Review article

THE ROLE OF HORIZONTAL WELLS WHEN DEVELOPING LOW-PERMEABLE, HETEROGENEOUS RESERVOIRS

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Abstract. The widespread use of horizontal drilling in recent years has shown that horizontal wells can be successfully used both at the initial and late stages of development. This is due to the fact that horizontal wells, in contrast to vertical wells, contact a larger area of the productive formation, while the surface of drainage of the oil-saturated layer, productivity of the wells due to the formation of cracks, and also the influence on thin layers increases. One of the methods of impact on the reservoir is the steam-thermal method. The main advantage of the use of the heat wave method in horizontal wells is a significant increase in the well production rate, a decrease in the water cut of the reservoir, a decrease in the oil viscosity, an increase in the injectivity of the injection well, and an increase in the inflow in producing wells.

As a result of the total effect, a significant increase in production is obtained throughout the entire deposit. Enhanced oil recovery from the injection of steam is achieved by reducing the viscosity of oil, covering the reservoir with steam, distilling oil and extracting with a solvent. All this increases the displacement coefficient. One of the most effective ways to increase oil recovery at a late stage of field operation is sidetracking in emergency, highly watered and low-productive wells. This leads to the development of residual reserves in weakly drained zones of reservoirs with a substantial increase in well productivity in low-permeable reservoirs. This approach assumes that the initial drilling of wells is a 'pilot' stage, which precedes the development of oil reserves in the late stages of deposit development.

In the fields of Western Siberia, multiple hydraulic fracturing of the reservoir has been improved due to a special stinger in the liner hanger of multi-packer installation, which excludes the influence of high pressures on the production column under the multiple hydraulic fracturing. Employees of BelNIPIneft RUPPO Belorusneft have developed equipment and technologies for creating a network of deep permeable radial filtration channels under the SKIF trademark, which is based not just on multiple hydraulic fracturing of a formation, but on hydraulic fracturing in each of the interlayers creating a network of deeply penetrating radial channels. The calculations show that the technology of deeply penetrating radial channels significantly increases the production rates in comparison with the multiple hydraulic fracturing technology. In China and other countries, deep-seated, low-permeability carbonate reservoirs are operated with the use of an acid fracturing in open horizontal trunks with two technological innovations at the final stage of drilling: reorientation of the fracture and retraction of the fluid.

Keywords: horizontal wells, multiple hydraulic fracturing, controlled directional wells, lateral trunks, steam-thermal action, filtering channels network, new equipment for hydraulic fracturing, acid fracturing of low-permeable carbonate layers.

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The widespread use of horizontal drilling in recent years has shown that horizontal wells can be successfully used both at the initial and late stages of development (Muslimov, Suleimanov, Fazlyev et al., 1998). This is due to the fact that horizontal wells, in contrast to vertical wells, are in contact with a larger area of the productive formation, that is, the drainage surface of the oil-saturated layer increases, well productivity is increased due to the formation of cracks, and the influence on thin layers increases. In other words, the profitability of developing low-permeability and depleted layers, as well as deposits with high-viscosity oil and natural bitumen is increasing.

One of the most effective methods of impact on the reservoir in horizontal wells is the steam-thermal effect.

• The point of the complex effect by thermal and wave fields is that the coolant is fed into the reservoir through a pressure oscillator installed in a horizontal well. In the emitter, 4-10 % of the potential and kinetic energy is converted into the energy of acoustic oscillations. As a coolant, both compressible liquid (steam gas, air, etc.) and incompressible (water, aqueous solutions, etc.) are used. When the wave field is formed, not the rock of the formation (the formation skeleton) but the liquid in pores, capillaries and cracks of the rock come into the vibrational motion. The horizontal well in the productive layer is a linear source of thermal and wave energy. The impact of wave energy is most effective when the waves propagate perpendicular to the roof or the bottom of the productive formation. Repeatedly reflected from the roof and the bottom, these waves are damped without leaving the reservoir limited by the length of the well (Gataullin, Marfin, Kokhanova, 2007).

