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Ultrasonic technology for enhanced oil recovery from failing oil wells and the equipment for its implemention

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ABSTRACT

A new method for the ultrasonic enhancement of oil recovery from failing wells is described. The technology involves lowering a source of power ultrasound to the bottom of the well either for a short treatment before removal or as a permanent placement for intermittent use. In wells where the permeability is above 20 mD and the porosity is greater than 15% ultrasonic treatment can increase oil production by up to 50% and in some cases even more. For wells of lower permeability and porosity ultrasonic treatment alone is less successful but high production rates can be achieved when ultrasound is applied in conjunction with chemicals. An average productivity increase of nearly 3 fold can be achieved for this type of production well using the combined ultrasound with chemical treatment technology.

1. Introduction

Despite the ever increasing interest in alternative green sources of energy to replace fossil fuel the search for new oilfields and the expansion of existing fields continues to be a prime aim of energy companies. Within existing oilfields there are many wells which have diminishing returns in terms of rate of extraction and yet may still contain large reserves of oil. These reserves are a great resource but recovery is not economic unless some form of downhole intervention can be used to release them.

In Western Siberia from 2000 until 2010 the main approach to the rejuvenation of failing oil wells has been through the use of hydrochloric acid and clay-acid treatment which are useful for removing blockages caused by limestone and dolomite. However the average efficiency of these treatments (defined as the additional production obtained after treatment) decreases after multiple applications from a figure of the order of 6 tons per day to 2 tons per day. To combat this reduction in efficiency larger volumes of acid solutions must be used inside the well. This is becoming less attractive because of the ever increasing cost of the chemicals. As a result there has been a sharp reduction in the number of acid treatments in clastic reservoirs i.e. reservoirs formed from fragmented rocks. In this context, the search of alternative technologies for intensification of oil recovery, in particular, based on the physical disruption of the strata at the bottom of the oil well (the bottomhole zone BHZ) has become urgent. One of the most promising of the modern technologies is the use of ultrasound or ultrasound applied together with chemicals treatment of the BHZ [1–3].

The effects of cavitation induced by ultrasound in liquid media and its influence on chemistry and processing has been studied for many years under the umbrella title of sonochemistry [4–6]. On the other hand the interaction between ultrasound and porous solid materials containing fluids has been less extensively studied although the washing of soils using ultrasound has proved successful [7,8]. This is closely related to the type of application of interest here i.e. the effects of ultrasound on subterranean oil trapped in surrounding rocks. Both of these processes require the penetration of a fluid into solid matrices, the break-up or deaggregation of minerals and leaching out of entrapped materials. In the case of oil recovery the combination of ultrasonic treatment with the downhole addition of chemicals may not prove to be true "sonochemistry" but undoubtedly the combination is very effective.

In order to revitalize a "dead" oil well through the use of ultrasound there are two aspects of sonication that are relevant (a) enhancement of the flow of oil through the rocks into the pumping pool and (b) reduction of the viscosity of the oil that would make it easier to pump. Certainly downhole sonication has been a subject of potential interest in the oil industry but up until now there have

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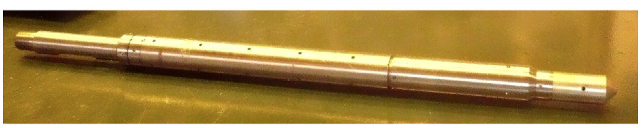
Table 1
Technical characteristics of the ground generator MUG 10/20-27.

Output power (kW)	10
Operating frequency (kHz)	18 – 27
Efficiency (%)	Not less than 85

(a)



(b)

Fig. 1. Photographs of the downhole tools (a) SP-42/1300 and (b) SP-102/1270.

been questions about the mechanism of such an effect and more importantly whether it could be applied in a real downhole situation.

The early use of sound to revitalize oil wells involved audible sound i.e. sonic waves of a much longer wavelength than ultrasound, often termed seismic waves. One of the oldest patents was taken out in 1939 [9]. The theory behind this was that when such a wavelength passes through porous media it will be dispersed into higher harmonics (ultrasonic waves) producing a series of effects that include: disruption of the surface film, coalescence of oil drops together with oscillation and the excitation of oil drops trapped in capillaries. The effect of ultrasound on oil trapped in capillaries has been investigated [10].

