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AN ULTRASONIC TECHNOLOGY FOR PRODUCTIVITY RESTORATION IN LOW-FLOW BOREHOLES

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An analysis is presented of the mechanisms for ultrasonic action on processes in oil boreholes. The nature and features of the acoustic flow are examined, together with the scope for controlling the parameters, which is due to the need to devise equipment and technology for low-flow boreholes, with the choice of efficient modes of operation and the provision of conditions under which the restoration of productivity has the maximum possible effect. Scientific principles are formulated that need to be considered in designing the ultrasonic apparatus for processing heavy crude oils. An industrial specimen of such equipment has been built and tested.

There is obviously a need to raise substantially the oil extraction factor, for which there are various physical and chemical methods. One method of restoring productivity is the use of ultrasound (US), or the AWS method [1, 2]. Immersed equipment is placed in the borehole at the depth of the productive stratal layer. High-power ultrasound increases the permeability of the surrounding stratum and the fluidity of the nonnewtonian liquids. Narrow channels in the porous medium in an oil borehole are unblocked to remove waxes and asphaltenes, clay particles, and so on.

To conduct acoustic tests under industrial conditions, members of VNIIgeosistem have devised equipment for US treatment in the bottom zone of strata. Research over many years has led to the production of various modifications of borehole equipment, and a recent one is equipment on a logging cable. Hundreds of boreholes have been given acoustic treatment with such apparatus. A design feature is that the active elements are magnetostriction rod converters moving in opposite directions and filled with oil and placed in a protective jacket. The axis of these converters coincides with that of the instrument [3]. In that case, strong US radiation occurs only in the zones between the converters (Fig. 1). Various estimates show that the performance factor is 50–70%, and it is appreciably lower on processing low-flow boreholes.

In spite of the theoretical and expensive field researches that have been performed, not much is known about the physical mechanisms that raise the permeability of the borehole walls in response to ultrasound, and no mathematical calculations have been performed. Then a major topic is the formation of the physical conception enabling one to explain constructively the physical essence of the effects observed in acoustic stimulation, and thus to set up an instrument for optimal use of them. The resulting understanding of the processes allows one to optimize the design and thus finally to raise the processing performance factor.

Theoretical Analysis of Nonnewtonian Liquid Flow in a US Field

The following are the most typical conditions for acoustic flow: the size of the steady-state motion region l is small by comparison with the wavelength λ but large by comparison with the penetration depth δL:

$$\lambda \gg l \gg \delta L.$$

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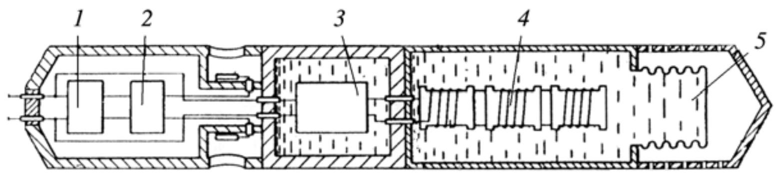


Fig. 1. Apparatus for ultrasonic treatment in the drilled stratal zone: *1*) power connection unit; *2*) oscillator; *3*) transformer; *4*) acoustic converter; *5*) corrugated membrane.

That condition allows one to distinguish a narrow boundary layer in which the flow velocity alters, and it is small by comparison with the speed of the sound, so the liquid may be considered as incompressible.

We envisage cylindrical geometry, which approximates to the actual conditions in an oil borehole. The azimuthal symmetry enables one to restrict oneself to two coordinates z and r, which determine the distribution of the measured quantities correspondingly along the cylindrical axis and along the radius.

The initial equation can be written as follows for the components of the flow speed $v\{v_r, 0, v_z\}$:

$$\partial_t v + (v\nabla)v - \upsilon\Delta v = -\frac{\nabla p}{\rho}, \tag{1}$$

where p is the pressure in the liquid, ρ density, and υ viscosity.

