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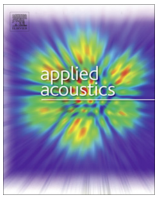

Selective ultrasonic treatment of perforation zones in horizontal oil wells for water cut reduction

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ABSTRACT

A technique for treatment of perforation zones of horizontal oil wells for water cut reduction based on selective ultrasonic treatment was suggested. The technique involves online geophysical studies of horizontal wells, determination of treatment intervals based on these studies, selective ultrasonic treatment of the chosen interval and subsequent pump-out using a specially designed jet pump. The technology does not involve reduction of the flow in the well. The developed innovative technique of water cut reduction using selective ultrasonic treatment is studied within this article. Theoretical estimations and computer modeling revealed that the position of the downhole ultrasonic tool near the sidewall of the well leads to more homogeneous distribution of the induced acoustical field and wider penetration of the acoustical waves. The developed method was tested on a horizontal well in Western Siberia, which was characterized by high water cut. Based on geophysical studies only zones with low water and high oil production were treated, this lead to a decrease of the water cut by 20% and an increase of oil production by 91% after treatment of the test well.

1. Introduction

The structure of the reserves of natural resources in Russia often does not allow economically efficient production of oil using the traditional methods of extraction [1–7]. Primarily this refers to reservoirs with low permeability since a big part of oil reserves would be uninvolved in the commercial development in case of extraction through vertical wells. In these circumstances improvement of the extraction efficiency may be achieved by the use of horizontal wells, which have an increased formation exposing surface, i.e. allow decreasing the filtration resistance in the perforation zones [8]. Horizontal wells not only have a higher oil production, they enable the producers to increase the recovery factor, which shows the efficiency of the recovery.

Horizontal wells are especially effective for fractured reservoirs with horizontal permeability; for areas with limited space for installation of drilling equipment; for Enhanced Oil Recovery (EOR) from reservoirs on a late stage of exploitation; in case of intensive formation of gas or water cones [9]. Horizontal strings, which go through several hundred meters of the producing reservoir, can open fractured zones with higher permeability in an inhomogeneous reservoir, this often lead to a significant advantage of horizontal wells above vertical wells in terms of production. Moreover, horizontal wells enable the producers to develop fields with extensive gas and oil reserves under a gas cap and water oil reserves with a much lower amount of wells and work with lower depressions during the development. Horizontal drilling techniques also contribute to the extraction of oil under pressures much closer to the initial pressures in the reservoirs, which is much more efficient and safe for the environment. A significant increase of the reservoir pressure comparing to the initial pressure lead to faster watering of the wells, decrease of the potential zones of exploitation during the second and third stages of exploitation. It is especially important to use horizontal drilling in case of inhomogeneous reservoirs. Thus the drilling and exploitation of horizontal wells is currently one of the most important topics of scientific and technical research in the area of oil production.

The analysis of the performance of horizontal wells show [10], that they mostly fulfill their tasks: provide higher production with lower water cut. Most of the horizontal wells produce oil with no

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or minimal water content (up to 20%), a low percentage of the horizontal wells produce fluid with water content of up to 60% and only single wells have a water cut of more than 80%. This is observed in particular in Western Siberia, in particular in cases, when the reservoir has a complicated profile. The dynamics of the performance of the horizontal wells of one of the reservoir in Western Siberia is shown in Fig. 1 [11].

One of the reasons of the tendency shown above is the deviation of the real trajectory of the well from the planned ideal trajectory. As a result of such deviation the well may come very close to the oil water contact, as shown on Fig. 2. In case the well is located as shown on Fig. 2b, watering of the well is inevitably.

In order to reduce the water cut it is first of all necessary to carry out geophysical studies. Currently well tractors or coiled tubing is used to deliver the geophysical probes to the horizontal strings. The probe is used to determine very precisely the locations of fluid influx and their orientation, to determine the water content and to build a "map" of fluid distribution. Onward annular chemical packers or the technology of expandable zonal isolation profiler (EZIP), based on expandable elastomers, are used to isolate the zones of water influx. Both technologies are based on limitation of flow into the well [12,13].

The methodology described above has two major drawbacks. First of all, the geophysical studies are carried out with offline probes and the interpretation is done after extraction of the tool. No online acquisition of the data is possible, thus an additional pulling-and-running operation is required, which is quite costly, especially for horizontal wells. The second drawback is the fact, that both technologies of water flow reduction are based on general reduction of the flow of the well, which might lead to the impossibility to recover a part of the potentially recoverable oil, thus decrease of the recovery factor is possible.

