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NEW METHOD FOR OIL FIELD DEVELOPMENT BASED ON THE GRAVITY DRAINAGE

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ABSTRACT

Traditional technologies of oil production on shelf have low oil recovery factor, and it causes an enormous damage to the environment, as it is evidenced by the increasing number of spills around the world. This paper presents a new method of oil field development that can significantly improve the oil recovery factor by using the artificially generated gravity drainage. Due to this fact, the new method of oil production is based on the principle of close well spacing and wells are drilled from the underground mine workings so that it can eliminate the environment pollution during the development of shelf fields. In comparison with the surface methods of oil production on a shelf, such as the development of artificial islands, oil platforms and racks, this method has a number of technological and economic advantages. The world experience of these technologies application is reviewed here. In order to give comparative analysis of methods of oil field development, the Krykmyltyk oil field is taken here as an example for calculation of wells flow rates and capital expenditures.

Key words: Enhanced oil recovery, Mining method, Gravity drainage.

INTRODUCTION

World experience of oil fields operating shows that out of 100% of geological reserves, an average of 34-40% are currently extracted, and the remaining 60-66% are in the depths, and at the fields of highly viscous oil and natural bitumen, extraction is rarely exceeds 20-30%. Increase of oil recovery factor up to 30-40% is equal to discovery of new oil fields at minimum cost for its construction and geological surveys, which are now have a great share of capital investment into the oil sector.

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The purpose of this work is to describe a new mining method (wells and galleries) of development for light and high-viscosity oil, both onshore and offshore. During the offshore fields development by the proposed method, costs will be greatly reduced and the environment damage will be minimum, as all the technological processes will be transferred to the underground workings. It means that the contact "well-water" will be excluded[1,2]. Already developed oil fields can be also reincarnated by mining method. In this paper, the calculation of flow rate and economic efficiency on the example of one of the fields of Kazakhstan is presented. As a result, distinct advantages of our proposed development method are revealed.

From all numerous reasons affecting the low coefficient of oil recovery factor, it is important to draw attention to the methods of opening, by traditional vertical or controlled directional well. In this case, for oil field drilling, vast areas of land are reserved in order to install these wells for oil lifting and associated water from the depths for its infield transportation and preparation. All this require great financing, which include cost for surface and underground equipment. As you can see, traditional methods of well completion cause several problems in delivering of crude oil and associated water from reservoir to the surface. Associated water is one of the main sources of pollution, as it appears from the fact that near the wells, there are huge technogenic oil pits, tanks with produced water, which form large accumulation of fluid, filled with a mixture of produced water with oil and other substances harmful to the environment.

Mining is often mistakenly associated with open excavation of rocks used in the development of open-pit bituminous shale and sand. Modern technologies are designed for creating of tunnels or mine shafts below the producing formation, from which to this formation, draining holes are drilled. With the purpose of safety ensuring, mine workings usually are created at stable formations, providing reliable isolation from the overlying oil formation[3].

First, deposits of natural bitumen and heavy oil, canned deposits with high-viscosity oil, worked out oil fields with significant remaining oil reserves and in perspective zone of continental shelf may be the objects for mine development[4,5].

References review

Mining recovery method for the first time on an industrial scale was used in several countries, but was not further developed; however, this method can improve oil production of oil fields. The most significant industrial sites, where the mining method was used are as follows[6-9,11].

Pechelbronn field (France), where due to the application of oil extraction by surface wells, the oil recovery from surface was 17%, and by the application of mining method were extracted additionally 43%.

Field Wietze, West Germany, where due to the use of surface wells, the oil recovery from surface was 20-25%, and the use of mining method gave an additional 60%.

At the field Sarata-Monteoru, Romania, due to the application of mining method, the oil recovery was about 55-60%.

In 1939 mining development of Yaregskii field (Komi Republic, Russia) started. These was created, tested and implemented on an industrial scale the thermal-mining development approach for heavy oil deposits, which allowed to bring the oil recovery ratio up to 50-60%, which exceed the ratio of oil recovery of oil fields development with small and medium viscosity based on traditional approach.

Thermal-mining approach is based on the exposure of heavy oil or natural bitumen by steam, hot gases, water, air and other heating mediums using special wells drilled in underground oil mines, shaft holes or chambers joined to it.

For the development in the Norwegian Sea, at the Troms II field, scientists offered to replace expensive oil platforms by tunnels of 30 Km long from onshore to the sea[12].