In this study we provide practical evidence obtained directly from oil well experiments which show conclusively that the use of ultrasonic downhole stimulation of oil wells is a viable process [10].

2. Equipment for ultrasonic and combined ultrasound with chemical treatment of the bottomhole zone (BHZ) of oil wells

The equipment for the combined ultrasound with chemical treatment of the BHZ consist of two parts, an above ground generator and a downhole ultrasonic tool, connected by a cable of the type used for the electronic logging of information. The technical characteristics of the generator are shown in Table. 1.

For ultrasonic treatment of the BHZ a downhole tool is employed SP-42/1300 or SP-102/1270 (depending of the well type), both are driven by magnetostrictive transducers. These tools provide radial vibrations through radiating surfaces and are shown in Fig. 1. The operating frequency of both tools is 25 kHz. The power of SP-42/1300 is 5 kW. The power of Sp-102/1270 is 10 kW.

- A short-term downhole treatment tool with a diameter of 42 mm (SP-42/1300 can be deployed in the producing zone of the well using a standard cable. It is used to treat the well when it has stopped pumping e.g. while undergoing a major maintenance or remedial treatment. The tool is dropped into the well to an operating depth of up to 5000 m. The treatment zone is determined based on geophysical data (such as flow profile) and the tool can be placed with a depth accuracy of around 1 m. The mechanism of its action has been described [11]
- A second type of downhole tool with the diameter 102 mm (SP-102/1270) can be put in place on a more permanent basis and is periodically switched on during the day. The tool is fixed on to the well casing. This device is designed for use in wells with heavy and high-viscosity oil because such wells are more subject to clogging and so ultrasonic cleaning must be done more frequently. The power is supplied via a cable like that used for centrifugal pumps and it is lowered by a similar process to that used for submersible pumps.

Both ultrasonic downhole tools provide similar physical effects: firstly, the high energy ultrasonic vibrations generate high particle accelerations so that the colmatants and asphaltene-paraffinic deposits are dislodged from the rock, i.e. the porous media is cleaned, secondly, the viscosity of oil is reduced due to destruction of micelles, this make the liquid media more mobile [12–14]. The differences between the two tools are the periodicity of treatment and the power.

The tools can be used either alone (for acoustic treatment) or in conjunction with chemicals which are injected at the same time as the tool is operating. In the case of combined ultrasound with chemical treatment the chemicals are delivered into the BHZ using a downhole pipe equipped at the end with a spray bar. This allows for the injection of the liquid mixture of organic and mineral reagents into the downhole region. The major advantage of using the ultrasonic tool in conjunction with these chemicals is that it will force a greater penetration of the chemicals into the region surrounding the BHZ due to the sonocapillary effect [15].

The most commonly used chemicals for production and injection well cleaning are solutions of acids (5–20% hydrochloric acid, hydrofluoric acid, sulfuric acid, etc.), with the addition of various inhibitors and surfactants to protect metal parts and the well casing. However there are some negative factors associated with the use of acids:

- it reduces the life of equipment and wells;
- it requires precautions to be taken for staff safety;
- all equipment used must be cleaned by washing with water;
- it is harmful to the environment.

For these reasons alternative more environmentally friendly oil well cleaning systems were developed by the Institute of Oil Chemistry of the Siberian Department of the Russian academy of Sciences [16]. Two of these IHN-60 and IHN-100 were used for the combined ultrasound with chemical treatment of production wells and are compositions based on surfactants and an ammonium buffer system. The components are inexpensive industrial products obtainable on a large scale and can also provide nitrogen based nutrients for the native reservoir flora. For each treatment 2 m^3 of reagents are used.

Their general properties are:

- mobile light or dark yellow liquids, density 1.050–1.070 g/cm^3 and pH at least 9.7 fireproof and explosion-proof.
- have low adsorption on the reservoir rock;
- increase the rate of filtration of liquid in the reservoir by 1.5–3 times;
- destroy interfacial layers on the border oil-water-rock;
- emulsify the oil-water emulsion.