The main factor in the development of deposits of any oil, especially heavy, is the heating of the reservoir and fluids contained in it. The conventional way of steam heating impact is to supply a certain volume of coolant through the injection wells to create a thermal rim and then move it along the reservoir to the producing wells with the help of cold water. Thus, the thermal rim, increasing the temperature of the reservoir, lowers the oil viscosity, density and interfacial ratios, and the vapor pressure increases, which increases oil recovery.

The viscosity of oil sharply decreases with increasing temperature in the range from 20 to 80 °C. Since oil production is inversely proportional to viscosity, well productivity is increased by 10-30 times or more, especially in the initial period. When a certain temperature is reached, the viscosity decreases. High-viscosity oils with high density cool faster (Baibakov, Garushev, 1988).

Usually hot water or superheated steam is used as the coolant. However, superheated steam is the most effective agent. The volume of injected steam can be 25-40 times greater than the volume of hot water, which allows almost 90% of oil from the porous medium to be displaced with steam (Gataullin, Marfin, Kokhanova, 2007). The injection of hot water is used in cases where steam injection is unacceptable (in deep wells, with swelling clays, etc.).

When the oil is displaced by steam, three displacement zones are formed (Fig. 1):

- Zone of oil displacement by steam;
- Hot condensate zone where oil is displaced by water under non-isothermal conditions;
- Zone where oil is displaced by water of the reservoir temperature.

The selected zones interact with each other.

The main advantages of using heat wave action on productive layers in horizontal wells are: multiple increase in oil recovery, reduced water cut of the reservoir, reduction in oil viscosity, increase in the injectivity of the injection well and inflow to production wells. As a result of the total effect across all wells, we have a significant effect in production throughout the deposit. The increase in oil recovery from the injection of steam is achieved by reducing the oil viscosity, which contributes to the reservoir sweep due to the increase in the volume of oil, fermenting it with steam and solvent extraction, which increases the displacement coefficient (Gataullin, Marfin, Kokhanova, 2007).

One of the most effective ways to increase oil recovery at a late stage of field development is sidetracking in emergency, highly watered and low-productive wells. This leads to the development of residual reserves from weakly drained zones with a significant increase in well productivity in low-permeability reservoirs. This approach assumes that the initial drilling of wells is a kind of "pilot" stage, which precedes the development of oil reserves in the late stages of reservoir development (Nuryayev, Medvedev, Sulima et al., 2007). So, in OJSC Surgutneftegas 7 types of lateral trunks are used (directional single-barreled, horizontal single-barreled, horizontal multi-barreled, etc.) that allow:

- Gradual full transition to lateral trunks during depression in the reservoir in low-permeability formations;
- Development of efficient technologies for the dual completion of multilateral wells with the ability to control operating modes for each trunk and other measures by which it is possible to significantly increase oil production in all types of deposits at various stages of their development (Nuryayev, Medvedev, Sulima, et al., 2007).

The experience of Oil and Gas Production Department Aznakaevskneft, which unites 6 areas of the Romashkino field (Taipova, 2016), is interesting. The development of oil reserves from low-permeable clay-stratified reservoirs by conventional methods is ineffective. The extraction of oil from such layers requires new technologies. In 30% of the newly constructed controlled directional wells for the last 6 years, collapsed overflows have been identified. To restore these wells, significant investments are needed. In this connection, a solution was proposed for the construction of wells with an address horizontal ending. The first well with 10 branched trunks was built in 1953 at the Kartashovsky field in Bashkortostan. The distance between the bottomholes was 322 m, and the longest horizontal trunk was 168 m. The production rate of this horizontal well was 120 tons/day versus 7 tons/day in vertical wells.