Oil offshore field development with the use of mining method excludes oil spills incidents, as there is no contact with sea wells, or other communications. Also, any weather conditions, winter season do not affect oil development due to the use of mining method and production can last for 24 hrs a day throughout the year[13,14].

The above mentioned examples show that mining method for deposits development of light oil achieves 60% of oil recovery and more. It can be also used for the redevelopment of light oil deposits, where conventional methods of oil recovery are useless.

The example of the development of the next field proves the ability to work at depths of more than 4 Km[15,16]. The deepest mine in the world is located not far from Johannesburg in South Africa in Carletonville, at the field of gold and uranium Witwatersrand. Shaft depth is 4.5 Km. Branches from the main hole are set at the distance of 800 Km. Every day 5,000 people work at mines, where all required conditions are created. A powerful ventilation system blows the whole mine with clean air. The required temperature for operation is 28 CP, while the temperature of primary rock is 55 CP. Huge amount of ice (16 tons/day) is transported through pipes for mine cooling.

Description of the production approach

The complex of new ways of opening and exploitation of oil fields on land and sea gives an opportunity to avoid all the above mentioned problems, this approach was developed by the Professor T. K. Ahmedjanov (Kazakh National Technical University after K. I. Satpayev)[17].

In order to improve wells productivity, oil recovery, environmental protection and safety of oil and gas production, this new approach of well opening and operation is offered. This approach provides an artificially created gravity drainage of formation work throughout the entire process of the field exploitation, and on the surface, there will be no wells and systems of oil collection and preparation. For this purpose, in the overlying formation from shaft holes the mine workings (crosscut) are made, through which the oil field is opened by wells constructed underground by drilling them from top to bottom from the mine workings (Figs. 1, 2).

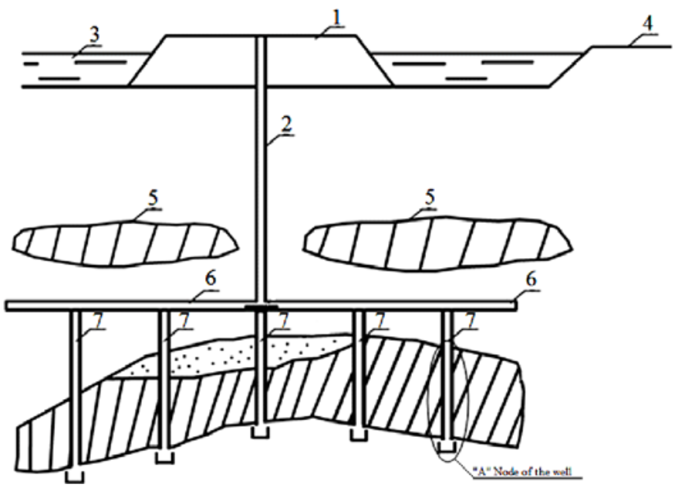

Fig. 1: Method of opening and exploitation of offshore and onshore oil reservoirs

The artificial island 1 is built on the shelf, under the location of the hydrocarbon reservoir, and wherein the salt dome does not exists through which the shaft hole 2 runs up to a depth below the level of the bottom of salt formation 5, and also crosscut 6, laying along the top of hydrocarbon formation; and from the crosscut short operating wells 7 are drilled with the diameter d_1 up to its intersection with oil or gas formation, is perforated below the level of the intersection with the formation; and it is exploited until the end of flowing drive; then the operating wells 7 are deepened below the formation. In order to move to gravity drainage of exploitation, wells are to be drilled to a larger diameter d_2 to such a length that the volume of wells with a larger diameter d_2 should be larger than the volume of the wells with a diameter d_1 (Fig. 2).