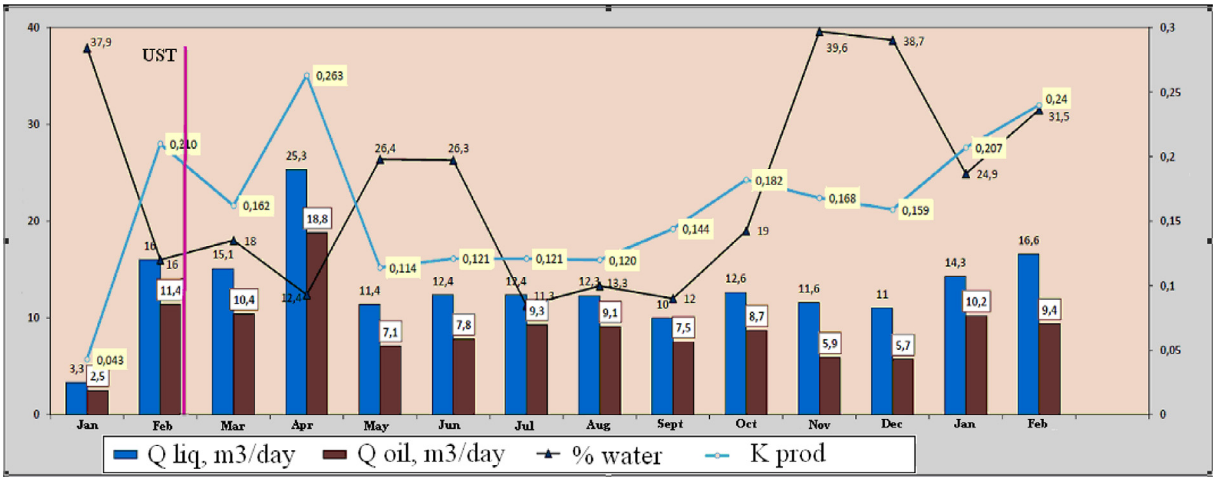


Fig. 2. Dynamics of flow rates before and after the ultrasonic treatment of well no. 34686: Q_{liq} – the daily production rate of fluid, Q_{oil} – the daily oil production rate, % water – percent water cut, K_{prod} – productivity coefficient.

The reagents may be used under different reservoir conditions, in reservoirs with the temperatures between 20 and 120 °C and permeabilities between 5 and 500 mD. The reagents are most effective on wells with low permeability. The syntheses of IHN-60 and IHN-100 are described in TU 2458-058-17197708-01 (in Russian).

Tests have shown that the combined ultrasound with chemical treatment of the BHZ is most effective when low pressure is created simultaneously in the well. Several different ultrasonic BHZ treatments in combination with known methods for enhanced oil recovery have been studied during field tests [17].

3. Field tests results

In the oil industry the wells are classified by type and those found in Siberia are divided locally into:

- AB reservoirs (permeability 20 mD and higher, porosity of 15% and above)
- BC reservoirs (permeability less than 20 mD, porosity of less than 15%)

67 producing oil wells (66 producing wells and 1 injection well) on AB reservoirs were treated in 2011 during field testing of the ultrasonic technology on the Samatlor oilfield (Western Siberia). Results proved positive on all but two of these wells.

On wells located on BC reservoirs ultrasonic treatment alone proved to be ineffective. In these cases (2 injection wells and 6 producing wells) the treatment used in 2011/2012 was a combination of ultrasound and chemical injection.

The effect of sonication on the wells lasted from between 6 months to one year after the first treatment (for both: ultrasonic treatment of wells on AB reservoirs and the combined ultrasound