Subsequently, everything was focused on methods and technologies for increasing productivity: flooding, chemical stimulation on the reservoir, development of only highly productive deposits. Only in 2012, Oil and Gas Production Department Aznakaevskneft began drilling a directed horizontal well No. 194521. As a result of drilling, a significant zonal inhomogeneity of the reservoir was revealed: porosity varied from 9 to 23%, permeability from 15 to 650 mD, oil saturation from 52 to 80%. The average production rate for the well was 20.5 tons per day, which is 5 times greater than the production rate of a neighboring vertical well. The projected payback period of the controlled directional well is 2.5 times less than in the next vertical well. Thanks to the technology of horizontal

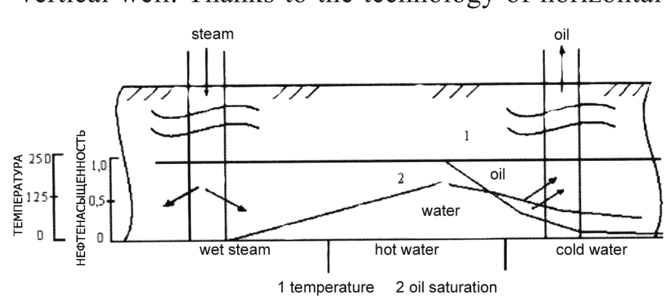


Fig. 1. Continuous steam injection scheme (Gataullin, Marfin, Kokhanova, 2007)

drilling, it became possible to increase oil reserves in the inter-well space of vertical wells. The results of drilling horizontal wells in Aznakaevo and Zelenogorsk areas are shown in Fig. 2. Horizontal drilling makes it possible to increase the efficiency of producing upper horizons, operated by the return stock of vertical wells. The experience of studying horizontal wells in Oil and Gas Production Department Aznakaevskneft showed that it is impossible to expect sustainable development without the use of horizontal drilling technologies (Taipova, 2016).

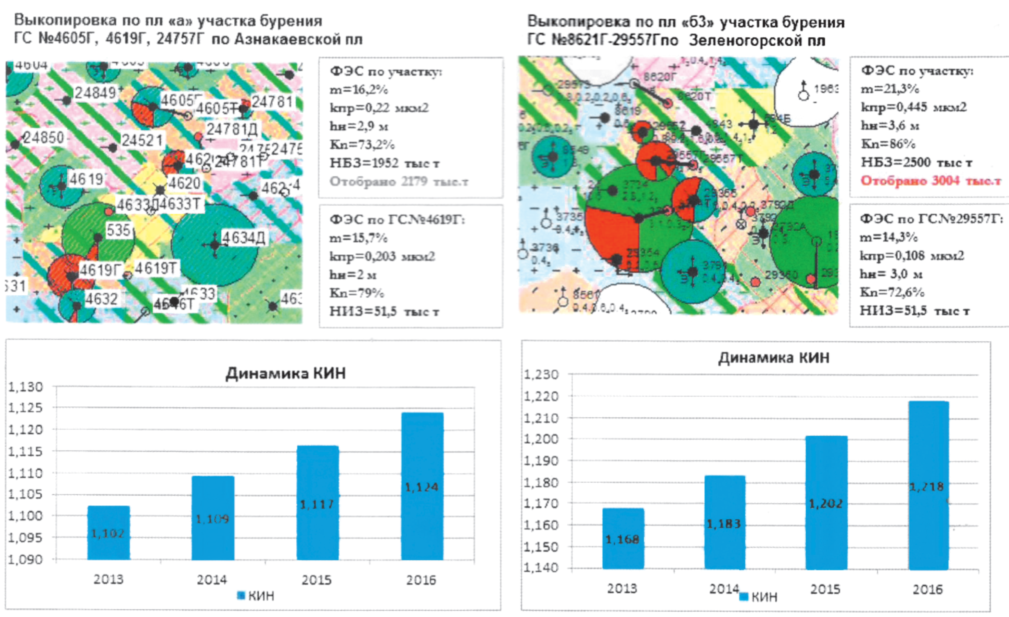
Employees of BelNIPIneft RUPPO Belorusneft developed equipment and technologies for creating a network of deep permeable radial filtration channels under the SKIF trademark (Demyanenko, Serebrennikov, Povzhik et al., 2017). Investigations have shown that in the construction of horizontal wells in hard-to-recover, highly heterogeneous, highly dissected low-permeability formations, it is more effective to complete not with multiple hydraulic fracturing of the reservoir, but to perform hydraulic fracturing in each of the interlayers, that is, penetrating radial filtration channels. If there is a significant heterogeneity of the reservoir (permeability 0.001-0.0001 μm^2), up to 5-stage fracturing is performed within a single zone of the horizontal trunk, that is, a reservoir fluid collection system consisting of 5 channels (cracks), which are directed in opposite directions from the trunk. This experiment was carried out in wells 204 and 310 of the Rechitsky field (Fig. 3).