Over the last few years there has been a developing interest in physical EOR techniques. This might be explained by the fact, that these methods involve the use of various physical fields instead of matter to affect the reservoir and do not require the use of chemical reagents, which might be very harmful for the environment. Moreover, such technologies are often more cost and energy effective compared to other methods [14]. According to [15–17] the acoustical method of EOR (including ultrasonic EOR) is one of the most promising wave methods, this method has been widely studied over the last 20 years [18,19] and was mainly used during capital or operational workover of wells in order to increase the production. The results of such treatments were very promising in most of the cases [14,20,21]. The effect of ultrasound on the well and the reservoir which leads to enhanced production, is based on two aspects of sonication that are relevant (1) enhancement of the flow of oil through the rocks into the pumping pool (including enhancement of flow because of removing of the deposits from the wellbore perforation zone) and (2) reduction of the viscosity of the oil that would make it easier to pump [14,20,21]. The methodology is particularly useful for older wells which are in the later stages of reduced yields.

However so far the use of ultrasonic treatment for water cut reduction was never reported in the literature, the changes in the water cut of oil wells after ultrasonic treatment was only reported as a side effect in a few papers [14,21]. It has been shown in [14] that selective treatment of the wellbore perforation zones with ultrasound result in a decrease of the water cut. The average changes of the water cut after selective ultrasonic treatment of 30 vertical wells in Western Siberia are shown in Fig. 3.

Ultrasonic treatment was done during capital workover of the well, together with optimization of pumping equipment. The changes of the water cut are compared with the average changes of the water cut observed after optimization of pumping equipment of 30 vertical wells without ultrasonic treatment. During ultrasonic treatment the oil bearing layers were treated using an ultrasonic downhole tool, fed by a 10 kW surface ultrasonic generator. More detailed the technique is described in [14]. The decrease of the water cut is achieved due to cleaning of the wellbore perforation zone only in the oil bearing layers, while the water bearing layers are not treated. The treatment intervals are determined based on the results of geophysical studies, carried out prior to the treatment. The technique does not involve flow limitation.

Bearing this in mind an innovative technique for treatment of perforation zones of oil wells for water cut reduction based on selective ultrasonic treatment was suggested. The technique involve online geophysical studies of horizontal wells, determination of treatment intervals based on this studies, selective

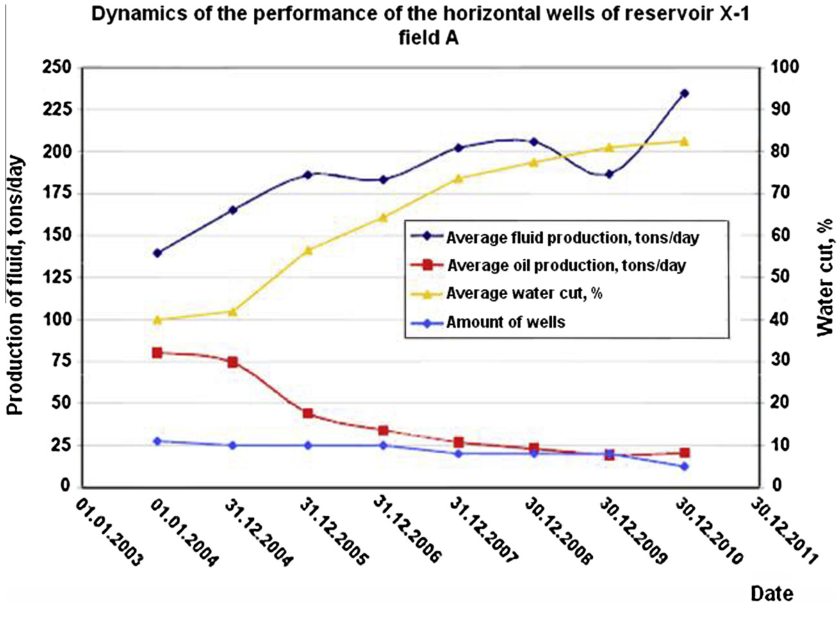


Fig. 1. Dynamics of the performance of horizontal wells on one field in Western Siberia.

