the hydrodynamic model of the field. As can be seen from Figure 2, the areas with the maximum residual oil saturation are located along the paleo channel in the central part of the field. Based on this, candidate production wells were identified in which horizontal sidetracks (HS) were designed (Figure 2). In total, three production wells were selected: 108, 114 and 120, which are located in the central part of the paleo-channel deposits with the highest effective oil saturation.
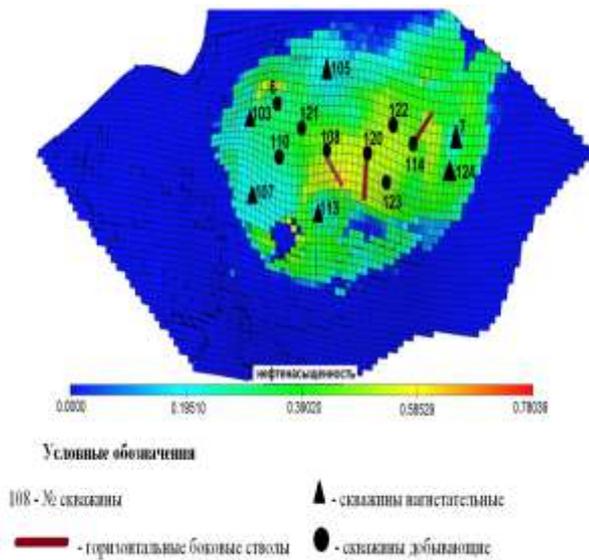
Figure 2 - Trajectory of horizontal sidetracks
in producing wells (108, 114, 120)

After determining the maximum residual oil reserves areas, various options for the horizontal sidetracks trajectory were calculated, which differed in many directions.

One of the characteristic features of the field is the occurrence of the aquifer below the oil reservoir, and due to intensive waterflooding, the water cut of the selected wells in 2015 was up to 95%. Therefore, it was decided to design the horizontal sidetracks trajectory along the paleochannel, closer to the top of the reservoir to reduce the water cut in the wells.

Fluid inflow to vertical and horizontal wells differs significantly. Thus, the inflow to a vertical well is radial, and streamlines are distributed parallel to the top and bottom of the formation, because a vertical well penetrates the entire thickness of the formation. With an increase in the penetrated formation thickness, the flow rate increases, the pressure distribution in the vertical plane does not change. For horizontal wells, fluid flow occurs both vertically and horizontally. Well flow rate is affected by horizontal and vertical permeability, reservoir boundaries, horizontal borehole length, presence of local depressions in the borehole (water and gas accumulate in them) and the behavior of the bottomhole formation zone [15].

In cases when horizontal sidetracks are drilled at a late stage of development, it is necessary to take into account the effect of continuously changing field conditions (the presence of residual reserves not covered by waterflooding, current

water cut, formation depletion, etc.) [15]. Application of hydrodynamic modeling allows these changes to be taken into account to the maximum extent.

The results of theoretical research carried out by P.Ya. Polubarinova-Kochina [16] can be used when the reservoir thickness is many times greater than the wellbore length. If the reservoir thickness is comparable to the length of the deviated well, then the formulas cannot be used.

In work [1] Yu.P. Borisov, an approximate solution to the problem of inflow to horizontal and deviated wells in a homogeneous reservoir was presented. Based on the method of equivalent filtration resistance, simple expressions were obtained to determine the productivity of horizontal and deviated wells in a reservoir with a circular external reservoir booundary (Figure 3).
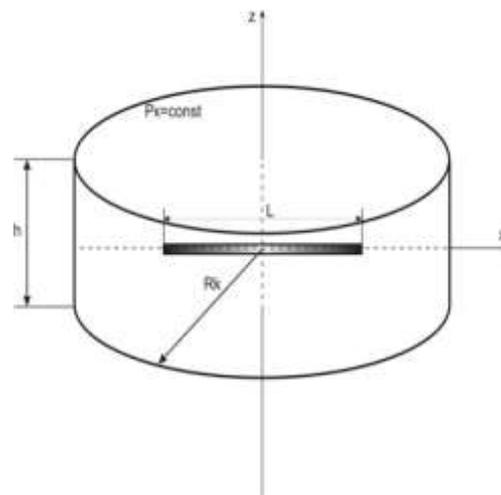

Figure 3 - Model of a circular formation with a central location of horizontal well

The total filtration resistance can be represented as the sum of two resistances: external - the inflow from external reservoir boundary to a rectilinear vertical gallery, and internal - the fluid flow in the vertical plane to the linear drain:

$$Q = \frac{2\pi kh\Delta P}{\mu\left[\ln\dfrac{4R_k}{L} + \dfrac{h}{L}\ln\dfrac{h}{2\pi r_c}\right]} \qquad (1)$$

In the work of S.D. Joshi [17] was considered a steady fluid flow to a single horizontal well located in an elliptical formation.