In the well 204 Rechitsky reservoirs are not identified at all in logging data. In these wells, 5-stage fracturing was performed within a 500-800 m horizontal trunk, creating 5 channels (cracks) of reservoir fluid oriented in the opposite direction from the well trunk. The calculations show that the creation of the technology of penetrating radial filtration channels significantly increases the production rates in comparison with the multiple hydraulic fracturing technology (Demyanenko, Serebrennikov, Povzhik et al., 2017).

Multiple hydraulic fracturing at the late stage of development to involve hard-to-recover reserves of the Achimovskian deposits from the Vyngayakhinsky and Yety-Purovsky fields was carried out by Muravlenkovskneft branch by drilling a horizontal end of the trunk followed by a multiple hydraulic fracturing of the reservoir. The technology of conducting the multiple hydraulic fracturing provides for the descent into the well of a special shank that uncouples the horizontal well trunk into separate sections in which hydrofracturing takes place alternately (Shirokov, Azamatov, Artamonov, 2013). The technology of multiple hydraulic fracturing using uncoupling swelling packers and special circulation couplings is widespread in the territory of Western Siberia. For the first time such options of multiple hydraulic fracturing was carried out in the Muravlenkovsneft branch on a well that was tested on the BP16 reservoir of the Vyngayakhinsky field (Fig. 4).

Features of downhole equipment for multiple hydraulic fracturing is that a special stinger device is installed on the tubing string, which is hermetically fixed in the liner hanger of the multi-packer arrangement and, thus, excludes the effect of high pressure on the main production column (Fig. 5c).

Technologically, the multiple hydraulic fracturing differs from the standard hydraulic fracturing by the necessity of discarding balls during the performance of the stimulation operation. The moment the ball is



год	2013	2014	2015	2016
Qн, год	9795	13301	14221	14832

год	2013	2014	2015	2016
Qн, год	33348	39147	45902	40900

Fig. 2. Dynamics of oil recovery factor for horizontal wells with "off-balance" production of reserves (Taipova, 2016)

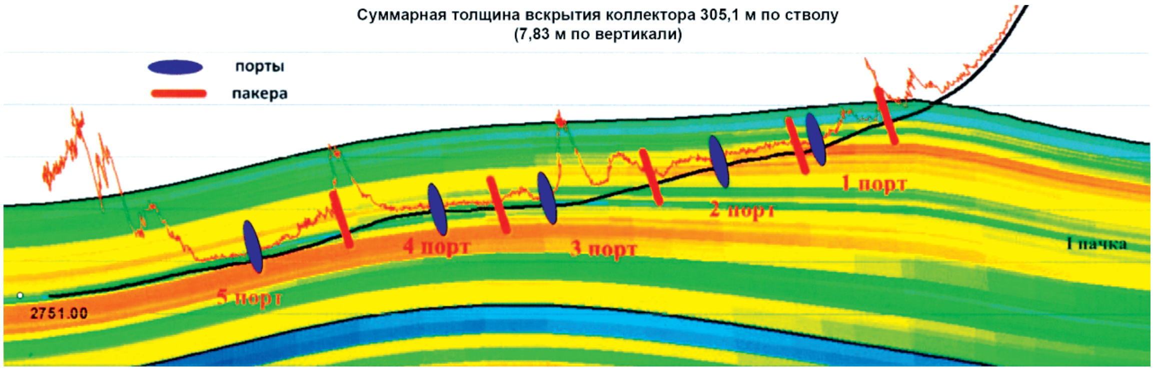


Fig. 3. Geological section within the horizontal section of the trunk of well 310 Rechitsky (Demyanenko, Serebrennikov, Povzhik et al., 2017)