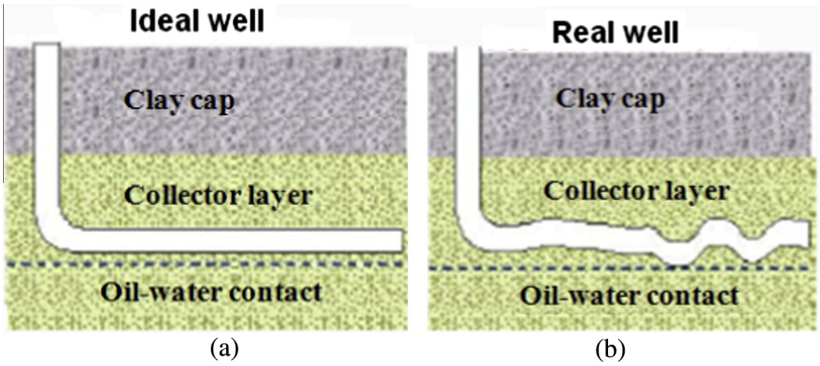


Fig. 2. Schema of ideal (a) and example of real (b) horizontal well.

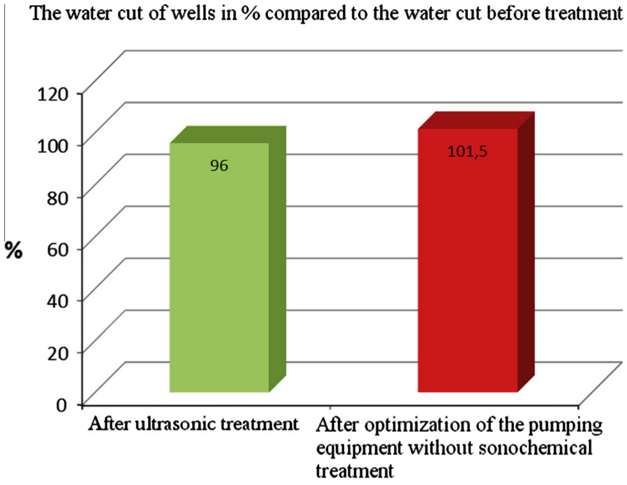


Fig. 3. Average changes of the water cut of wells after ultrasonic treatment and optimization of pumping equipment.

ultrasonic treatment of the chosen interval and subsequent pump-out using a specially designed jet pump.

2. Materials and methods

Equipment, specially designed by Viatech Ltd. for treatment of horizontal wells [20] has been used for selective ultrasonic treatment of horizontal wells perforation zones.

The equipment contained of a special ultrasonic generator, an downhole tool with the diameter 44 mm and a specially designed cable (Fig. 4a), installed on a "mini coiled tubing" wireline truck (Fig. 4b).

The downhole tool included a sonotrode with magnetostrictive transducers, a probe for online measurement of the necessary parameters and a special jet pump for horizontal wells. The frequency of the sound was 18 kHz. During the treatment the following parameters has been measured by the probe:

- Pressure
- Temperature
- Natural radiation of the rock
- Flow of the fluid
- Magnetic location of the couplings
- Termoconductive flow
- Resistance
- Soil/water content

The ultrasonic generator with the maximum power of 10 kW was modified in such a way that it could automatically adapt to the changes of the technological load due to changes in the well conditions. The energy delivered through the cable to the load was up to 5 kW. The average load acoustic power of the magnetostrictive transducer used was 1.5 kW. The ultrasonic generator also included a unit for processing of the pressure and temperature data.

In order to determine the optimal treatment modes in horizontal wells computer stimulation has been carried out.

The casing size used in the stimulations was 102 mm. The 44 mm magnetostrictive downhole tool was chosen as the source of acoustic waves. Its working frequency was 18 kHz.

The amplitude of the oscillations of the tool was 3.8 μm in continuous oscillation mode. This was based on measurements carried out prior to the stimulation.

