Development of ultrasonic equipment and technology for well stimulation and enhanced oil recovery

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ARTICLE INFO

Article history:
Received 4 December 2013
Accepted 24 October 2014
Available online 2 December 2014

Keywords:
enhanced oil recovery (EOR)
asymmetric well stimulation
ultrasound
ultrasonic treatment
ultrasonic equipment
ultrasonic technology

ABSTRACT

An ultrasonic well module and an ultrasonic technology for oil well stimulation and enhanced oil recovery are developed. The parameters of the ultrasonic radiating systems of downhole tools are calculated, and their optimization is performed. The conducted field tests of the ultrasonic well module as a part of an ultrasonic well complex in oil fields in Russia (Western Siberia and Samara Region) and the United States indicate a high efficiency of the developed equipment and technology. The developed ultrasonic equipment and technology can be offered to oil-producing companies as one of the promising methods for well stimulation and enhanced oil recovery.

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1. Introduction

In recent years, oil recovery remains to be a challenge in the world. The average values of an oil recovery factor, which characterizes the ratio of recoverable oil reserves to the oil in place, vary from 0.25 to 0.5 in the world at present. In the USA beginning from 1990, the oil recovery factor has increased from 0.35 to 0.41. In Russia over the same period, the oil recovery factor has decreased from 0.39 to 0.31 and continues to decrease. It has been calculated that an increase in the average oil recovery factor for the world industry by only 1% is equivalent to an increase in global recoverable oil reserves by approximately 4.5 billion tons. The oil recovery factor for the fields serviced by the most progressive oilfield companies reaches up to 50% due to the application of advanced methods for enhanced oil recovery.

The applied methods of electromagnetic or wave treatment use the physical fields of various natures, rather than a substance, as a "working agent". These methods are less resource- and energy-intensive and economically more expedient in comparison with those used at present. According to a few studies (Workin and Chant Sharp, 1985; Kobayashi et al., 2000; Mason et al., 2004; Amro et al., 2007; Hamida and Babadagli, 2007b; Abramov et al., 2008; Calcedo, 2009; Tunio et al., 2011; Hamidi et al., 2012), acoustic treatment, in particular, in the ultrasonic range, is one of the most promising techniques among wave methods for increasing well production rates. The efficiency of this method can be substantially increased due to the development of high-efficiency equipment, the correct selection of candidate wells, and the mathematical modeling of physical processes that accompany acoustic well stimulation (Mullakaev et al., 2008, 2009a, 2009b; V.O. Abramov et al., 2012; Abramov et al., 2013).

The early use of sound to revitalize oil wells involved sonic waves of a much longer wavelength than ultrasound (often termed seismic waves) which were used to restart the flow. One of the oldest patents was taken out in 1939 (Brammer, 1939). The theory behind this was that when such a wave passes through porous media it will be dispersed into higher harmonics (ultrasonic waves) producing a series of effects that include: the disruption of the surface film, the coalescence of oil drops together with oscillation, and the excitation of oil drops trapped in capillaries. The theory underlying the use of ultrasound for oil recovery continues to be of interest (Hamida and Babadagli, 2007b).

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 (V. Abramov et al., 2012).

This study deals with the development of an ultrasonic well module and an ultrasonic technology for well stimulation and enhanced oil recovery and their field testing as a part of an ultrasonic well complex in oil fields in Russia (Western Siberia and Samara Region) and the United States.

2. Calculation of ultrasonic radiating system of downhole tool PSMS-42

A downhole tool PSMS-42 is a waveguide made of titanium alloy BT6 with magnetostrictive transducers connected on each side (Fig. 1). Protective housings are welded on at the locations of

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http://dx.doi.org/10.1016/j.petrol.2014.10.024
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the nodes of waveguide vibrations. The waveguide consists of two symmetric parts joined by welding. The magnetostrictive transducers manufactured from permendur plates have a vibration resonance frequency of 19.963 kHz.

When a vibration system is designed, its dimensions should be calculated so that the frequency of its mechanical resonance is in the frequency range of electrical resonance in the generator-electroacoustic transducer system, at which the maximum values of vibration quantities that determine to a considerable extent the efficiency of ultrasonic treatment are attained.

To calculate the natural frequencies of solids, the homogeneous Helmholtz equation was used (Gallagher, 1975):

\[
\nabla \left( \frac{1}{\rho_m} \nabla p \right) - \frac{\omega^2 p}{\rho_m c^2} = 0,
\]

where \( p = P_0 e^{\text{det}} \) is the acoustic pressure, \( N/m^2 \); \( P_0 \) is the amplitude of acoustic pressure, \( N/m^2 \); \( t \) is time, \( s \); \( \rho_m \) is the density of the medium, \( kg/m^3 \); \( c \) is the sound velocity, \( m/s \); \( \omega = 2\pi f \) is the angular frequency, \( Hz \); and \( f \) is the natural frequency, \( Hz \).