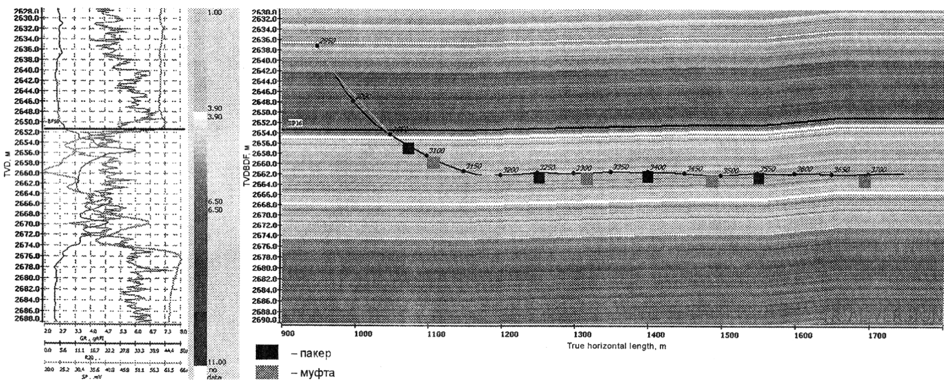


Fig. 4. Actual profile of the horizontal well trunk of the Vyngayakhinsky field (reservoir BP16) for a four-stage multiple hydraulic fracturing (Shirokov, Azamatov, Artamonova, 2013)

launched is fixed with metallic noise at the wellhead. The ball should be run in a stitched-in-place system to reduce the amplitude of the oscillation during injection and only after this completes the stage of the sale. For the next stage of the multiple hydraulic fracturing, it is possible to immediately start the injection test through the open circulating coupling (Shirokov, Azamatov, Artamonova, 2013).

Unlike standard fracturing operations, the implementation of the multiple hydraulic fracturing does not involve the use of proppant with a special coating that is sintered by the temperature of the reservoir and prevents the proppant from drifting into the well trunk after the end of the operation. The result of a comparative analysis of the production data showed that the efficiency of the multiple hydraulic fracturing conducted on a horizontal well is 2.5 times higher than the efficiency on an controlled directional well with a standard fracturing operation (Fig. 6).

The experience of developing complex carbonate reservoirs in China is very interesting (Table 1), where two new methods of wells completion have been

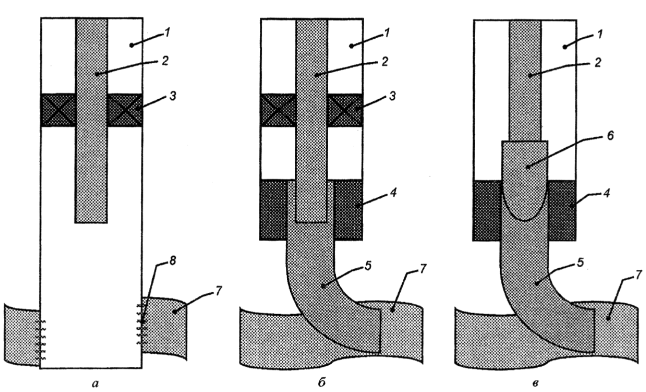


Fig. 5. Scheme of descent of underground equipment for standard hydraulic fracturing on a controlled directional well (a), standard hydraulic fracturing on a horizontal well (b) and multiple hydraulic fracturing on a horizontal well (c). 1 – the main production column; 2 – tubing string; 3 – hydraulic fracturing packer; 4 – liner hanger; 5 – shank; 6 – stinger; 7 – reservoir; 8 – interval of perforation (Shirokov, Azamatov, Artamonova, 2013)