To calculate the effective range of the device, the amplitude of the displacement is converted into the amplitude of the pressure waves. Therefore, the following equation was used:

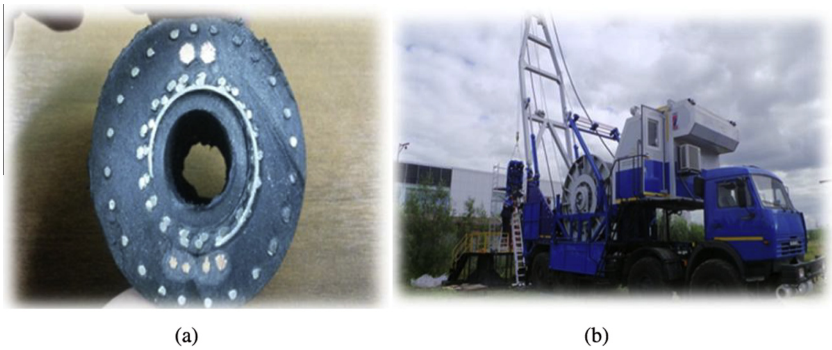


Fig. 4. Equipment used for selective ultrasonic treatment of horizontal wells: (a) cable (b) "mini coiled tubing" wireline truck.

$$P_A = 2\pi f \rho c A, \tag{1}$$

where A is the displacement amplitude, π is the constant Pi = 3.14, f is the oscillation frequency, c is the speed of sound = 1300 m/s for fluid and ρ is the density of the media (900 kg/m^3). Eq. (1) shows that the amplitude of the pressure waves in the immediate vicinity of the device was P_A = 5 bar.

The attenuation constant α of the acoustic waves is dependent on frequency of the wave:

$$\alpha = \omega / c * 1/Q, \tag{2}$$

where c is the speed of sound, $\omega = 2\pi f$, Q is the quality factor.

For the crust (rock in the formation), the following values can be used for Eq. (2) normally: c = 2000 m/s, Q = 300 [22]. Here one must remember that it is a porous medium and the sound wave is attenuated more. Therefore, it was suggested in using the quality factor of 30 in this case [22]. This means that the attenuation constant for acoustic waves at the frequency of 18 kHz α = 1.88 1/m. The crust is located 51 mm from the center of the well. The pressure amplitude of P_r as a function of the distance r can be determined by the following equation:

$$P_r = P_A e^{-\alpha r}, \tag{3}$$

The interference pattern was calculated using the program code COMSOL Multiphysics. Axial and horizontal cross sections of the calculated interference patterns around the well are shown in Fig. 5. Two cases have been modeled: the tool is located in the middle of the well, which is the case when the well is vertical (Fig. 5a and c) and the tool is located near the sidewall of the well, which is the case if the well is horizontal (Fig. 5b and d).

The amplitude of the pressure near the ultrasonic downhole tool reaches 5 bar. According to the modeling results the ultrasound is distributed radially and at least one meter of the formation is treated effectively. During the treatment the tool is moved along the well, which enables to treat the required intervals of the perforation zone. The intervals are chosen based on geophysical studies. The radial penetration of 1 m is enough to remove the deposits from the wellbore perforation zone, since most of the deposits are located near the wellbore. In case of a horizontal well, when the tool is located near the lower sidewall, the distribution of the pressure amplitude around the well is more homogeneous. The amplitude in the rock is higher in case of the position of the tool near the sidewall.

In order to explain this phenomenon we have considered the well as a cylindrical tube (the casing). The cross-sections of the model well in the case when the ultrasonic tool is placed in the middle of the tube (a) and near the sidewall of the tube (b) are shown in Fig. 6.

Considering the deformation forces which affect the cylindrical tube at one moment of time, we have calculated the elastic force T in the tube, induced by the external force F at a specific moment of