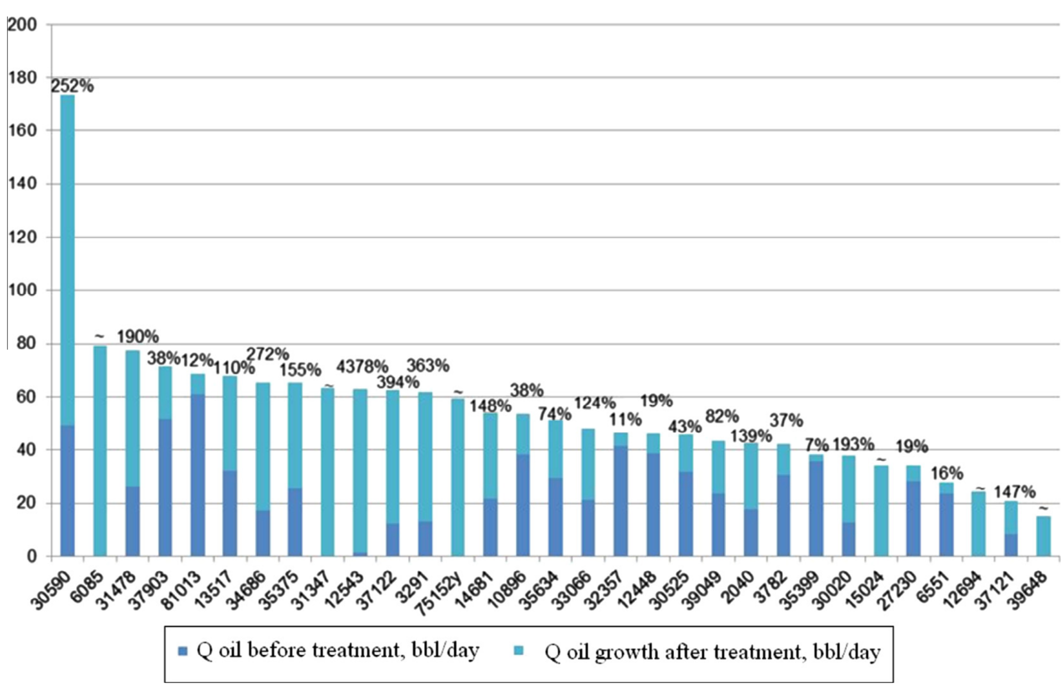


Fig. 3. Production changes after the ultrasonic treatment of the BHZ of wells in AB reservoirs.

Table 2
Average production parameters before and after ultrasonic treatment.

	Parameter	Before ultrasonic BHZ treatment	After ultrasonic BHZ treatment
1	Average flow rate of oil wells (tons)	3.17	7.62
2	Average water cut of oil wells (%)	49.5	36.6
3	Average productivity coefficient of oil wells	0.12	0.25

Table 3
Average production parameters of production oil wells (BC reservoir) before and after combined ultrasound and chemical treatment.

	Parameter	Before sonochemical treatment	After sonochemical treatment
1	Production per day (tons/day)	2.9	8.1
2	Percentage of water (%)	48.5	35.1
3	Production coefficient	0.14	0.29

with chemical treatment of wells on BC reservoirs). For many of these wells an improvement is still present.

The flow rates dynamics of the well number 34686 on the Samotlor field (a typical example of a well on an AB reservoir) before and after ultrasonic treatment is shown in Fig. 2. Here the productivity coefficient is the ratio of the well production to the difference of the pressure in the reservoir and the pressure in the well.

Analysis of Fig. 2 shows that ultrasonic treatment of the well leads to an increase of the productivity coefficient and to a decrease of the percentage of water in the fluid. A clearly visible effect lasts for 3 months, but even after that period the average daily oil production is approximately 2–3 times higher than before the treatment and the effect of deposit removal by ultrasound lasts up to a year.

Fig. 3 shows the production changes after the ultrasonic treatment of the BHZ of 30 wells in AB type reservoirs and the average results of treatments for all wells are presented in Table. 2.

Fig. 3 and Table 2 show that the average daily production rate of oil wells increased by a factor of 2.4, and the average productivity coefficient doubled. The average water cut of the treated oil wells decreased by 26%, due to the selective nature of ultrasonic treatment on different layers. The absolute increase of the average daily production rate of all wells was 4.45 tons.

These numbers are comparable to those obtained using other methods of intensification used in Western Siberia. For example, the average absolute production rate increase after hydro fracturing is 6.1 tons/day and after reperforation (the creation of new holes in the oil well tubing opposite to oil-bearing reservoir zones) and hydrochloric acid treatment is about 2–3 tons/day. However the cost of an ultrasonic treatment is much less than the others at about 8 200 Euros compared with the cost of hydrochloric acid treatment (20 m^3) of about 12 400 Euros, and the cost of hydro fracturing of about 22 350 Euros.

The results obtained suggest that this type of ultrasonic treatment is especially effective on AB reservoirs where the major factor that determines flow rate in the BHZ is the reduction in bottom-hole pressure. Such treatment has a significant impact on the reduction of solid particulate impurities (colmatants) that block the porous channels around the reservoirs.