The summation of the filtration resistances of the two flat solutions allows obtaining an expression for determining the productivity of a horizontal well:

$$Q = \frac{2\pi kh}{\mu B\left[\ln\left(\dfrac{a+\sqrt{a^2-(L/2)^2}}{L/2}\right)+\dfrac{h}{L}\ln\dfrac{h}{2r_c}\right]} \quad (2)$$

где

$$a = \frac{L}{2}\left\{0{,}5+\left[0{,}25+\left(\frac{R_k}{L/2}\right)^4\right]^{0{,}5}\right\}^{0{,}5} \quad (3)$$

Joshi's formula for calculating the production rate of a horizontal well taking into account the formation anisotropy is as follows:

$$Q = \frac{2\pi kh\Delta P}{\mu B\left[\ln\left(\dfrac{a+\sqrt{a^2-(L/2)^2}}{L/2}\right)+\dfrac{h\beta^2}{L}\ln\left(\dfrac{h}{2\pi r_c}\right)\right]} \quad (4)$$

denoting the anisotropy coefficient

$$\beta = \sqrt{\frac{k_h}{k_v}} \quad (5)$$

The most accurate formula for calculating the horizontal well flow rate is Joshi's formula, taking into account heterogeneity (anisotropy). Thus, for calculation the flow rate of the selected wells (108, 114, 120) with horizontal sidetracks, Joshi's formula was used, presented below:

$$Q = \frac{2\pi kh(P_e - P_{wf})}{B_o\mu\left[\ln\left(\dfrac{a+\sqrt{a^2-(L/2)^2}}{L/2}\right)+\dfrac{h\beta^2}{L}\ln\left(\dfrac{h}{2\pi r_c}\right)+S\right]} \quad (6)$$

where L is the length of the horizontal wells, m; R_k is the radius of the circular external reservoir boundary, m; r_w is the well radius, m; h is the effective formation thickness, m; a is the main semiaxis of the drainage ellipse in the horizontal plane; k_h is the formation horizontal permeability, m²; k_v is the formation vertical permeability, m²; P_e is the reservoir pressure, Pa; P_{wf} is the well pressure, Pa; μ is the reservoir oil viscosity, Pa·s; B_o is the oil formation volume factor; S is the skin factor.

Consider a calculation of the flow rates of the wells (108, 114, 120) with the horizontal sidetracks, taking into account the reservoir parameters and different length of horizontal sidetracks. For all

selected wells, we take the general values of the parameters presented in Table 2.

Table 2 - General parameters for calculating the horizontal wells flow rate

Parameter	Sign	Value	Unit
Well radius	r_C	0.057	m
External boundary radius	R_K	150	m
Rerservoir oil viscosity	$\mu_{o\ res}$	2.31	mPa·s
Reservoir oil density	$P_{o\ res}$	783	m³/d
Oil formation volume factor	B	1.166	unit fraction
Average reservoir permeability	k_{av}	0.0215	mkm²
Formation anisotropy	β	3.162	unit fraction

An increase of the wellbore horizontal length leads to an increase in hydraulic losses and a continuous decrease in the drawdown in the lateral direction of the well. Studies by various authors [[15], [16], [17], [18]] have shown that when opening high-permeability sections of horizontal wells, frictional pressure losses along the length of the horizontal section can lead to a significant decrease in well productivity. Friction pressure losses in a horizontal wellbore depend on the horizontal wellbore length, the diameter of the well (liner), fluid velocity, roughness of the inner pipe surface, fluid density and flow pattern (Figure 4). Therefore, it is important to choose the optimal length of the horizontal wellbore, which will provide high rates of flow rate and NPV with minimum well drilling costs.
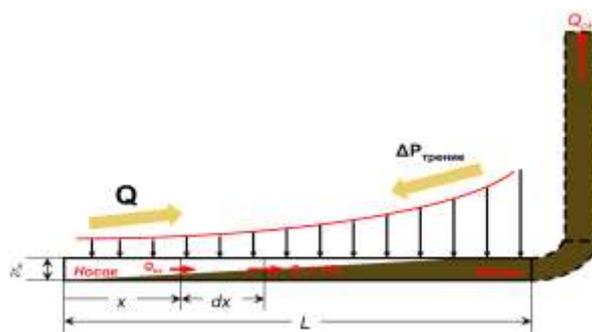