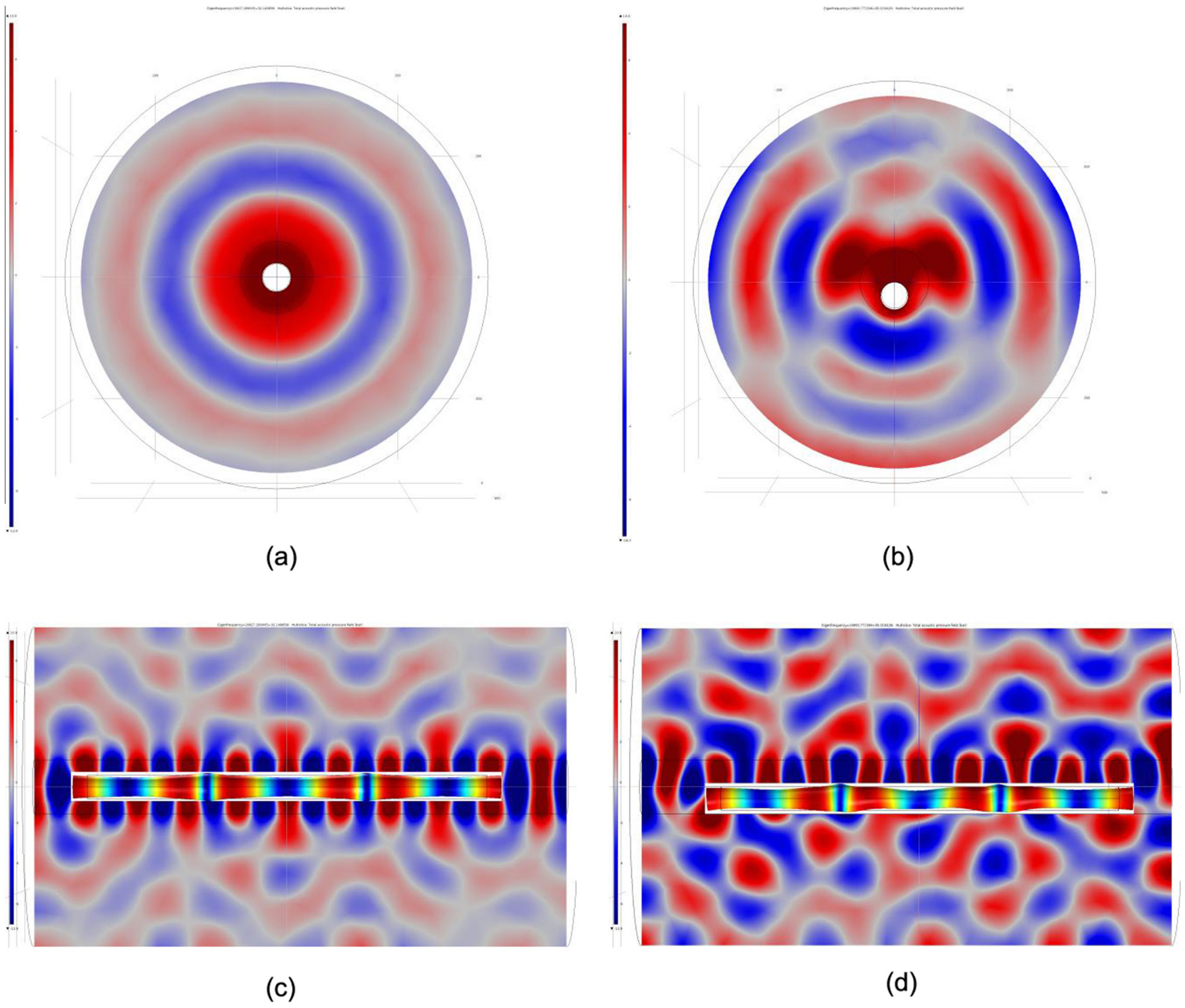
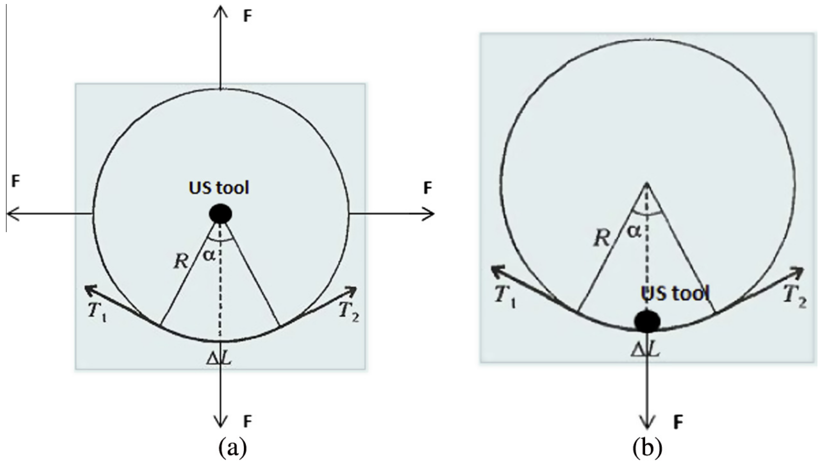


Fig. 5. Calculated interference patterns around the well.



