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IMPROVING THE PRODUCTIVITY OF WELLS BY MEANS OF ACOUSTIC IMPACT ON HIGH-VISCOSITY OIL IN THE CHANNELS OF THE FACE ZONE OF A WELL

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The effect of an acoustic field generated by a submersible device on the viscosity of oil present in the channels of the face zone reservoir of a well is considered. It is shown that forced vibrations of the walls of the porous structure of the stratum induce a flow of constant velocity in the viscous liquid, which may be interpreted as a decrease in the effective viscosity. An experimental verification of the calculations was performed and confirmed the reliability of the mathematical calculations and demonstrated the efficacy of ultrasound.
Keywords: *stimulation of oil production, acoustic field, face zone of well, fluctuations in a fluid, reservoir channels, effective viscosity of oil.*

Acoustic methods of stimulating oil production are based on different physical processes that occur in or are created in the face zone under the effect of ultrasound. By investigating these processes, we are able to identify the basic physical mechanisms of the phenomenon of acoustic impact, one of which is the nonlinear interaction of the ultra-sound wave with the liquid filling the porous structure of a reservoir.

Powerful acoustic radiation generated by a submersible device propagates in the face zone of a well principally through its solid structures. The porous structure of an oil reservoir consists of a set of channels, cracks, and capillaries that connect the cavities and support overflow of their liquid contents. The function of ultrasound impact is to stimulate this flow by different means in order to increase the output of the end product from the boreholes. There are methods oriented towards decolmation of an oil reservoir (elimination of obstacles in the path of flows of oil under the effect of ultrasound [1, 2]). Other methods are oriented towards the force capabilities of the intake of the liquid-phase stock through the creation of optimal suction conditions by means of the effect of acoustic flow [3, 4] or an increase in the porosity of the oil stratum [5]. Ultrasound is also used for acoustic heating of individual sections of the face zone [6] as well as in conjunction with chemical agents [1].

In the present study, we will consider forced vibrations of a fluid at the frequency of an incident sound wave in the channels of a reservoir with the radius of the channels small by comparison with the wavelength. The resulting vibratory deformations of the walls of the channel induced by the propagating ultrasound field are transmitted to the fluid, creating not only high-frequency disturbances, but also motion of the liquid with constant velocity capable of increasing the transport of liquid through the channel cross-section. By the action of ultrasound, therefore, the liquid in such a channel acquires another effective viscosity, the magnitude of which is substantially lower. Calculations are performed and are presented within the framework of a simplified, though practically significant model.

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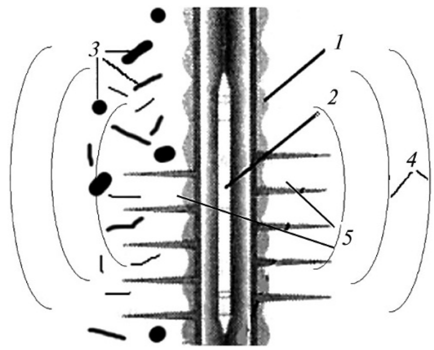

Fig. 1. Interaction of ultrasound with the porous structure of an oil stratum with acoustic stimulation of wells: *1*) cement stone; *2*) submersible device; *3*) porous structure of stratum (channels, cracks, capillaries, pores); *4*) front of traveling sound wave; *5*) perforation channels.

Calculation of Acoustic Impact on the Effective Viscosity of Oil in the Channels of the Face Zone of a Well. In the general case, a sound wave possesses a spherical (in the case of a point source) or cylindrical (for extended filamentary generation) front (Fig. 1). Calculations with such a statement of the problem are substantially complicated, since the spatial distribution of the field of acoustic deformations in the solid structure of a stratum is no longer described by an exponential expression as in the case of a plane front, but instead by means of spherical or cylindrical functions.

Calculations related to the interaction of ultrasound with the liquid found in channels, cracks, capillaries, and pores of the face zone of a well were performed for a one-dimensional planar ultra-sound wave with wavelength λ substantially exceeding the radius of the channels.

The simplification employed here is not essential and only slightly influences the numerical value of the coefficients in the resulting expressions while significantly reducing the cumbersome of the calculations.