The eigenvalue \( \lambda \) is related to the natural frequency by the following equation:

\[
\lambda = 4\pi f = \omega.
\]

The velocity of a longitudinal wave is

\[
c_p = \sqrt{\frac{K + 4 \mu}{\rho_m}}
\]

where \( K = E/(3(1-2\nu)) \) is the bulk modulus, \( G = E/(2(1+\nu)) \) is the shear modulus, \( E \) is the modulus of elongation, and \( \nu \) is Poisson’s ratio.

The velocity of a transverse wave is

\[
c_s = \sqrt{\frac{G}{\rho_m}}
\]

The finite element method was used to solve the Helmholtz equation (Desciaux, 1973; Vladimirov and Zharinov, 2004).

To increase the accuracy of calculations, the physicomechanical characteristics of titanium alloy BT6 were refined, and natural frequencies in the range of 0–20,000 Hz were experimentally determined for a workpiece with a diameter of 45 mm and a length of 1102 mm. In the COMSOL Multiphysics environment, the physical characteristics of material BT6 were refined using computational modules (they compute the natural frequencies of solids by Eqs. (1)–(4)) and the finite element method (Table 1):

\[
E = (1.175 \pm 0.005) \times 10^{11} \text{ [Pa]}, \quad \rho_m = 4505 \pm 39 \text{ [kg/m}^3].
\]

In the COMSOL Multiphysics environment, with the help of modules for computing the vibrations of solids, which employ Eqs. (1)–(3), the dimensions of a waveguide were calculated using the finite element method and the refined physicomechanical characteristics of titanium alloy BT6. Fig. 2 shows the ultrasonic vibration system of the downhole tool PSMS-42.

A waveguide-radiating system of the downhole tool PSMS-42 was manufactured from titanium alloy BT6 according to the developed drawing.

Fig. 3 presents the vibration spectrum of the manufactured individual link of a waveguide.

The resolution of frequencies in the experimental curve is 43 Hz. As can be seen from Table 2, calculated and experimental acoustic characteristics agree within the error limits, from which it follows that the calculation of natural frequencies by Eqs. (1)–(3) using the finite element method in the COMSOL Multiphysics environment yields satisfactory results.

The performed calculations of the natural frequencies of the whole waveguide have shown that the mode of longitudinal vibrations with three nodes that is of interest to us corresponds to 19,969 Hz.

The natural frequency of the entire vibration system (a waveguide-radiating system with two magnetostrictive transducers) is 19,968 Hz (Fig. 4).

3. Development and bench testing of ultrasonic well module MSUM

An ultrasonic well module MSUM based on magnetostrictive radiators consists of surface and downhole equipment. The module was calculated and designed by the authors and was manufactured at the Kurnakov Institute of General and Inorganic Chemistry.

Surface equipment includes an upgraded ultrasonic generator TS10W that consists of the following main units: power supply unit; amplifier unit; biasing unit; and control unit. In contrast to previous-generation generators, the controller of the new

![Fig. 1. Downhole tool PSMS-42: 1 - waveguide, 2 - cable lug, 3 - transport plug, 4 - fairing, and 5 - magnetostrictive transducer.](image)

![Table 1 Experimental and calculated natural frequencies of a workpiece made of titanium alloy BT6.](image)

<table>
<thead>
<tr>
<th>Mode</th>
<th>Frequency (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculation</td>
<td>Experiment</td>
</tr>
<tr>
<td>One node</td>
<td>2316</td>
</tr>
<tr>
<td>Two nodes</td>
<td>4627</td>
</tr>
</tbody>
</table>

![Fig. 2. Ultrasonic vibration system.](image)
generator includes a unit that ensures the receipt of data on pressure and temperature in a well from a downhole tool, their processing and transmission to an external computer.

Downhole equipment consists of downhole tools with magnetostrictive transducers with a diameter of 42 mm (PSMS-42) and a diameter of 102 mm (PSMS-102), which are made in the form of a hollow cylinder, that transform excited longitudinal elastic vibrations into radial vibrations that affect the near-wellbore region.

The final choice of a waveguide-radiating system was performed using the results of experiments on a test bench shown in Fig. 5. The diameter of the high-pressure chamber of the test bench was selected to be close to the diameter of the casing of an oil well. In addition, it was taken into account that the effective zone of ultrasonic treatment is a region with a radius of 1–2 m depending on geological and technological characteristics of wells (Kuznetsov and Yefimova, 1983). The efficiency of the operation of waveguide systems was estimated by measuring the vibration amplitude of the lateral surface of the chamber using special sensors.