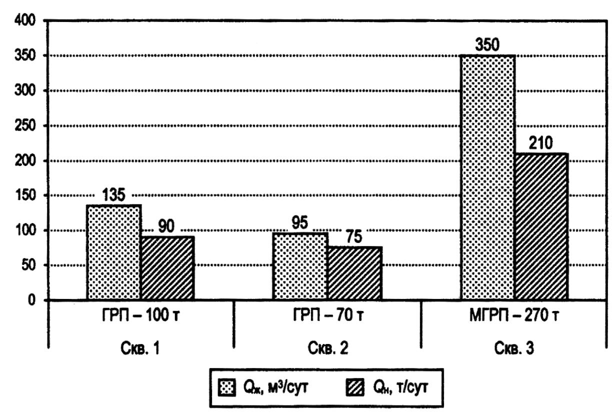


Fig. 6. Comparative results of standard hydraulic fracturing and multiple hydraulic fracturing for liquid and oil flow rates: Well 1 – controlled directional well with a standard fracturing of 100t proppant; Well 2 – controlled directional well with a standard fracturing of 70t proppant; Well 3 – horizontal well with a multiple fracturing performed with a total volume of 270 t proppant (Shirokov, Azamatov, Artamonova, 2013)

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	Tarim basin	Sichuan basin			Ordos basin
Gas field	Tazhong	Yuanba	Puguang	Moxi-Anyue	Daniudi
Productive formation	Ordovician	Permian	Triassic	Cambrian	Ordovician
Depth, m	5100–6600	6710–7500	4350–5200	4600–4800	3000–3600
Thickness, m	120–270	10–75	102–411	80–120	90–120
Pressure, Mpa	65,68–68,1	66,33–69,23	55–57	78	31,68
Temperature, ^0C	150–160	145–159	120–134	144,8	90–120
Porosity, %	0,001–0,8	0,62–24,65	0,94–25,22	2,0–8,0	0,58–14
Permeability, mD	0,001–19,67	0,002–2385,5	0,002–3354	0,01–10	0,011–5,89
Formation fluid	Oil, gas, water, H_2S, CO_2, N_2	Gas, water H_2S, CO_2	Gas, water H_2S, CO_2	Gas, water H_2S	Gas, water
Content of H_2S, %	6,2	3,71–6,61	15,16	2	–
Content of C_o2, %	4,65	3,33–15,51	8,64	0	–
Lithology	Psammitic limestone	Limestone Dolomitite	Dolomitite	Psammitic Dolomitite	Limestone

Table 1. Characteristics of China's carbonate reservoirs (Guo Jian-Chun, Gou Bo, Yu Ting, 2015)

successfully implemented, which solve acid fracturing problems in open horizontal trunks. Using these methods, production was increased in the Tarim, Sichuan, Ordos oil and gas basins (Fig. 7) (Guo Jian-Chun, Gou Bo, Yu Ting, 2015).

Reservoirs of these fields have:

- low porosity and ultra-low permeability;
- extremely heterogeneous due to random distribution of cracks, cavities and pores of dissolution;
- depth of occurrence of these rocks is 5000-7000 m;
- the reservoir temperature reaches 160 °C;
- Reservoir pressure up to 78 MPa.

To increase the flow rate of such wells, it is necessary to drill horizontal wells perpendicular to natural cracks in order to cover the maximum possible space with hydrocarbon accumulations (cavities, dissolution pores and cracks). In order to create a grid of communicating cracks connecting the accumulation sites and hydrocarbon filtration pathways, multiple acid fracturing is necessary. However, because of three reasons, the following is impossible:

1) Conventional acid fracturing is not effective in heterogeneous reservoirs with intermittent cracks and pores. The usual crack of acid fracturing controls only a few zones of hydrocarbon accumulations (Fig. 8a);

2) as a rule, gel-like acids are used in low-permeability carbonate reservoirs, but at high reservoir temperatures their viscosity drops to 10 MPa/sec. This factor contributes to a greater consumption of acid, reduces the length of the crack of acid etching, reduces the productivity of the well after treatment;

3) at high temperatures and pressures

Fig. 7. Recently discovered gas fields in China (Guo Jian-Chun, Gou Bo, Yu Ting, 2015)