As mentioned above on BC type reservoirs ultrasonic treatment alone is not so successful however for such wells the combined treatment proved to be very effective. This was shown during field tests on two injection wells (51240 and 51220) that were treated with chemicals and ultrasound. A third injection well 6550 was subjected to ultrasonic treatment only (to compare the effect of ultrasonic treatment and the effect of combined treatment). The experimental results are shown in Fig. 4 where Q is the amount of liquid injected into the well per day (it is measured in m^3 per day) and the injectivity change means the change of the amount of liquid that is injected inside the well during one day. It can be clearly seen that a synergetic effect of ultrasound and the chemical treatment is achieved.

The results of combined ultrasound with chemical treatment on producing wells are shown in Table 3. These are average results for all 6 wells.

The production increase is significantly higher after combined treatment (5.2 tons/day) compared with only ultrasonic (0.14 tons/day) or chemical treatment alone (1 ton/day).

4. Modeling of the influence of the combined ultrasound with chemical treatment of the BHZ on oil recovery

It is not possible to recover all the oil in a given reservoir and typically recovery factors (the ratio of recoverable oil reserves to the oil in place in a reservoir) lie in the range 30–60%. In assessing the role of ultrasonic treatment it was assumed that regular ultrasonic treatment of the BHZ results in an effective increase in the perforated area thickness. In order to estimate the effect of combined ultrasound with chemical treatment on the oil extraction

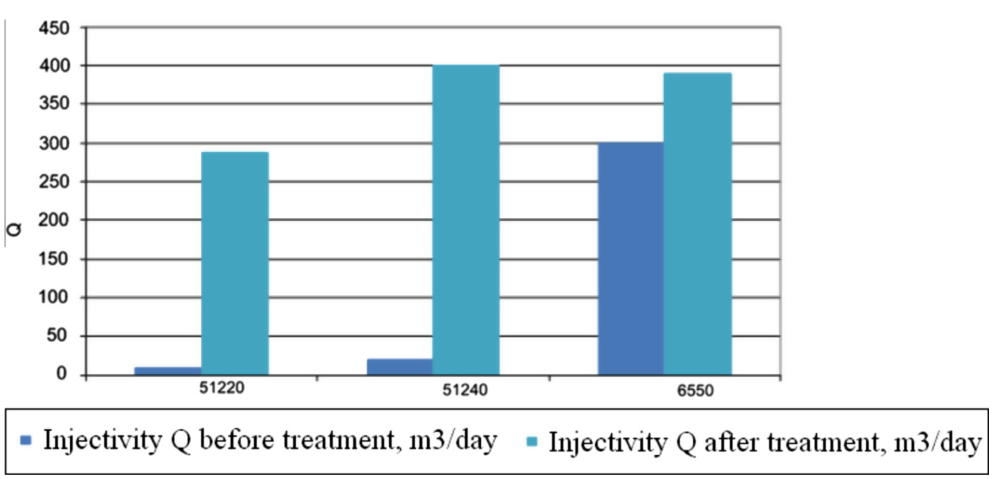


Fig. 4. Injectivity change of injection wells in BC reservoirs after combined ultrasound and chemical treatment.

percentage this increase was modeled in conjunction with the practical work conducted in the oilfields in terms of the recovery factor (RF) i.e. the percentage (or efficiency) of oil extraction from the reservoir. The model used the software package ECLIPSE (developed by Schlumberger). Using this model the dynamics of oil production were modeled using the following average parameter values: effective oil saturated thickness – 6.9 m, porosity – 0.17, initial oil saturation – 0.787, initial oil reserves 212.4 thousand tons, the size of the computational grid cells 100 × 100 × 1 m.

For the hydrodynamic calculations an isothermal two-phase three-component (oil, water, gas dissolved in oil) model of a weakly compressible fluid under filtration in a porous medium was used. The displacement efficiency was assumed to be 0.52 and the viscosity of the oil – 1.76 cP. The model site consists of a group of wells allocated according to a five point grid with a distance of 500 m.

The bottomhole pressures are different depending on the type of well. Thus for the simulation a number of parameters were assumed. A producing well has a bottomhole pressure of 77 atm. which is 3 atm. higher than the saturation pressure and an injection well has a bottomhole pressure of 250 atm. and this requires a factor for the overpressure for extraction by injection of 1.1.

The economics of hydrocarbon production from wells are such that wells are typically shut in when oil production is less than 1 m^3/day with a water cut of >98%. Calculations were performed for two average area permeabilities, which were 13 mD and 114 mD.