(a) (b)

Fig. 6. Cross-sections of the model of the well in two cases: (a) central position of the ultrasonic downhole tool; (b).

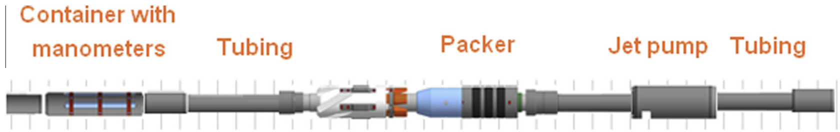


Fig. 7. Configuration of downhole equipment during treatment.

time. In the case when the tool is located in the center, the external force F is applied simultaneously to the whole tube, deforming it radially, thus the elastic force is equal $F/2\pi$. In the other case the application of the force F will be shifted in time and the elastic force induced in the tube will be equal $F/2$, which is three times higher. This result is in a good agreement with the calculated pressure amplitude distributions.

Thus position of the tool near the sidewall of the well does not affect the efficiency of the treatment negatively. In this case the treatment modes and the construction of the tool are determined by the conditions of the well: a magnetostrictive transducer needs to be used, since the risk of damage of such a construction is less; the acoustical power of the tool should be increased in order to reduce the treatment time.

The treatment time can be roughly estimated using the following equation [20]:

$$\tau_p = \frac{E_0}{2R_c^2 R_{cr}\eta\sqrt{\pi\omega} f\rho c A} \qquad (4)$$

In the above Eq. (4) f is the frequency of ultrasound, A is the amplitude of the signal, c is the speed of sound, ρ is the density of the media, and η characterizes the percentage of energy of the ultrasonic treatment, which goes to bond destruction. Thus, by increasing the amplitude of the ultrasound the treatment time can be reduced. Based on this the following operating parameters were chosen for the equipment: operating frequency was equal 18 kHz, the generator output power was up to 10 kW, the energy delivered through the cable to the downhole tool was up to 5 kW.

3. Field experiments and discussion

In order to verify the method of selective ultrasonic treatment of horizontal wells a field test has been carried out.

A horizontal well of the Samotlor oilfield with the following parameters has been chosen for treatment, which was a typical example of a horizontal well with a high water cut in Siberia. The reservoir type was AB 1(3). The initial parameters of this well were: fluid production – 25 tons/day, oil production – 32.9 bbl./day, water cut – 80%.

The following operations were carried out during capital workover of the well:

The packer and the jet pump were installed on the tubing as shown in Fig. 7 and lowered to the perforation zone.

After that the ultrasonic downhole tool with the geophysical probe is lowered to the perforation zone on the special cable. The geophysical studies are carried out while pressure difference is obtained using the jet pump. Based on the measurements the treatment intervals are determined.

The results obtained in the test well after interpretation of the measured data are presented in Fig. 8. Gamma-ray logging and magnetic collar location determination is done only for referencing. In case of temperature only the temperature change is relevant, since a drop of temperature is an indication of flow. The geothermic gradient (one step) by default is equal to 3 degrees per 100 m of formation. The sensors of a termoconductive flow meter are temperature sensors, heated to a specific temperature. During geophysical studies the termoconductive flow meter shows the real changes of the geothermal gradient in conventional units. During interpretation of the data the flow is determined qualitatively. Line five on the graph below shows a qualitative characteristic of the flow into the well in conventional units. The measured deviations from the typical parameters were ±15 degrees. The resistivity is a characteristic of the specific resistance of the rock and the fluid. Interpretation is carried out using tabular data. Resistivity changes are relevant for detection of water content in the fluid.

In case of this well according to the data of the oil producing company the productive layer was located between 1972.03 and 2049.48 m. But the geophysical studies revealed, that the zone between 1955 m and 2049.48 produced mainly water, probably due to its vicinity to the oil–water contact. Thus only the interval between 1892 and 1909 m was chosen for treatment.