In describing the propagation of a sound wave in the solid material of the structure of a stratum, it is necessary to proceed on the basis of the elasticity equation, which takes into account the viscosity and thermal conductivity of the stratum, for a vector **U** of the corresponding displacement:

$$\rho_0 \partial_{tt}^2 \mathbf{U} = \left[\rho_0 (c_l^2 - c_t^2) + \varsigma_0 + \frac{\eta_0}{3}\right] \nabla \operatorname{div} \mathbf{U} + (\rho_0 c_t^2 + \eta_0) \Delta \mathbf{U} - \frac{E\alpha}{3(1-2\sigma)} \nabla T, \tag{1}$$

and the equation of thermal conductivity in a solid [9] for temperature T:

$$C_V \partial_t T + \frac{C_p - C_V}{\alpha} \partial_t \operatorname{div} \mathbf{U} = \chi \Delta T, \tag{2}$$

where ρ_0 is the density of the material; c_l and c_t, the velocities of the longitudinal and transverse vibrations in the solid, respectively; E, Young's modulus; σ, Poisson's coefficient; C_p and C_V, heat capacities with constant pressure and constant volume, respectively; ζ_0 and η_0, coefficients of primary and secondary viscosity; α, coefficient of thermal expansion of material; and χ, coefficient of thermal conductivity.

If the direction of propagation of the sound wave is selected along the z-axis and the radiation source is placed at the coordinate origin $z = 0$, the boundary condition for a displacement U of the longitudinal wave will be represented by the equality

$$U(z = 0, t) = U_m \exp(-i\omega t), \tag{3}$$

where U_m is the amplitude of the displacement at the output of the radiation source, and ω is the frequency of the vibrations of the source.

When the sound wave encounters a cavity filled with a liquid of density ρ in its path, it induces (expressed through vibrations of the walls) disturbances in the liquid medium characterized by a velocity **v**. The system of Navier–Stokes equations for such disturbances consists of two equations, one of which is a continuity relationship

$$\partial_t \rho + \operatorname{div}(\rho \mathbf{v}) = 0, \tag{4}$$

and the other the motion equation of the liquid,

$$\partial_t \mathbf{v} + (\mathbf{v}\nabla)\mathbf{v} - \nu \Delta \mathbf{v} = -\nabla p / \rho, \tag{5}$$

where p is the pressure in the liquid, and ν is the kinematic viscosity ($\nu = [3\zeta_0 + 4\eta_0]/3\rho$).

In studying the behavior of disturbances in a liquid induced by vibrations of the walls bounding the volume of liquid, a natural boundary condition is equality of the components of the velocities of the wall and liquid at the interface site directed along the normal to the boundary. Here it is assumed that the liquid fills the entire space and that there is no air-gas interlayer.

The system of equations with boundary conditions (1)–(5) is the initial system for studying both slow, steady-state movements and the rapid vibratory disturbances that arise as a result of the action of external forces or fluctuating perturbations. As it is a linear system as regards the description of a solid-state phase, the system of equations is quite general in nature, which makes it possible to investigate the broad class of phenomena that arise in the interaction of a solid with a liquid, the behavior of which fully corresponds to Eqs. (4) and (5) in light of nonlinearity.

Within the framework of the proposed model, it is above all necessary to calculate the behavior of the displacement vector $\mathbf{U}(z, t)$ with distance from the radiation source. For this purpose, the solution of the linear system (1), (2) may be found in complex form, taking into account longitudinal vibrations and their damping in the case of propagation in the solid structure of a stratum:

$$U(z, t) = U_m \exp(-i\omega t + ikz - \kappa z), \tag{6}$$

where $k \equiv 2\pi/\lambda$; κ is the spatial decrement created by the thermal conductivity and viscosity of the material of the solid matter.

Using the (6) representation for the displacement and temperature, which undergo changes as a result of external actions, the following expression for the decrement in the spatial damping may be obtained from Eqs. (1) and (2):

$$\kappa = \frac{\omega^2}{2\rho_0 c_l^2}\left[\left(\frac{4}{3}\eta_0 + \varsigma_0\right) + \frac{\alpha^2 \chi T \rho_0^2 c_l^2}{3C_p^2}\left(1 - \frac{4c_t^2}{3c_l^2}\right)^2\right]. \tag{7}$$

The frequency ω here turns out to be related to the length of the longitudinal wave by the well-known dispersion relationship $\omega = kc_l$.