Figure 4 - Friction pressure loss in horizontal wellbore

To select the optimal length of the horizontal sidetrack of the wells, curves of production rate versus length of the horizontal sidetracks were built

taking into account the friction pressure losses (Figures 5-8). As can be seen from Figures 5-8, the optimal length of a horizontal wellbore is a length not exceeding 500 m.
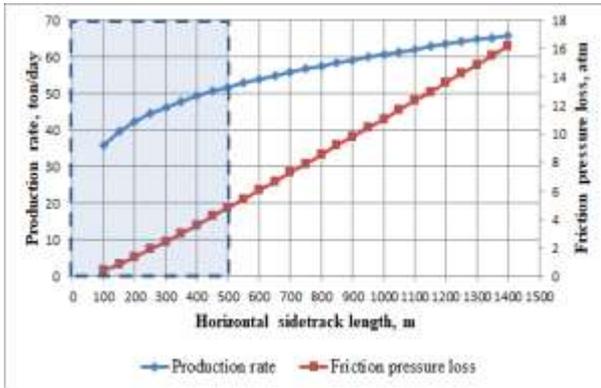

Figure 5 - Production rate versus horizontal sidetrack 108 length with the friction pressure loss
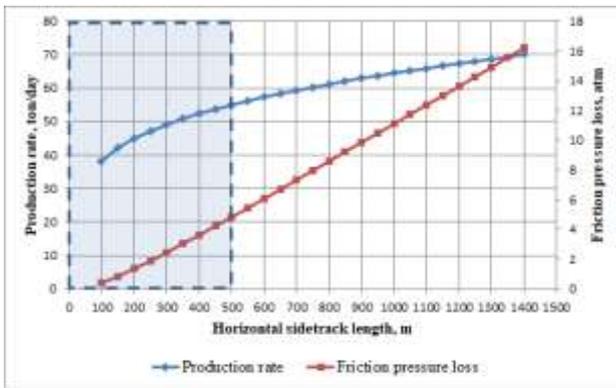

Figure 6 - Production rate versus horizontal sidetrack 120 length with the friction pressure loss
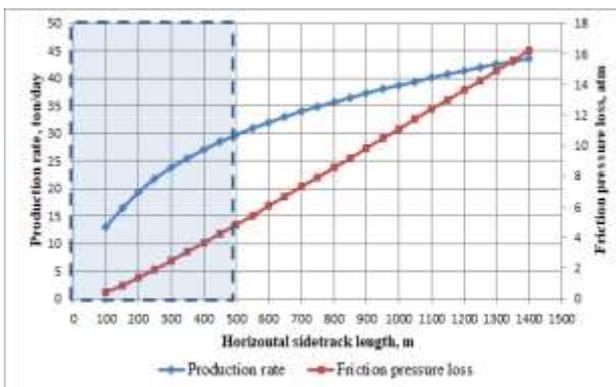

Figure 7 - Production rate versus horizontal sidetrack 114 length with the friction pressure loss

The anisotropy over the reservoir was taken equal to 3.16. It can be seen from the graphs 5-7 that the drop in drawdown (as a result of friction) along the length of the wellbore horizontal section limits the flow rate only after 600-700 meters. It is

also necessary to take into account the technological criteria - pump productivity and economic criteria - capital costs for the horizontal wellbore drilling. The economic criteria is the accumulated discounted cash flow - NPV. The optimal well length is at which the NPV will be maximum.

$$NPV = -K + \sum_{i=1}^{T} D^i \lambda_i \qquad (7)$$

where D^i is the cash flow in the i-th year; λ_i - discounted rate; K -capital expenditures.

For the calculation of the economic criteria field hydrodynamic simulation conducted with changing the horizontal length of the well. The length increases from 100 to 500 meters. Further increase in the horizontal length of the well is impractical due to the small reservoir drainage area. As a result, the diagram of NPV versus horizontal length of the well was obtained (Figure 8).