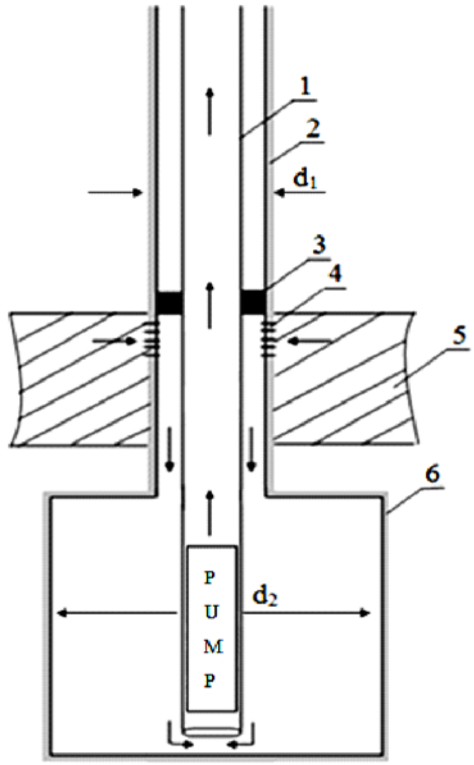

Fig. 2: "A" Node of the well

This creates the effect of "leaky bucket", from which the liquid (oil and produced water) would constantly flow in the underground mine workings. Then well production will be collected and prepared from it. This will result in constant gravity drainage of formation, formation water is pumped back into the reservoir through underground wells, and pure oil and gas will flow through only one mine working by pipelines to the surface. This method of well drilling and oil production will increase productivity 7-15 times, oil recovery will be enhanced by 1.5-2.0 times, construction of a large number of artificial islands and allocation of vast areas on the surface for well-drilling are excluded, as well as the length of production wells is reduced, environmental pollution is minimum, including marine. Also during exploitation of offshore fields in the Caspian Sea, this method enhances the security of facilities, including an attack from the air.

This new way of well opening and development can be used not only at new discovered fields, but also at the existing and earlier worked out wells. Moreover, all the existing oil recovery methods can be used more effectively.

Technical and technological calculation of the efficiency of oil production using the mining method (on base of Krykmyltyk field)[18]

In "Krrykmyltyk" oil field, chalk and Jurassic deposits are productive. Jurassic sediments are major industrial developments of present time. This can be seen by the following indicators: the number of active wells in Jurassic horizons - 23, chalk- 4. The main reason for this distribution is the difficulty of extraction of chalk deposits, for high viscosity index of oil and low reservoir pressure. Our calculation is made for the development of productive chalk horizons.

Upper chalk deposits have no commercial oil reserves and all reserves are concentrated in the lower chalk horizons, so that we will be interested only in productive intervals of lower chalk deposits (Table 1).

Table 1: Initial data on the horizon MI – A; MII - A, B, C; MII - A, B, C

Horizon	MI - A	MII - A, B, C	MIII - B + MIV - A
Reservoir depth – H, m	300	500	600
Average permeability of the reservoir – k, м^2	$1377{,}4\times10^{-15}$	$1377{,}4\times10^{-15}$	$1377{,}4\times10^{-15}$
Reservoir density at reservoir conditions - ρ_n, kg/m$^{3;}$	885.6	819.2	819.2
Net pay thickness of the reservoir – h_{net}, m	11.2	29	12
Average reservoir pressure – P_f, MPa	2.7	5.1	6.1
Dynamic viscosity of oil – μ, mPa*s	620	350	124.05
Radius of oil-bearing contour - r_c, m	1300	1300	1300
Radius of well - r_w, m	263×10^{-3}	263×10^{-3}	263×10^{-3}
Avg. day flow rate, m^3/day	0.3	5.5	5
Avg. day flow rate, t	0.24	4.5	4.5

Lower chalk deposits consist of 6 productive horizons - MI, MII, MIII, MIV, MV and MVI, which in turn are exploited at present by four wells. Below, there is a table of present day data from these horizons. In this calculation, we consider shaft and well below the horizon MI - A. As, there is the most viscous oil in comparison with the other horizons, the depth of the deposits is the smallest and wells that operate this formation, at this time is the most low-rate with respect to other wells.

In this case, the radius of the well is equal to - $r_w = 160 \times 10^{-3}$ m $\times e^{0.5} = 263 \times 10^{-3}$ m (from practical and theoretical data of up-hole and down-hole drilling). Construction of the vertical section of the shaft goes to a depth of 400 meters, that is 100 m below the depth of interest of the productive horizon. The length of the horizontal section of the shaft along the reservoir is 1500 m, i.e. the construction goes up to the middle of the deposit. This is the calculation for only one experimental well, which is located at the center of the deposit. The further development with expansion in the number of wells, the length of the horizontal section of the shaft will be extended up to the length of the entire deposit.