Incompressibility condition:

$$\operatorname{div} v = 0. \tag{2}$$

Equations (1) and (2) allow one to describe the complicated motion of a viscous liquid subject to appropriate boundary conditions determined by the geometry. In the present case, the high-power standing sonic wave is produced by a waveguide, whose boundary lies on a circle of radius $r = r_0$. We write the speed $u(t, z)$ produced by that wave along the OZ axis as

$$u \equiv u(t, z) = u_0 \cos kz \cos \omega t, \tag{3}$$

which corresponds to the standing-wave structure, and we assume that the pressure oscillations are related to the amplitude of this wave by Bernoulli's equation:

$$\partial_t u + u\partial_z u + \frac{\partial_z p}{\rho} = 0.$$

The parameters k and ω in (3) characterize the spatial behavior and time dependence of the standing acoustic wave.

To solve system of equations (1) and (2), we use successive approximation [4] based on the amplitude u_0, with the function $\varphi(r, z, t)$:

$$v_z = \frac{1}{r}\frac{\partial}{\partial r}(r, \varphi); \quad v_r = -\frac{\partial \varphi}{\partial r}; \quad \varphi(t, z, r) = \varphi^{(0)}(z, r) + \varphi^{(1)}(t, z, r) + \ldots \tag{4}$$

This provides automatic obedience to (2), the condition of motion continuity. We assume that the waveguide wall executes radial displacements with frequency ω and amplitude ξ_{r0}, and then we have approximately $u_0 \cong \omega\xi_{r0}$.

A similar argument gives as a first approximation for the velocity $v_z(t, z, r)$ that

$$v_z^{(1)} = \mathrm{Re}\,\{u_0[\xi(r) + 1]\cos kz\, \mathbf{e}^{-i\omega t}\}.$$

The solution for $\xi(r)$ in general form is

$$\xi(r) = \xi_0 J_0(\beta r) + \xi_1 N_0(\beta r); \quad \beta = (1+i)/\delta,$$

in which $\delta = (\upsilon/\omega)^{1/2}$; $\xi_{0,1}$ = const; J_n and N_n (n = 1, 2, ...) are Bessel and Neumann functions.

In the second approximation, we get the static solution (not dependent on time), i.e., the harmonic $v_z^{(0)}(r, z)$ in the following form:

$$v_z^{(0)}(r, z) = u_0^2 \xi^{(0)}(r) \sin 2kz.$$

Then (1) reduces to the following second-order ordinary differential equation:

$$\frac{1}{r} d_r (r d_r \xi^{(0)}) = f(r) \equiv -\frac{k}{2\upsilon}\left\{1 - |W_1|^2 - \frac{1}{2}\left[W d_r W_1^* + W^* d_r W_1\right]\right\}, \tag{5}$$

in which $W_1 = 1 + \xi(r)$;

$$W(r) \equiv \frac{\beta r}{2} + \xi_0 J_1(\beta r) + \xi_1 N_1(\beta r),$$

in which $\beta = (1 + i)/\delta$.

Integrating (5) gives the following expression for $\varphi^{(0)}(r)$:

$$\varphi^{(0)}(r) = \frac{1}{2} A_0 \left(r \ln r - \frac{r}{2} \right) + B_0 \frac{r}{2} + \frac{C_0}{r} + F_1(r),$$

in which

$$F_1(r) = \int_{r_0}^{r} r' dr' \int_{r_0}^{r'} \frac{dr''}{r''} \int_{r_0}^{r''} r''' f(r''') dr''', \tag{6}$$

where A_0, B_0, and C_0 are parameters determined by the boundary conditions and the symmetry requirements.

The radial velocity of the liquid within its volume differs from zero and provides radial displacement in various directions with various intensities for various values of the radius r. At the same time, the liquid does not accumulate anywhere and is not mixed. Then the integral flux in the radial direction is zero, which imposes an additional constraint on the solution to (6), which allows us to formulate three equations for the three parameters A_0, B_0, and C_0.