In deriving formula (7), the adiabaticity of the processes occurring in the propagation of an ultra-sound wave, when the following thermodynamic relationship is valid [7], is taken into account:

$$C_p - C_V = \alpha^2 T \rho_0 c_l^2 (1 - 4c_t^2 / 3c_l^2), \tag{8}$$

and the following equality, which is entailed by the definition of longitudinal and transverse velocities expressed in terms of the modulus of elasticity [7], is used:

$$\frac{E}{1 - 2\sigma} = 3\rho_0 c_l^2 (1 - 4c_t^2 / 3c_l^2). \tag{9}$$

If there is nonlinearity present, the characteristic absorption length of ultrasound $L_{\text{us}} = 1/\kappa$ may prove to be significantly greater than the value determined by formula (7), which substantially increases the influence of ultrasound on the face zone of the well.

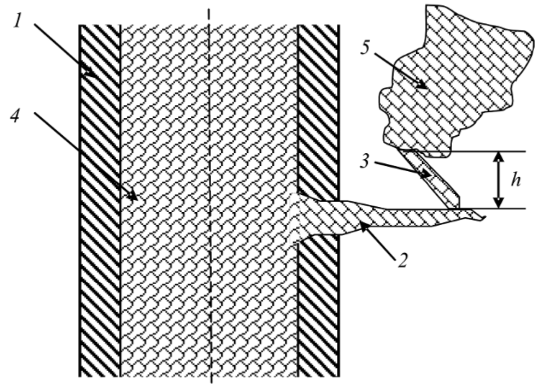

Fig. 2. Structure of face zone of well in which ultrasound stimulation of the flow of liquid may be realized: *1*) wall of casing pipe; *2*) perforation channel; *3*) connecting capillary; *4*) fluid in well; *5*) cavity with liquid.

A fragment of the structure of an oil stratum that illustrates the standard mechanism of overflow of liquid from the face zone into the wellbore is presented in Fig. 2. From cavity *5*, the liquid flows into the perforation channel through capillary *3* under the effect of a pressure drop Δp at the ends of the capillary. The magnitude of this pressure drop may be related to gravitational attraction whenever the ends of the capillary are at different heights with a pressure drop h: $\Delta p = \rho g h$ (g is free-fall acceleration). A study of the influence of the ultrasound field on the flow of fluid through narrow channels will be the subject of a subsequent discussion.

In calculating the action of ultrasound on the properties of a liquid, we will proceed on the basis of the Navier–Stokes equations (5), written both for the steady-state motion of a liquid with velocity **v** and for fast vibrations under the action of ultrasound with known frequency $\omega = 2\pi f$ and velocity **u** depending on a specified amplitude ξ of ultrasound vibrations:

$$\overline{(\mathbf{u}\nabla)\mathbf{u}} = \nabla p + \mu\Delta\mathbf{v}\,; \tag{10}$$

$$\rho\partial_t \mathbf{u} = i\mathbf{k}p_0 e^{-i\omega t + i\mathbf{kr}} + \mu\Delta\mathbf{u}, \qquad \xi = kp_0/(\rho\omega^2), \tag{11}$$

where **k** is the wave vector of the ultrasound vibrations related to their wavelength in a liquid by the relationship $\lambda = 2\pi/k$; p_0, amplitude of high-frequency pressure, which constitutes the part of the magnitude established by the ultra-sound generator, which, by (6), has reached the cavity being considered here in reduced form due to dissipation; p, steady-state pressure created by external forces; μ, dynamic viscosity; and **r**, spatial vector coordinate (the overline denotes averaging over time during the vibration period $T_s = 2\pi/\omega$).

The spatial decrement of the damping of ultrasound in the liquid κ_s described by the relationship

$$\kappa_s = k^2\mu/(\rho\omega) = \omega\mu/(\rho s^2) \tag{12}$$

may be found from formula (2), where s is the modulus of the rate of propagation of an ultra-sound wave in the liquid. For viscous liquids, generally $\kappa \ll \kappa_s$, and we will henceforth consider just this case of the occurrence of forced vibrations in a liquid.