The calculations below show the increase in production rate and, accordingly, the recovery rate of the formation. Since the well is located in the center of deposits and thus, there is plane radial fluid filtration, we have the right to use the basic formula of Dupuis for calculating of well production. Initially it has the form:

$$Q = \vartheta \times S \qquad \ldots(1)$$

where V is the velocity of fluid filtration,

S is the square of cross-section of the well. The velocity of fluid filtration can be represented as:

$$\vartheta = \frac{\kappa}{\mu} \times \frac{\partial P}{\partial r} = \frac{\kappa}{\mu} \times \frac{P_{пл} - P_c}{\ln \frac{r_k}{r_c}} \times \frac{1}{r_c} \qquad \ldots(2)$$

and $$S = 2\pi r_c h \qquad \ldots(3)$$

Thus, substituting (2) and (3) in the formula (1), we obtain the final Dupuis formula[19-21]:

$$Q = \frac{2\pi \kappa h}{\mu} \times \frac{P_{пл} - P_c}{\ln \frac{r_k}{r_c}} \qquad \ldots(4)$$

However, Dupuis formula takes a somewhat different view for our new technology. During normal operation of wells, pressure in well is equivalent to the bottom hole pressure and it is equal to the hydrostatic pressure, which creates backpressure on the reservoir, $P_c = \rho gh$.

The main idea of our new development lies in the fact that we do not have the hydrostatic pressure, i.e. there is no backpressure on the reservoir, because oil under the positive influence of gravity goes down instead of upwards as it goes usually. On the basis of the Dupuis formula, we see that once the bottom hole pressure is almost equal to zero, so, it can be ignored, as it is much smaller than the reservoir pressure, and therefore, the depression in the reservoir will be maximum and close to the reservoir pressure. Practically with the help of this technology, we can obtain the so-called absolute open flow, obtaining which with use of the existing methods of development, is just impossible. In the theoretical calculations, it only describes the potential of wells, but in practice, it has never been implemented.

So this way, we get a modified Dupuis formula for our technological conditions, which can be represented as:

$$Q = \frac{2\pi\kappa h}{\mu} \times \frac{P_{пл}}{\ln \frac{r_k}{r_c}} \qquad \ldots(5)$$

With the requirement that we develop the horizon with a very high viscosity oil, a booster pump is to be installed in the flow line for constant fluid collection and creation of additional depression in the reservoir. It is the booster pump, which relieves the backpressure on the reservoir, constantly selecting the incoming fluid.

The well is perforated by ZPK-89-AT-09. This is the most unique charge of «Big Hole» series. When the diameter of the entrance hole is 19 ± 1,5 mm and the density of 20 holes at 1 meter, the depth of the channel is 350 ± 50 mm, this charge is unique not only among domestic producers, but also have no analogues in the world. Due to the structural feature of the charge and formed cumulative jet, the exit hole of the perforating system is small (11 ± 1,5 mm). Deep penetration is unique for cumulative charges of «Big Hole» types, which enables for perforation canals to penetrate deeply into the reservoir and to establish the hydrodynamic connection with the reservoir. This charge has proven itself perfectly at all types of collectors and capacities in the reservoirs of Western Siberia, Middle and Upper Volga regions.

Due to perforation of well, we get a hydrodynamically-imperfect system by the nature of formation penetration. Therefore, in the calculations, we take the reduced radius of the well. It is equal to:

"Dependence *C=f (nD, α,l)* where *l=1*"

$$r_{cnp} = r_c \times e^{-c} \qquad \ldots(6)$$

where *C* is a specified geometrical characteristics.

*T*his C coefficient is obtained with the help of the Schurov nomogram - "Dependence *C = f (nD, α, l)* for *l = 1"*.

Initial data on the ZPK-89-AT-09 perforator:

- Hole diameter - d_{hole} = 19 mm;
- Depth of perforations - h = 350 mm;
- Perforation density - n = 20;
- Well diameter - D = 320 mm.

l = h / D = 350 mm / 320 mm = 1.09375;

α = d_{hole} / D = 19 mm / 320 mm = 0.059; 3 - α;

n * D = 320 * 20 * 10^{-3} = 6.4; *C* = - 0.5.

Substituting the corresponding values in the formula (6), we obtain the reduced radius:

$$r = 160 \times 10^{-3}\ \text{m} \times e^{0,5} = 263 \times 10^{-3}\ \text{m}$$

Substituting the corresponding values in the formula (5), we obtain a new flow rate for our well:

According to the calculations, it is clear that the production rate is increased by 14 times compared to the current production rate of 0.3 m^3/day from the wells of 90-M and 79-M.

The calculations for the remaining horizons: MII - A, B, C and MIII - B + MIV - A, operated by the wells, respectively 16- M and 21- M, in case, if the shaft was designed on the basis of these productive reservoirs.

Similarly, according to the formula (5), we calculate the flow rate along the horizon MII - A, B, C:

According to the calculations, it is evident that flow rate is increased by 7 times in comparison with the current flow rate and is equal to 5.5 m^3/day.