The calculated dynamic rates of daily oil production for average permeabilities of 13 mD (case without ultrasonic treatment) and 114 mD (case after ultrasonic treatment) are shown in Fig. 5a and b, respectively. The different options on the graph refer to

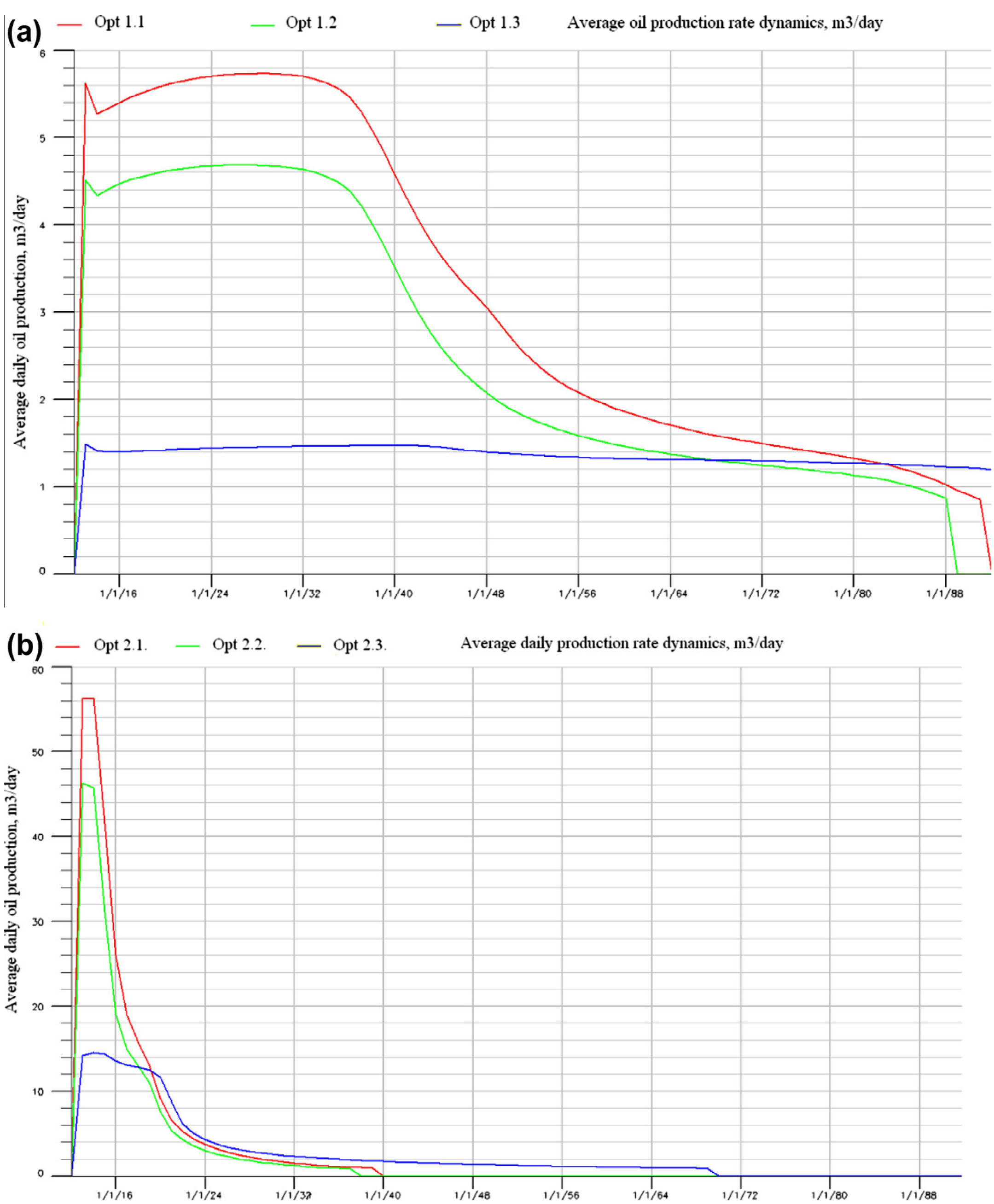


Fig. 5. Dynamics of average daily oil production for an area with permeability 13 mD (a) and 114 mD (b).