As a problem of critical importance, let us consider how Poiseuille's flow formula changes for the case of ultrasound impact on a liquid in a cylindrical cavity of radius R. We will assume that the coordinate z is directed along the axis of the cylinder (we denote the length of this pipe by L). This means that for a stimulating sound wave incident at an angle β to this axis, we must use the projection of the wave vector $k\cos\beta$ to this axis in place of the wave number k. We will consider the case $kR \ll 1$ and $\kappa \ll \kappa_s$. Then from (10) we may write:

$$v = \{\Delta p/L + \rho\xi^2\omega^2\kappa\}(1/4\mu)(R^2 - r^2). \tag{13}$$

We determine the flow rate of the fluid Q from the formula

$$Q = \rho \int_0^R r dr \int_0^{2\pi} d\varphi v = \frac{\pi R^4 \rho}{8\mu} \left\{ \frac{\Delta p}{L} + \rho \xi^2 \omega^2 \kappa \right\}, \tag{14}$$

where φ is the azimuthal variable in a cylindrical coordinate system.

It is evident from (14) that ultrasound effectively increases the fluidity of a liquid, thereby increasing its flow rate. Dividing the flow rate of the liquid into a spontaneous part Q_0 and a forced part Q_s (associated with ultrasonic impact), expression (14) may then be written in the form:

$$Q = Q_0 + Q_s, \quad Q_0 = \frac{\pi R^4 \rho}{8\mu} \frac{\Delta p}{L}, \quad Q_s = \frac{\pi R^4 \rho^2 \xi^2 \omega^2 \kappa}{8\mu}. \tag{15}$$

Introducing the effective viscosity μ_{eff}, which takes into account the influence of ultrasound in a form that makes it possible to preserve the standard form of Poiseuille's formula, in which μ_{eff} occurs in place of μ, we obtain

$$Q = Q_0 \frac{\mu}{\mu_{\text{eff}}}; \quad \mu_{\text{eff}} = \frac{\mu}{1 + Q_s / Q_0}. \tag{16}$$

From (16); it is evident that the effective viscosity is always less than the value which is inherent to an undisturbed liquid, i.e., $\mu_{\text{eff}} < \mu$. This points to an increase in transport of liquid in the presence of ultrasound.

The method of acceleration of transport of liquid in the field of a sound wave is of the nature of a direct action (the process arises directly at the site where the effect is realized). This distinguishes it from such methods of reworking wells as the use of acoustic flow, which is created within the well between the surfaces of the casing pipe and the submersible device, and the resulting eddy motion exerts an effect even in the face zone. Therefore, the use of this effect proves to be most effective at local sites where the influence of other methods of action produces a significantly weaker effect.

Experimental Verification of the Influence of Ultrasonic Impact on the Viscosity of Oil. In steady-state laminar motion of a viscous incompressible liquid, the per-second volumetric flow is determined by Poiseuille's formula:

$$Q = \frac{\pi d^4 \Delta p}{128 \mu \Delta l},$$

whence the coefficient of dynamic viscosity, Pa·sec,

$$\mu = \frac{\pi d^4 \Delta p}{128 Q \Delta l}, \tag{17}$$

where $\Delta p = p_2 - p_1$ is the pressure drop at the ends of the capillary, Pa; Q, volumetric flow rate of liquid, m^3/sec; d, diameter of pipe, m; and Δl, length of pipe, m.

The relative variation in viscosity may be calculated by means of the formula

$$\varepsilon = (|\mu_{\text{eff}} - \mu|)/\nu.$$

Recalling (16), we obtain

$$\varepsilon = (|Q_0 - Q|)/Q, \tag{18}$$

where Q and Q_2 are the volumetric flow rates of oil with, respectively, without ultrasonic impact, m^3/sec.

In order to estimate the effect of ultrasound on the viscosity of oil from different fields, a test bench (Fig. 3) was developed for experimental determination of the viscosity of oil under maximally similar conditions and with and without the use of ultrasound.

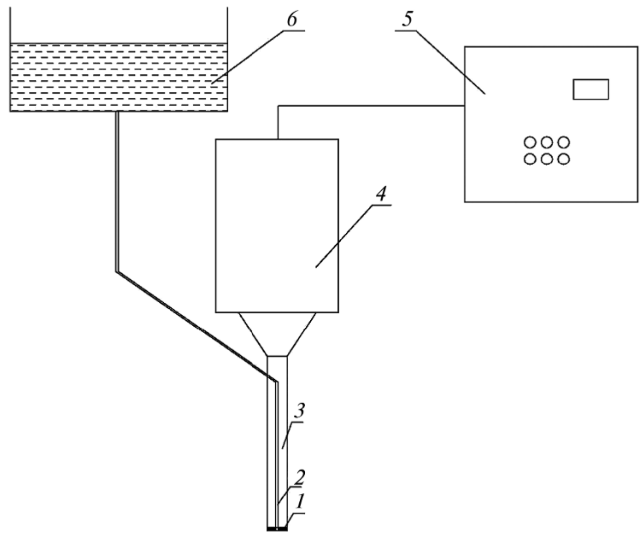

Fig. 3. Test bench for determining the viscosity of oil subjected to ultrasonic impact: *1*) layer absorbing ultra-sound wave; *2*) cylindrical opening; *3*) waveguide radiating system; *4*) MSP 2/22 magnetostriction transducer; *5*) UZG 2/22 ultrasound generator; *6*) reservoir with oil.