Similarly, according to the formula (5), the flow rate is calculated along the horizon MIII - B + MIV-A:

According to the calculations, it is evident that the flow rate is increased by 10 times in comparison with the current flow rate and is equal to 5 m^3/day.

From the Table 2, we see that the greatest increase of the flow rate in comparison with the current was along the horizon MI - A (increased by 14 times), where is the most viscous oil in the whole field. We can conclude that this is a highly new technology for the extraction of high heavy oils.

The proposed method of oil field development enables to enhance oil recovery by improving flowing and use of gravity drainage of wells exploitation, allows to increase the number and the reliability of wells operating and can be used for offshore exploration and usual fields without effect on marine and the environment.

Below, there is a comparison chart of flow rates.

Table 2: Comparison chart of flow rates

Productive horizons	Current flow rate, m^3/day	Estimated flow rate, m^3/day
MI - A	0.3	4,285
MII - A, B, C	5.5	37.129
MIII - B + MIV - A	5.5	51.848

In the Figs. 3 and 4, we see that the high initial viscosity ensures the higher increase of oil viscosity due to new oil recovery method. As a result, the higher oil viscosities give higher flow rates.

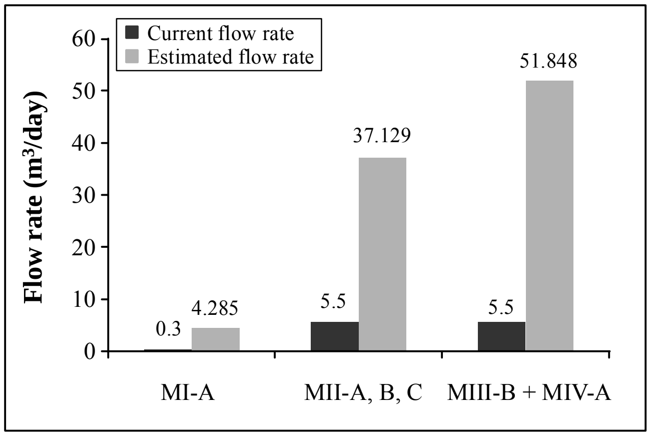

Fig. 3: Comparison diagram of flow rates

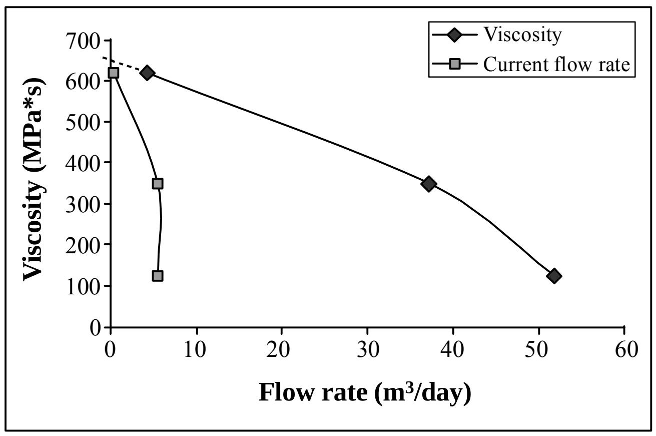

Fig. 4: Viscosity versus flow rate

Also it is required now to show the increase of oil recovery ratio as compared with the current. Since we do not specify a particular time of the field exploitation with the help of this technology, and we have only one drilled experimental well, the oil recovery factor is calculated for one well per year. For the calculation, we take the well along the horizon M I - A.

$$K_1 = Q_{prod1} / Q_{geol} \quad \ldots(10)$$

where K_1 is the oil recovery coefficient for the current existing well – 90 M;

Q_{prod1} is the amount of oil produced from one well with the current rate of 0.25 tons/day for one year, and it is equal to: Q_{prod1} = 0.25 t/day × 365 days = 91.25 t;

Q_{geol} are geological reserves equal to 2210 thousand tones

Then substituting in the formula (10) we obtain the corresponding values of K_1 = 0.004%.

$$K_2 = Q_{prod2} / Q_{geol} \quad \ldots(11)$$

Similarly, K_1, only by our new well with a flow rate equal to 3,795 t/day, Q $prod_2$= 3,795 tons/day × 365 days = 1385.175 t. Substituting into the formula (11), we obtain the corresponding values of K_2 = 0.062%.

According to the proposed schedule, the ratio of K_2 to K_1 shows us the effectiveness of the annual increase of oil recovery and it is equal to K_2/K_1 = 0.062/0.004 = 15.5 i.e. the increase of oil recovery factor by 15.5 times for high-viscosity oil.