We get a system of three algebraic equations for A_0, B_0, and C_0:

$$A_0\{a\} + B_0\{b\} + C_0\{c\} = \{d\}. \tag{7}$$

Here the braces symbolize columns, and each element in these is denoted by the corresponding character appearing in these braces and noted by the subscript, which denotes the assignment to one of the three equations. Here

$$a_1 = \ln r_0 - 1/2; \quad a_2 = \ln R - 1/2; \quad a_3 = \ln R - r_0^3 (\ln r_0)/R^3 - 5 r_0^3 / 6R^3;$$

$$b_1 = b_2 = 1; \quad b_3 = 1 - r_0^3 / R; \quad c_1 = 2/r_0^2; \quad c_2 = 2/R^2; \quad c_3 = 6(R - r_0)/R^3;$$

$$d_1 = -2F_1(r_0)/r_0; \quad d_2 = -2F_1(R)/R; \quad d_3 = -\frac{1}{6R^3} \int_{r_0}^{R} F_1(r) r dr.$$

The general solution to (7) can be written in terms of the determinants of the corresponding matrices, each of which consists of three columns and three rows as follows:

$$A_0 = \|d, b, c\|/D; \quad B_0 = \|a, d, c\|/D; \quad B_0 = \|a, b, d\|/D; \quad D = \|a, b, c\|.$$

Here $\|a, b, c\|$ denotes the determinant of matrix $|a, b, c|$ consisting of three-element columns $\{a\}$, $\{b\}$, $\{c\}$.

Calculations give the determinant D as

$$D = 2(1 - q^2)(2 + q)(\ln q)/R^2, \tag{8}$$

in which $q = r_0/R$; from (8) it follows that under real conditions $r_0 < R$ one always has $D \neq 0$, i.e., a solution in the form of (8) always exists.

The solution in the form of (6) and (8) completely describes a steady-state motion of the viscous liquid, which is called acoustic flow, and is produced by US vibrations with a standing-wave structure in cylindrical geometry. From (4) and (6) one can derive all components of the constant speed of the liquid, which is of nonlinear nature and vortex character.

Figure 2*a* shows the coordinate dependence of the dimensionless radial velocity $v_r(r, z) = v_r^{(0)}(r, z)/c_s$, while Fig. 2*b* shows the dependence of the dimensionless axial velocity $v_r(r, z) = v_z^{(0)}(r, z)/c_s$; these functions are sign-varying as the radius r increases from r_0 to R. This shows that the acoustic flow is of vortex character and leads to the liquid circulating in the space between the cylindrical walls.

The motion in that space can also be represented clearly from the motion of a selected element initially at $t = 0$ at a given point in the volume. We can estimate the motion of the liquid element over the radius on the assumption that at $t = 0$ that element is at the point $r = r_q(t = 0)$. The time course of that position ($r_q \equiv r_q(t)$) is described by

$$d_t r_q = v_r^{(0)}(r_q)$$

or

$$r_q(t) = v_r^{(0)}(r_q)t + r_q(t = 0). \tag{9}$$

It follows from (9) that for $t \to \infty$ we have the condition $v_r^{(0)} \to 0$, i.e., $r_q \to r_0$ or $r_q \to R$, since the steady-state radial velocity at the walls is zero, i.e., the liquid moves towards the walls. However, there is simultaneous displacement along the cylindrical axis, so it is clear that during motion in the region of the values of z where the velocity $v_r^{(0)}$ has another sign, the particle begins to move towards the other wall and so on. One can thus speak of the vortex motion of the liquid in the space between the cylinders in the presence of a high-power standing US wave.

These expressions for the flow speeds show that the dependence on the parameter $q = r_0/R$ is an important mechanism for the action on the vortex cell and the correspondence between the various components of the steady-state motion. One can vary q and also the ultrasound wavelength to bring about the necessary effect in relation to the force and direction of the liquid flow near the wall, which it may be desirable to break up or alter. Such flows occur mainly in viscous media, so they play a certain part in intensifying the oil extraction. In the present case it is characteristic that the effect instantly vanishes when the US source is switched off.