TABLE 1. Averaged Physicochemical Properties and Fractional Composition of Oil from Different Fields

Parameter	Site		
	Borov	Ust-Tegus	Samotlor
Density, kg/m^3, at 20°C	910	892	851
Dynamic viscosity, mPa·sec, at 20°C	146	363	289
Solidification temperature, °C	–15	–5.6	–9
Mass content, %:			
sulfur	3.50	–	1.2
silicate gel resins	12.54	35.7	3.7
asphaltenes	5.90	1.2	0.2
paraffines	8.81	12.3	8.2

Oil draining out of the reservoir *6* enters a cylindrical opening *2* of diameter 3 mm drilled in the center of the rod waveguide *3*. An MSP 2/22 transducer *4* (powered by the UZG 2/22 generator *5* of power 2 kW) is used as the source of the ultrasound vibrations. Ultrasound treatment is performed at a resonance frequency of 21.8 kHz with amplitude of the vibrations of the face of the radiator 3 μm. An absorbing layer *1* is glued to the face of the radiator in order to absorb the reflected ultra-sound wave at the metal–air interface and prevent the formation of standing waves in the waveguide.

The dynamic viscosity of oil was determined on an INPN SX-850 meter of low-temperature indicators of oil products, which is a rotary viscometer (it measures torque at a constant shear rate of 250 rad/sec). The precision of temperature measurements of a sample was ±0.2°C, and the precision in the determination of dynamic viscosity, 2%. Thermostatting of the sample for 20–30 min at a temperature of 20°C was performed prior to measurement of the dynamic viscosity.

The experiments were performed with the use of oil from several fields possessing different structural-group and fractional compositions and different physicochemical properties (Table 1).

TABLE 2. Volumetric Flow Rate of Oil With and Without Ultrasonic Impact

Site	Volume of oil, liters, draining in flow, min					
	without ultrasonic impact			with ultrasonic impact		
	15	30	45	15	30	45
Borov	1.51	3.22	4.69	2.15	4.52	7.45
Ust-Tegus	0.69	1.31	2.02	0.86	1.71	2.63
Samotlor	0.67	1.44	2.21	1.05	1.97	3.27

TABLE 3. Influence of Ultrasonic Impact on the Dynamic Viscosity of Oil

Field	Values						
	computed			experimental	measured		
	μ, mPA·sec	μ_{eff}, mPA·sec	ε_c	ε_e	μ, mPA·sec	μ_{eff}, mPA·sec	ε_m
Borov	146	103	0.29	0.37	138	106	0.23
Ust-Tegus	363	256	0.30	0.23	371	263	0.29
Samotlor	289	204	0.29	0.32	267	176	0.34

In the course of the experiments (Table 2), the volume of oil draining through a pipe in a given time interval (experimental values of Q and Q_0) was established.

The values of the dynamic viscosity of the different types of oil were then determined:

computed values of viscosity by means of formulas (15) and (16) with the use of known parameters: $R = 3$ mm; $L = 20$ mm; $\nu = 21.8$ kHz; $\xi = 3$ μm; and $\Delta p = \rho g L$;

experimental values of viscosity with respect to the flow rates of the oil Q and Q_0 on the test bench (the relative variation in the dynamic viscosity was then calculated using formula (18)); and

direct measurements of viscosity were performed on a viscometer.

A decrease in the dynamic viscosity of the oil of 23–34% on average was observed following ultrasonic treatment (Table 3).

The computed, experimental, and measured values of the dynamic viscosity of oil from three fields, taking into account the limits of the accepted errors, were approximately equal, which confirms the consistency of the calculations that have been presented here.

The results that have been obtained are of great importance for the development of complex equipment and a technology for management of the process of restoration of oil reservoirs, where the effect that has been studied here may be used as a means of delivering chemical agents to remote sectors of the face zone of a well.

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