Economic feasibility

Many petroleum companies are skeptical of mining technology, referring to high cost of shafts and crosscuts. For comparative purposes, you can find the results of economic calculation of capital expenditures for the mining method and conventional method that shows a clear economic benefit. The calculation of mining method will be made in US dollars according to the methodology[22].

The calculation is made under conditions of the Krykmyltyk field with a depths of 600 m. 10 wells are drilled from underground area (crosscut) compared with 10 surface wells. The shaft and the crosscut are drilled above the production formation closer to the top. From the crosscut short penetrating shafts are drilled, which are exploited until the end of the fountain mode. After that these wells are deepened below the level of the base of the productive formation and then it can be exploited in the gravitational mode upon its completion.

This method includes transportation of oil from well to a mouth of vertical shaft by the pipe system. Two pipelines are required; one is for transportation of oil to the surface of wells, and the other for transportation of agent for wells injection. We recommend using steel pipes with the diameter of 108 mm. From the source[23], the cost of 1 Km of these pipes is $ 5,400. This price includes: cost of welding and assembly work, cost of pipes, cost of materials and parts. The length of pipes depends on the entire length of transportation across the shaft. The length of transportation across the shaft is the sum of the lengths of crosscut and vertical shaft. If we need two rows of pipes, then we multiply the sum of the lengths by 2.

The cost of drilling of 1 m vertical well is $ 365 plus 30% from the total cost for completion and development, plus 10% from the costs for tripping operations of injection and production equipment.

The undocumented expenses are costs spent for safety activities, lighting and communication within the well, repairing works and maintenance of wells during the construction of shaft, rising costs of works at winter season, survey and design works, and others. We take 10 deep vertical wells, each have 600 m length - it will be an alternative to the mining method.

Table 3: Economic calculation for new and conventional methods

Name of expenditure	Cost (thousands of $)
Mining method	
Vertical shaft	569,25
Horizontal mining working (crosscut)	757,90
Construction of the shaft inset and pipeline	161,98
Drilling of 10 vertical wells	315,78
Undocumented expenses	451,22
Capital expenditures	2256,13
Conventional method	
10 vertical wells	2922,92

The Table 3 shows that the mining method is cheaper than the conventional surface method, because the lengths of 10 vertical surface wells are much longer than 10 subsurface wells. Length of the shaft plays great role in cost determination, but it is very dangerous to work with a deep depth field. But TauTona's experience reports that the depth is equal about 5 thousands of Km and it is possible to exploitation. In our case, the depth is equal 600 meters, and the cost reduction of new method is 600-700 thousands of US dollars or 33%.

The calculations shown here are made for the comparison of traditional and new method, which are represented in the Table 4, which shows the advantage of our proposed mining method. Final oil recovery factor is two times bigger in case of new method than conventional method. Environment pollution possibility is low due to lack of contact of water with well.

Table 4: Comparison of the development methods by the criteria

Criteria	Name of the development method	
	Conventional method (vertical wells)	**New method (mining method)**
Capital expenditures, ths. $	2922,92	2256,13
Environment pollution possibility	Very high (there is a contact of water with well)	Low (there is no contact of water with well)
Final oil recovery	0.3-0.4	0.6-0.8

CONCLUSION

Thus, in order to enhance the oil recovery of wells and in order to avoid the discharge of oil into the marine environment, it is recommended to develop oil fields not on the surface but from underground, from where wells are to be drilled. Special construction of wells allows to create an artificial gravity mode, that will lead to a multiple increase of flow rate and therefore to the increase of oil recovery factor of the whole well. Isolation of extraction, treatment and transportation processes from surface into the crosscut will protect the marine environment from pollution by harmful substances. Implementation of this method is economically feasible. If network of wells consists not of 10 wells, as shown in the economic calculation, but of a large number of wells, the advantage of underground mining will increase with the number of wells.

The proposed method of well penetration and exploitation is protected by the innovation patent of the Republic of Kazakhstan and can be implemented at oil and gas fields of Kazakhstan and abroad. All this will lead to the increase of oil reserves, oil field productivity, will improve the environmental state and safety of oil and gas production, as well as to the creation of additional jobs in the oil and gas production regions. For implementing this project, there are powerful shaft construction and mining industry, equipped with the necessary facilities and professionals that can implement it together with petroleum engineers. Incorporation of shaft construction, mining and oil industries will enable oil, gas and bitumen industries to succeed in production and reserves of hydrocarbons will significantly increase.

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