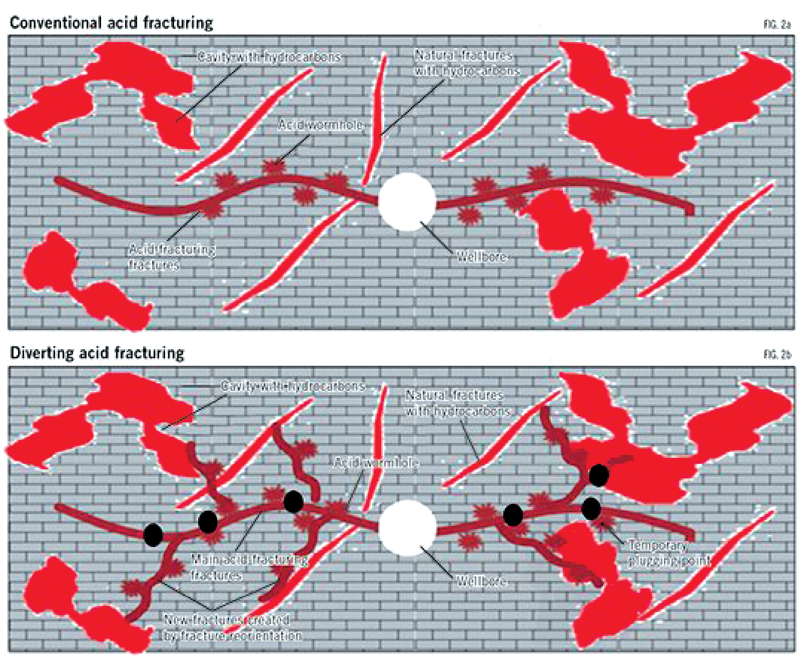

Fig. 8. Normal (a) and deflecting (b) acid fracturing (Guo Jian-Chun, Gou Bo, Yu Ting, 2015)

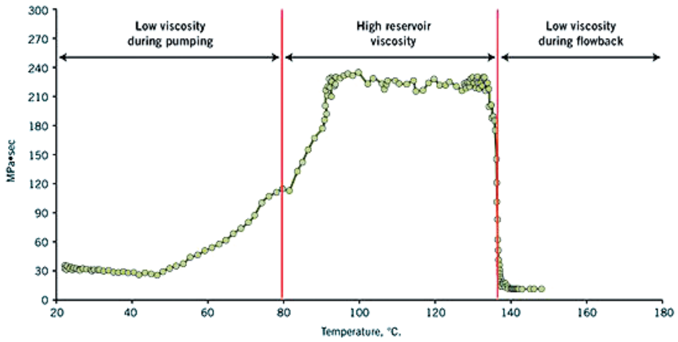

Fig. 9. Dependence of the acid viscosity on temperature (Guo Jian-Chun, Gou Bo, Yu Ting, 2015)

of China's carbonate deposits, acid treatment of fracs contributes to the release of a large amount of gases (hydrogen sulphide and carbon dioxide) that cause corrosion of equipment and other complications.

To overcome these difficulties, two new technologies were introduced, which are combined in a deflecting acid frac. Such an approach involves a reorientation of the fracture and a deviation of the fluid and allows more channels of hydrocarbon accumulations to be channeled than in the conventional way (Fig. 8b).

To reduce the rate of acid reaction with the rock and to reduce the amount of acid leakage, two types of TCA and SDA acids are used at once, which allow minimizing frictional drag and provide acid treatment and protection of the layer in deep-lying, high-temperature and complex carbonate reservoirs. The TCA acid has a low viscosity when pumped, which is favorable due to a higher feed rate and less friction loss. However, in the well, its viscosity rises to 220 MPa/sec, which leads to acid rejection and an increase in crack length. When working out, its viscosity drops, and it is freely carried out (Fig. 9).

The SDA acid contains viscoelastic surfactants when pumped as single molecules; it is easy to pump. After pumping in the reservoir, its viscosity increases to and above 350 MPa/s. This is due to a decrease in the acid concentration and an increase in the concentration of calcium and magnesium ions during the reaction of acid with the rocks of the reservoir. At the same time, a grid of viscoelastic surfactants is formed. After processing, the structure of the grid is destroyed by hydrocarbons, its viscosity decreases and it easily escapes from the well. For separate completion of complex horizontal wells in the acid fracturing of carbonate reservoirs, special downhole tools are used in China (Fig. 10).