As a result of calculations and experiments, a series of downhole tools PSMS-42 and PSMS-102 based on magnetostrictive transducers is developed that makes it possible to perform the treatment of the near-wellbore area in the frequency range from 13 to 26 kHz at a radiated acoustic power from 2 to 10 kW.

The technical characteristics of downhole tools PSMS-42 and PSMS-102 are given in Table 3.

The main units of the downhole tool PSMS-102 are shown in Fig. 6.

4. Field testing of ultrasonic well module MSUM

The studies have shown (Watkins and Chant Sharp, 1985; Kobayashi et al., 2000; Mason et al., 2004; Hamida and Babadagli, 2007b; Abramov et al., 2008, 2013; Mullakaev et al., 2008, 2009a, 2009b; Tunio et al., 2011; V.O. Abramov et al., 2012) that under the effect of an acoustic field a large complex of physicochemical processes is initiated in rocks and formations, from which the following are the most pronounced and most studied:

1. destruction of stable bonds at the interface between the pores and the fluid that hinder the motion of the liquid under the effect of vibrational energy created in an elastic field by ultrasound;
2. alteration of the rheology of a fluid and bringing the properties of high-viscosity oil closer to the properties of a Newtonian fluid;
3. complete coverage of formation thickness by elastic vibrations, including interlayers with low filtration characteristics; and
4. destruction of mineral scale and deoiling.

It is found (Apašov et al., 2011, 2012) that when selecting candidate wells for the ultrasonic treatment of the near-wellbore region, it is necessary to be guided by the criteria given in Table 4.

Field tests were performed in Western Siberia and Samara Region by the oilfield service company CUT-Service with the direct involvement of the authors. Test programs and procedures were developed by the authors, and the mounting and dismounting of ultrasonic downhole tools and the check of the efficiency of the
Table 3
Technical characteristics of downhole tools PSMS-42 and PSMS-102.

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PSMS-42</td>
</tr>
<tr>
<td>Allowable depth of submergence into the well, m</td>
<td>Up to 3000</td>
</tr>
<tr>
<td>Operating mode</td>
<td>Cylindrical</td>
</tr>
<tr>
<td>Power consumption, kW</td>
<td>No more than 1.6</td>
</tr>
<tr>
<td>Resonance frequency, kHz</td>
<td>4 ± 1</td>
</tr>
<tr>
<td>Bias current, A</td>
<td>90 ± 30</td>
</tr>
<tr>
<td>Impedance at the resonance frequency, Ohm</td>
<td>380/480 (50 Hz)</td>
</tr>
<tr>
<td>Power supply, V</td>
<td>0.42 x 1340</td>
</tr>
<tr>
<td>Dimensions, mm</td>
<td></td>
</tr>
<tr>
<td>Mass, kg</td>
<td>No more than 8</td>
</tr>
<tr>
<td>Ingress protection rating according to GOST 14.254</td>
<td></td>
</tr>
<tr>
<td>Operating conditions</td>
<td>From +5 to +100</td>
</tr>
<tr>
<td>Ambient temperature, °C</td>
<td>No more than 35</td>
</tr>
<tr>
<td>Hydrostatic pressure, MPa</td>
<td></td>
</tr>
<tr>
<td>Lifetime</td>
<td></td>
</tr>
<tr>
<td>Mean-time-between-failures, h</td>
<td>No less than 1000</td>
</tr>
<tr>
<td>Overhaul period, h</td>
<td>2800</td>
</tr>
</tbody>
</table>

Fig. 6. Main units of the downhole tool PSMS-102: 1 – reducer NKT-60, 2 – cable lug, 3 – magnetostrictive radiator, 4 – hydrocompensator of excess pressure, 5 – housing of the tool, 6 – housing of the magnetostrictive radiator, and 7 – tip.

Table 4
Criteria for selecting candidate wells for ultrasonic treatment.

<table>
<thead>
<tr>
<th>Well characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Decrease in formation pressure from the initial one, %</td>
<td>No more than 25</td>
</tr>
<tr>
<td>Current water cut, %</td>
<td>No more than 80</td>
</tr>
<tr>
<td>Number of interlayers in the perforated interval</td>
<td>No more than 10</td>
</tr>
<tr>
<td>Minimum thickness of a producing formation, m</td>
<td>3</td>
</tr>
<tr>
<td>Spontaneous potential</td>
<td>Higher than 0.5</td>
</tr>
<tr>
<td>Permeability, μm²</td>
<td>More than 0.25</td>
</tr>
<tr>
<td>Clay content, %</td>
<td>No more than 15</td>
</tr>
<tr>
<td>Decrease in the oil production rate for the last 1–2 years that is not associated with a decrease in formation pressure or technical reasons</td>
<td>2 Times or more</td>
</tr>
<tr>
<td>Dynamic viscosity under formation conditions, mPa s</td>
<td>No more than 25</td>
</tr>
</tbody>
</table>

developed technology were conducted under the supervision of the authors during the scheduled repair of wells.