Methods in Laboratory Experiments and Testbed Conditions

Recently, US techniques for liquid-phase loads have begun to employ radiators in the form of tubes, in which longitudinal oscillations are excited and transform to radial ones, which are emitted into the load.

In these devices, the electroacoustic converter may be established either on the same side as the radiator [5] or on both sides (two-cycle Push-Pull system) [6]. Principles have been given [7, 8] for calculations on tubular radiators, which convert longitudinal oscillations to radial ones. The radiator is a hollow cylinder of specified length, and of specified internal and external radii. Calculations can readily be performed on the resonant dimensions of such radiators and the relations

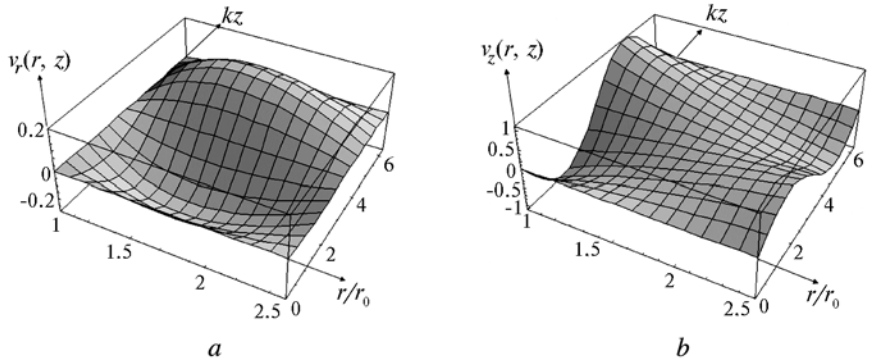


Fig. 2. Spatial changes in velocity components of acoustic flow for a viscous liquid (with certain given parameters for the viscous liquid and US excitation): *a*) radial velocity; *b*) velocity along cylindrical axis.

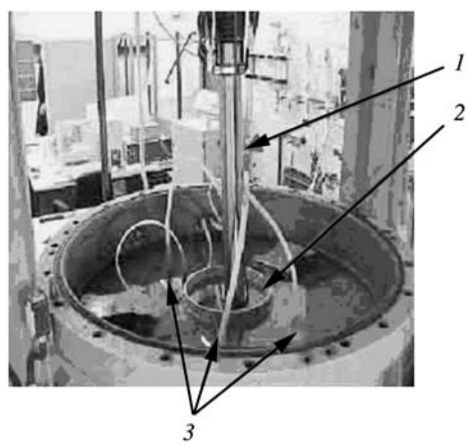


Fig. 3. Experimental system simulating a borehole: *1*) ultrasonic waveguide; *2*) filtration screen; *3*) hydrophones.

between the radial and longitudinal displacement amplitudes by using the finite-element method. The calculations were performed with the ATILA program.

Two oscillating systems were built for the experiments:

1) with four magnetostriction rod converters in the device (system A);

2) with two rod magnetostriction converters joined in a Push-Pull system with the source, which has a developed radiating surface (system B).

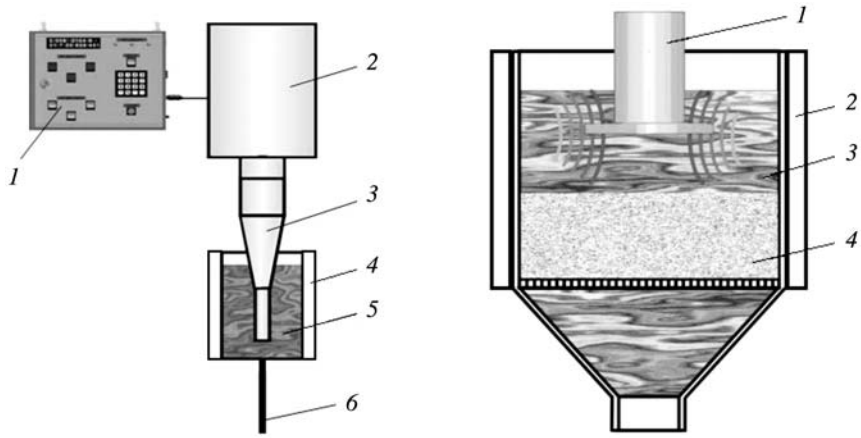
The power supplies were electric generators of power up to 10 kW joined to the system by a supply cable leading to the submerged centrifugal pumps.