From the digram of the NPV versus horizontal length, it can be seen that the maximum NPV is achieved with a horizontal wellbore length of 100 m (Figure 8). A further increase in the length of the horizontal wellbore leads to a decrease in NPV. This is due, firstly, to a decrease in oil prices, and secondly, interference of wells, a small amount of residual reserves, and a small oil-productive area. By comparing the technical and economic criteria of the optimal horizontal wellbore length was obtained of 100-300 meters.
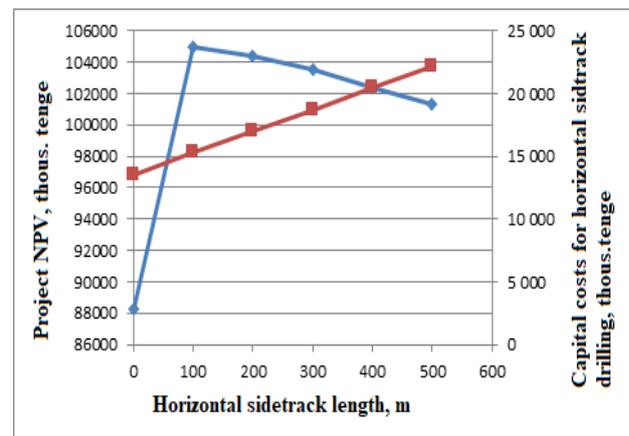

Figure 8 - NPV project versus horizontal sidetrack length

Results discussion

The parameters of the horizontal sidetrack wells, as well as the results of the calculated flow rates of horizontal sidetracks wells according to the Joshi formula are shown in Table 3.

Table 3 - Well parameters with horizontal sidetracks

Parameter	Well #		
	108	114	120
Horizontal length (L), m	236	230.9	263
Reservoir thickness (h), m	19	20	18.8
Draw-down pressure (ΔP) – the difference in external boundary and bottomhole pressure, MPa	3.3	2.5	3.1
Calculated well flow rate, m³/d	98.5	70.7	109.8

The calculated flow rates were used in the hydrodynamic model to define the input parameters oil and water flow rates. As a result, the field development parameters were obtained depending on the geological and physical conditions of the reservoir, the properties of reservoir fluids and the production capabilities of the wells in the hydrodynamic model.

Table 4 - Wells production rate on X oil field of the Zhetybai group (in 01.2016)

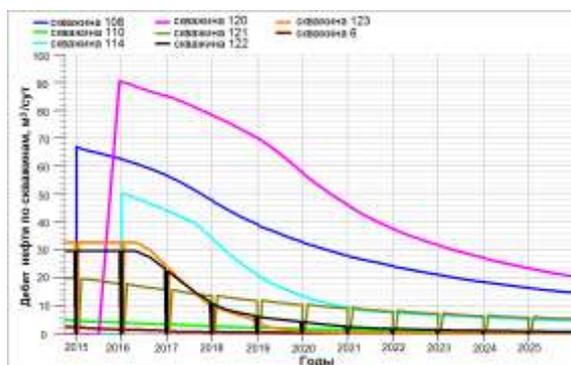| Well #	Oil production rate, m³/d	Water production rate, m³/d	Watercut, %
6	1.5	28.4	94.9
108 с ГБС	67.07	47.4	41.4
110	4.1	52.3	92.7
114 с ГБС	50.3	39.6	44.04
120 с ГБС	90.4	59.7	39.7
121	17.2	25.6	59.8
122	29.6	22.9	43.6
123	24.5	33.06	57.4

Figure 9 - Oil production dynamics by wells (2015-2025)

Comparison of the results of the vertical wells flow rates and horizontal sidetrack wells showed a clear advantage of wells with horizontal sidetrack in all criteria (Table 4, Figure 9). Figure 9 shows that the horizontal sidetrack wells flow rates are higher than drilled new wells flow rates for the analyzed period from 2015 to 2025, except for well 114, the flow rate of which decreases from 2021 to 10 m³/day. Oil flow rates vary from 4.7 to 90.4 m³/day, with an average of 35.7 m³/day. The inlet water cut of horizontal sidetrack wells at the beginning of production reached 40%, which is explained by the close location of the bottom water and water flooding by the injected water.

In general, the oil production rates of wells operating with horizontal sidetracks are on average 5-6 times higher (35.7 m³/day versus 6.2 m³/day), water cut is 1.2 times lower for conventional wells (70.65% versus 88.2%) (Figure 9). Taking into account that the water cut is 1.2 times lower for wells operating with horizontal sidetracks, it can be assumed that previously not drained layers will be involved.

Conclusions

Based on the study results, the following brief conclusions can be drawn:

1. To select the optimal length of the horizontal sidetrack of the wells, curves of the production flow rate versus horizontal sidetrack length were built, taking into account the friction pressure losses. It can be seen from the graphs that the drawdown drop (as a result of friction) along the horizontal section length of the wellbore limits the flow rate only after 600-700 meters.