The field testing of the ultrasonic well module MSUM was performed within an ultrasonic well complex that has the following equipment:

1. well logging truck hoist PKS-5G T with an umbilical cable;
2. pumping unit SIN-32;
3. tank truck ATs-10 with service water;
4. ultrasonic well module MSUM and workstation in the well logging truck hoist PKS-5G T;
5. geophysical complex Sova in the truck hoist PKS-5G T;
6. recorder of geophysical parameters Yugra in the truck hoist PKS-5G T;
7. lubricator; and
8. feeder for an umbilical cable.

The sequence of preparatory operations is as follows:

1. A well is killed, the tubing is lowered, and a packer is set (at a distance of no more than 1 m above the perforated zone).
2. The hoist and pumping unit are grounded and connected to the power supply.
3. The ultrasonic module MSUM and workstation are changed over from the position for transportation to the operating position.
4. A hose pipe for the supply of chemical reagents to the tubing is connected to the pumping unit, and power supply is connected to the distribution board 220/400 V in the hoist and then through the link to the workstation.
5. An external service tank with chemical reagents is connected through a hose pipe to the suction pipe connection of the pumping unit.
Fig. 11 shows the total change in the production rate of three wells in the course of acoustic well stimulation during May-October 2008. The historical production of three wells was 290 barrels. Well stimulation using the ultrasonic technology led to the additional production of 3476 barrels during half a year.

During the testing of equipment with a power of 10 kW, it was found that the bottomhole pressure (according to logging measurements) is 2500–3000 kPa before ultrasonic treatment and more than 6000.3 kPa after ultrasonic treatment. The difference was more than 3000 kPa.

Well stimulation was conducted during scheduled repair; therefore, total expenditures on ultrasonic treatment were considerably reduced. The average increase in the production rate after ultrasonic well stimulation was 4.45 tons (32.6 barrels) of oil per day, and the duration of the effect after treatment was not less than 6 months. In addition, it is necessary to take into account a decrease in expenditures on the pumping of water due to a considerable decrease in the water cut.

Thus, the results of field tests on restoring well productivity in the oil fields of Western Siberia and Samara Region (Russia) and the Green River Formation (United States) under various geological and physical conditions by ultrasonic treatment of the near-wellbore area indicate a high efficiency of the proposed technology, which can be considered by oil-producing companies as one of the promising methods for well stimulation and enhanced oil recovery.

5. Conclusions

(1) An ultrasonic well module MSUM consisting of an upgraded ultrasonic generator TS10W and downhole tools with diameters of 42 mm (PSMS-42) and 102 mm (PSMS-102) is developed and tested.

(2) An ultrasonic technology for well stimulation and enhanced oil recovery and the equipment for its implementation are developed.

(3) The field tests of ultrasonic well complex and technology in Russia have shown the following:

(i) average increase in the production rate after ultrasonic well stimulation was 4.4 tons per day for Western Siberia and 10.2 tons per day for Samara Region;

(ii) increase in the well productivity index was on average 33%;

(iii) decrease in the water cut of the well fluid was on average 4%;

(iv) percentage of successful treatments is up to 90%.

(4) The field tests of ultrasonic well complex and technology on high-viscosity oil in the United States have shown the following:

(i) average increase in the production rate after ultrasonic treatment was 4.45 tons (32.6 barrels) per day;

(ii) duration of the effect after treatment was not less than 6 months;

(iii) considerable decrease in expenditures due to conducting ultrasonic treatment during the scheduled repair of wells;

(iv) decrease in expenditures on the pumping of water due to a substantial decrease in the water cut of wells.

(5) The advantages of the proposed ultrasonic technology are also as follows:

(i) possibility of conducting treatment selectively;

(ii) possibility of introducing the reagents of various chemical natures into the near-wellbore zone;

(iii) low energy consumption;

(iv) absence of a negative effect on the production string and the cement sheath.
(v) absence of a negative impact on the environment and the health of operators;
(vi) considerable duration of the effect after treatment (from 4 to 24 months).

References


Which one(s) of these are critical (or most important) for the main argument(s) in this paper?