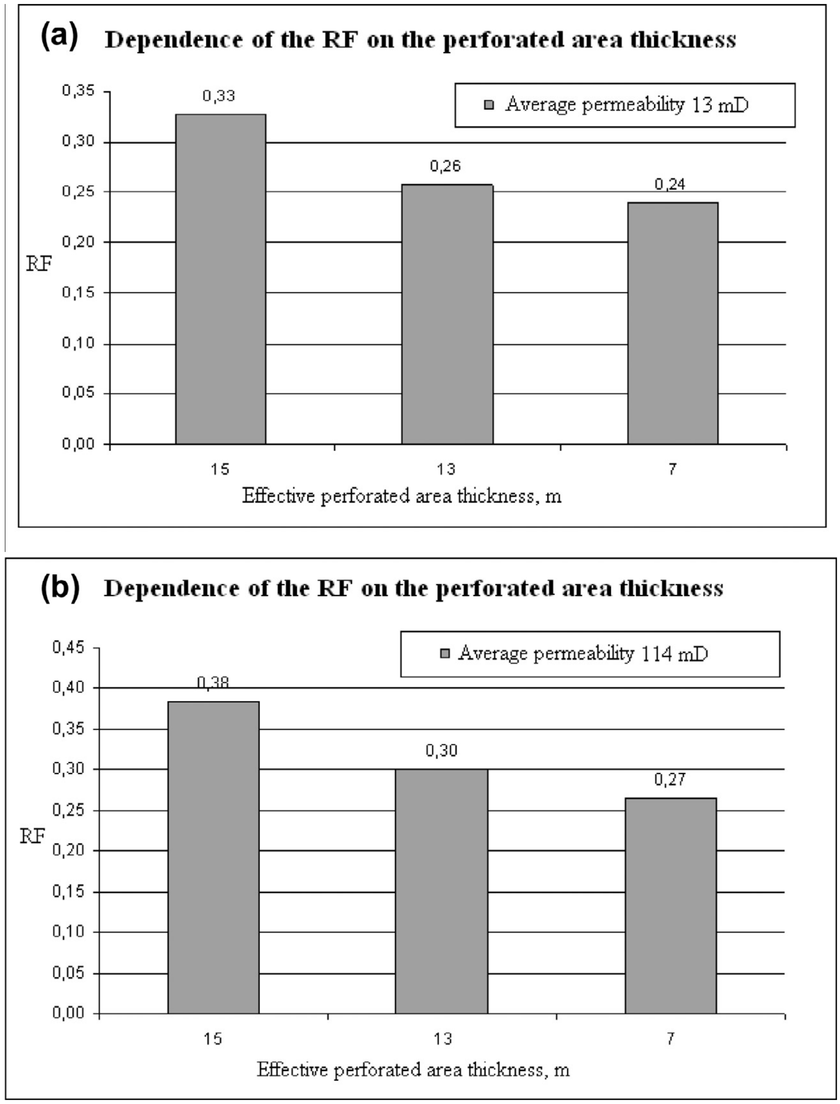


Fig. 6. Dependence of the recovery factor on the perforated area thickness for an area with permeability 13 mD (a) and 114 mD (b).

different effective perforated area thicknesses (15 m, 13 m and 7 m respectively).

The calculations predict that for an area with high permeability the period of increase in production will reduce due to intensive extraction during the initial period. The calculations also show that there is a uniform reduction of the RF with a decrease in the effective thickness of the perforated zone. Thus, the model predicts that regular combined ultrasound with chemical treatments appreciably affect not only the dynamics of the average daily oil production rate, but can also lead to an increase of the RF (Fig. 6).

5. Conclusions

The research revealed that ultrasonic technology can significantly enhance oil recovery by 30–50% or more on wells with permeability higher than 20 mD and porosity higher than 15%. The methodology is simple, environmentally safe and is successful for the appropriate types of well in up to 85% of cases. The effect of ultrasonic treatment lasts from 3 to12 months or longer. The method increases the permeability of the bottomhole zone and can alleviate blockages due to the presence of mineral particles. On reservoirs with lower permeability and porosity ultrasonic treatment proved to be ineffective. For these wells a method combining ultrasound with chemicals has been developed and tested on production and injection wells. The production for such wells is significantly higher after combined ultrasound with chemical treatment compared with ultrasonic or chemical treatment alone.

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