2. From the NPV versus the horizontal length, it can be seen that the maximum NPV is achieved with a horizontal wellbore length of 100 m. A further increase in the horizontal length leads to a decrease in NPV. This is due, firstly, to a decrease in oil prices, and secondly, interference of wells, a small amount of residual reserves, and a small oil-productive area. By comparing the technical and economic criteria of the optimal horizontal wellbore length was obtained of 100-300 meters.

3. Comparison of the results of the vertical wells flow rates and horizontal sidetrack wells showed a clear advantage over the latter in all respects. The flow rates of horizontal sidetrack wells are higher than the new drilled wells flow rates for the analyzed period from 2015 to 2025.

Conflict of interests. On behalf of all authors, the author declares that there is no conflict of interest.

Гидродинамикалық модельдеу әдісімен көлденең бүйірлік ұңғыманың тиімділігін зерттеу (Қазақстандық кен орны мысалында)

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ТҮЙІНДЕМЕ

Шағын кен орындарын тиімді игерудің заманауи тәсілдерінің бірі күрделі архитектурасы бар ұңғыларды (көлденең ұңғымалар, көлденең бүйір ұңғымалар, көп оқпанды ұңғымалар) салу және пайдалану болып табылады. Көлденең бүйір ұңғыманы бұрғылау арқылы апаттық жағдайдағы немесе технологиялық себептермен жұмыс істемей тұрған ескі ұңғыманы қалпына келтіруге мүмкіндік береді. Бұл бұрын игерілмеген қабаттарды ашып, ластанған немесе суланған аймақтарды айналып өту арқылы іске асады. Бұл зерттеуде Жетібай тобына кіретін кен орнындағы жұмыс істеп тұрған ұңғымаларда көлденең бүйір оқпанды пайдалану мүмкіндігі қарастырылған. Ұңғымалардың көлденең бүйірлік оқпанының оңтайлы ұзындығын таңдау үшін үйкеліске байланысты қысымның жоғалуын ескере отырып, дебиттің көлденең ұңғыманың ұзындығына тәуелділік графигтері салынды. NPV көлденең ұңғыма оқпанының ұзындығына тәуелділігінен максималды NPV көлденең ұңғыма оқпанының ұзындығы 100 м болғанда қол жеткізілетінін көруге болады. Көлденең ұңғыма оқпаны ұзындығының одан әрі ұлғаюы NPV төмендеуіне әкеледі. Бұл, біріншіден, мұнай бағасының төмендеуімен, екіншіден, ұңғымалардың интерференциясымен, қалдық қорының аздығымен және мұнайлы аймақтың аз болуымен байланысты. Техникалық-экономикалық критерийлерді салыстыру нәтижесінде көлденең ұңғыма оқпанының оңтайлы ұзындығы 100-300 метр аралығында болады. Тік ұңғымалар және көлденең ұңғыма оқпаны бар ұңғымалардың дебитін салыстыру барлық жағынан екіншісінің айқын артықшылығын көрсетті.

Түйін сөздер: көлденең бүйір оқпан, гидродинамикалық модельдеу, дебит, үйкеліске байланысты қысымының шығыны, таза дисконтталған мән – NPV.

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АННОТАЦИЯ

Одним из современных подходов для эффективной разработки небольших залежей является строительство и эксплуатация скважин со сложной архитектурой: горизонтальных скважин (ГС),

боковых стволов (БС, БГС), многозабойных скважин (МЗС). Бурение боковых стволов дает возможность реанимировать старую скважину, находящуюся в аварийном состоянии или бездействии по технологическим причинам, за счет вскрытия пластов, ранее не разрабатываемых, обхода зон загрязнения или обводнения пласта. В настоящем исследовании рассмотрена возможность применения горизонтальных боковых стволов на действующих скважинах месторождения Жетыбайской группы. Для выбора оптимальной длины горизонтального бокового ствола скважин были построены графики зависимостей изменения дебита от длины горизонтальной скважины с учетом потерь давления на трение. Из зависимости NPV от длины горизонтального ствола видно, что максимальный NPV достигается при длине горизонтального ствола 100 м. Дальнейшее увеличение длины горизонтального ствола приводит к снижению NPV. Это обусловлено, во-первых, снижением цен на нефть, во-вторых интерференцией скважин, небольшим объемом остаточных запасов, малой площадью нефтеносности. В результате сравнения технических и экономических критериев оптимальная длина горизонтального ствола составляет от 100 до 300 метров. Сопоставление результатов дебитов вертикальных скважин и скважин с горизонтальными боковыми стволами показало явное преимущество за вторыми по всем показателям.

Ключевые слова: горизонтальный боковой ствол, гидродинамическое моделирование, дебит, потери давления на трение, чистый дисконтированный доход – NPV.

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