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

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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.

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 few studies (Watkins and Chant Sharp, 1985; Kobayashi et al., 2000; Mason et al., 2004; Amro et al., 2007; Hamida and Babadagli, 2007b; Abramov et al., 2008; Caicedo, 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, 2007a).

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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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):

$$\nabla\left(-\frac{1}{\rho_{\mathrm{m}}}\nabla p\right)-\frac{\omega^2 p}{\rho_{\mathrm{m}}c^2}=0, \tag{1}$$

where $p=p_0e^{i\omega t}$ is the acoustic pressure, N/m^2; p_0 is the amplitude of acoustic pressure, N/m^2; t is time, s; ρ_{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 λ is related to the natural frequency by the following equation:

$$\lambda=i2\pi f=i\omega. \tag{2}$$

The velocity of a longitudinal wave is

$$c_{\mathrm{p}}=\sqrt{\frac{K+4G/3}{\rho_{\mathrm{m}}}}, \tag{3}$$

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 ν is Poisson's ratio.

The velocity of a transverse wave is

$$c_{\mathrm{s}}=\sqrt{\frac{G}{\rho_{\mathrm{m}}}}. \tag{4}$$

The finite element method was used to solve the Helmholtz equation (Descloux, 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):

$$E=(1.175\pm0.005)\times10^{11}\ [\mathrm{Pa}],\quad \rho_m=4505\pm39\ [\mathrm{kg}/m^3].$$

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

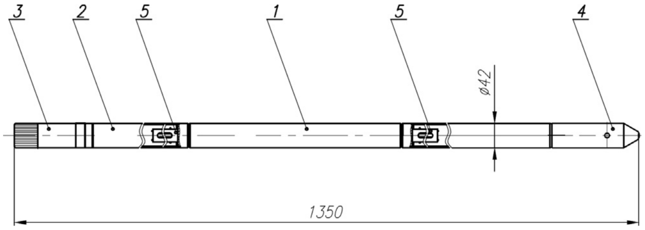

Fig. 1. Downhole tool PSMS-42: 1 – waveguide, 2 – cable lug, 3 – transport plug, 4 – fairing, and 5 – magnetostrictive transducer.

Table 1
Experimental and calculated natural frequencies of a workpiece made of titanium alloy BT6.

Mode	Frequency (Hz)	
	Calculation	Experiment
One node	2316	2336
Two nodes	4627	4594

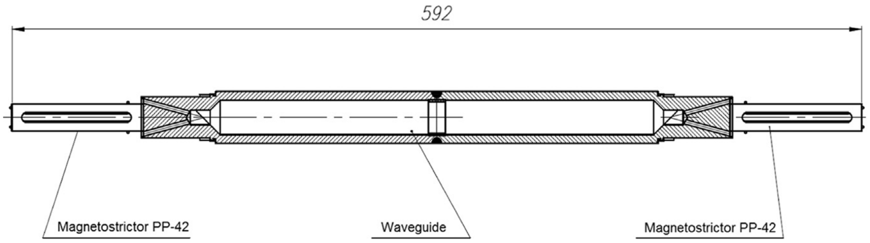

Fig. 2. Ultrasonic vibration system.