After geophysical studies the chosen interval was treated with the ultrasonic downhole tool. During treatment flow was obtained

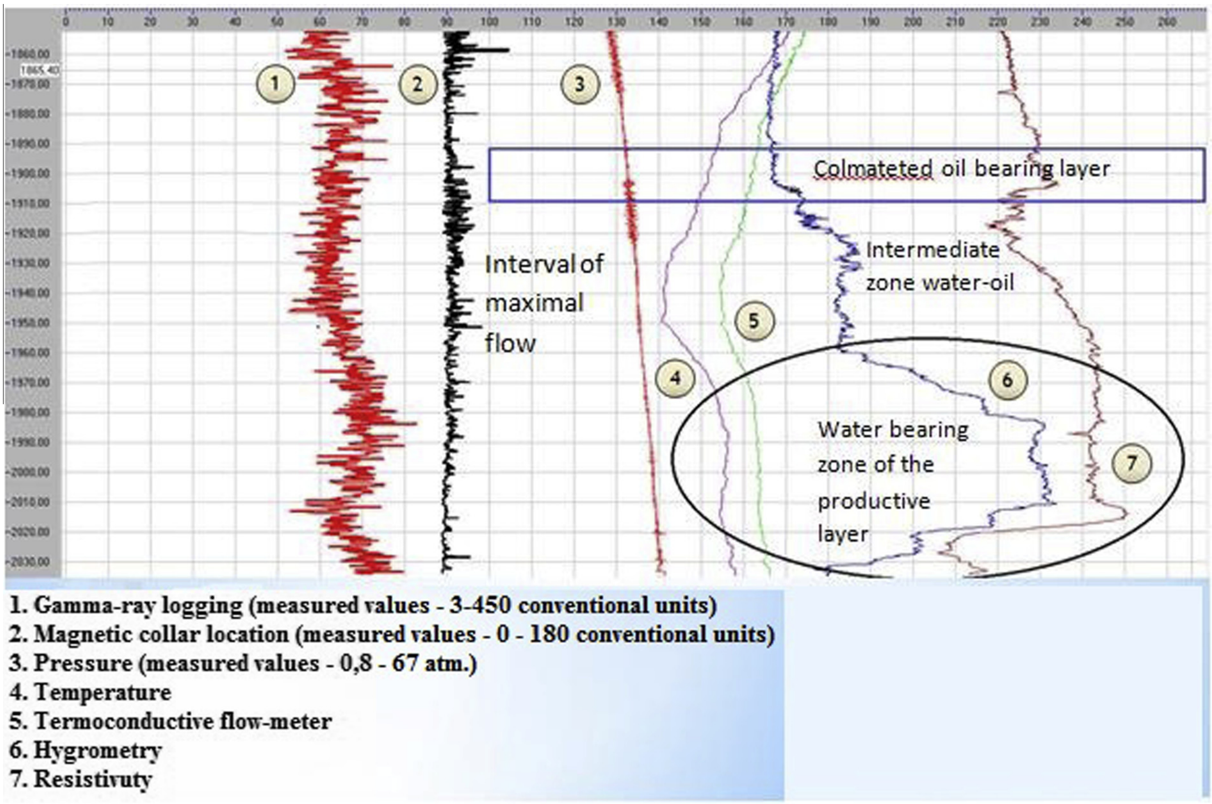


Fig. 8. Results of geophysical studies of the well.

Table 1
Results of the selective ultrasonic treatment of a horizontal well.

Parameter	Before treatment	After treatment	Difference
Fluid production, tons/day	28	26	−2
Oil production, bbl./day	32.9	63	30.1
Water cut, %	80	59.3	−20.7

in the treatment zone using the jet pump. This was crucial in order to insure removal of the deposits.

The results of the selective ultrasonic treatment of the horizontal well are presented in Table 1.

4. Conclusions

A method of selective ultrasonic treatment of the perforation zone of horizontal wells has been developed.

Theoretical estimations and computer modeling revealed, that the position of the downhole ultrasonic tool near the sidewall of the well leads to more homogeneous distribution of the induced acoustical field and wider penetration of the acoustical waves. However in order to reduce the treatment time a magnetostrictive push–pull construction of the downhole tool with the diameter of 44 mm was used. Its acoustical impedance was matched with the acoustical impedance of the cable and the ultrasonic generator, which enabled us to deliver up to 5 kW to the ultrasonic probe.

The developed method was tested on a horizontal well in Western Siberia, which was characterized by high water cut.

During treatment a specially developed jet pump for horizontal wells was used to create flow in the well. This enabled us to carry out geophysical studies prior to the treatment and select optimal zones for selective treatment.

Based on geophysical studies only zones with low water and high oil production were treated, this lead to a decrease of the water cut by 20% and an increase of oil production by 91% after treatment of the test well.

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