The first option is the most popular. The completion layout consists of an installation packer, a lifting pipe, open hole packers, a sliding sleeve and a ball seat (Fig. 10a). This method provides up to 15 completion stages in long horizontal wells.

The second way of completing consists of an installation packer, an open packer lifting pipe, perforated tubes with filters and a ball seat (Fig. 10b).

These new technologies were applied in 677

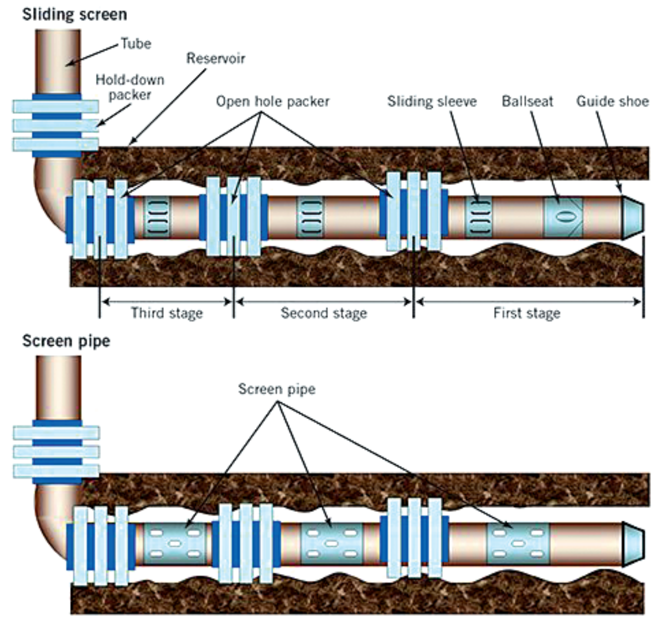

Fig. 10. Methods of separate completion of horizontal well in acid fracturing in an open trunk (Guo Jian-Chun, Gou Bo, Yu Ting, 2015)

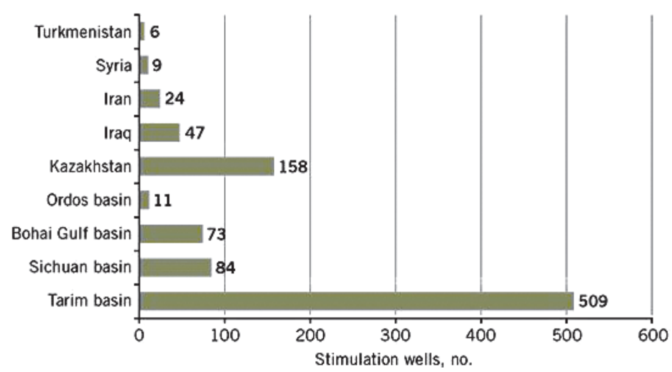

Fig. 11. The scope of new technologies for the completion of horizontal wells with acid fracturing (Guo Jian-Chun, Gou Bo, Yu Ting, 2015)

horizontal wells of China's carbonate reservoirs in the Tarim, Sichuan and Ordos oil and gas basins, as well as in the Bohai Sea, ensuring an increase in production. Similar successful results were also obtained in other countries (Fig. 11).

Thus, horizontal wells solve the following problems in low-permeability heterogeneous reservoirs:

- increase the productivity of wells by increasing the filtration area of low-permeability, heterogeneous layers of small thickness,

-continue the period of anhydrous operation,

- increase the efficiency of water injection into the reservoir,

- develop hard-to-reach areas of oil and gas deposits,

-increase the oil recovery of well by reducing the oil viscosity and increasing coefficient of displacement when exposed to steam,

- facilitate hydrocarbons recovery from deep-seated, low permeable carbonate reservoirs with acid fracturing, etc.

The equipment of horizontal wells is constantly being improved, which contributes to the reduction of accidents and more safe extraction of hydrocarbons from the subsoil.

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