The testbed experiments were conducted with the borehole equipment in a pressure chamber (Mainz University, Germany) of diameter 1000 mm and height 1235 mm in the pressure range 0.5–15 bar.

The diameter of the horizontally slotted filter made of PVC polymer was 250 mm. The layer of filter grid was 5–8 mm thick.

Four hydrophones recorded the acoustic pressure, which were located at about 160 mm from the chamber axis (about 50 mm from the filter) and at a depth of about 400 mm from the surface of the filling (Fig. 3).

To determine the causes of the low US performance factor for low-flow boreholes, experiments were made on the effects of ultrasound on the flow speeds for crude oils of various origins in thin tubes.



a *b*

Fig. 4. Testers for ultrasonic effects: *a*) for determining fluidity of crude oil (*1* – US generator; *2* – magnetostriction converter; *3* – waveguide radiating system; *4* – thermostatic jacket; *5* – reactor containing oil; *6* – outlet tube); *b*) for determining porous-medium permeability (*1* – US radiator; *2* – thermostatic jacket; *3* – oil; *4* – sand).

Figure 4*a* shows the experimental tester for estimating the ultrasound effects.

The laboratory studies were made on oil from the Pashino deposit (υ = 21.5 mm^2/sec, specimen 1), the West Tebuk deposit (υ = 40.9 mm^2/sec, specimen 2), and East Sochemu-Talyus (υ = 53.5 mm^2/sec, specimen 3), and also on oil with a high wax content (25.4 wt.%, specimen 4).

The elastic oscillations were injected into the working medium *5* in the thermostatic reactor *4* (volume 1 liter) by means of a rod waveguide *3* (diameter of working end 65 mm). The ultrasonic source was the magnetostriction converter *2*, which was connected to the generator *1* of power 0.5 kW.

In the US treatment, the oscillation amplitude of the radiator was 3–5 μm (resonant frequency 24 kHz), diameters of the outgoing tubes 5–1.5 and 4 mm. The experiments were performed at 20°C.

Figure 4*b* shows the tester used to estimate the ultrasonic effects on the permeability of porous media. The thickness of the porous medium was 30 mm.

Results of Laboratory Experiments and Testbed Data

The testbed data were obtained for borehole equipment tested in the pressure chamber and showed that system A revealed considerable changes in acoustic pressure in accordance with the position of the hydrophone in relation to the axis of the magnetostriction converter. At points between the radiating ends of the two converters, the acoustic pressure was 5–6 times larger than near the middle of the converter.

An oscillatory system consisting only of rod converters (system A) provided US emission into the medium mainly perpendicular to the side surfaces of the converters, while when a tubular sound guide was used (system B), the emission was axially symmetrical and the US intensity was appreciably higher.

As the static pressure p increases, the acoustic pressure p_m for system B initially rises sharply and then hardly varies in the range p_m = 1–15 bar.

System A showed a more complicated variation in acoustic pressure, which increased with p in the range 0–1 bar and then fell somewhat (at p = 3 bar), after which it rose again and attained its maximum at p = 5 bar, then decreasing for static pressures p = 10–11 bar.

These pressure chamber data unambiguously show considerable advantage of the system based on a sound guide with extensive radiating surface (system B), and such systems should be used in processing low-flow boreholes, particularly for high-viscosity crude oil.

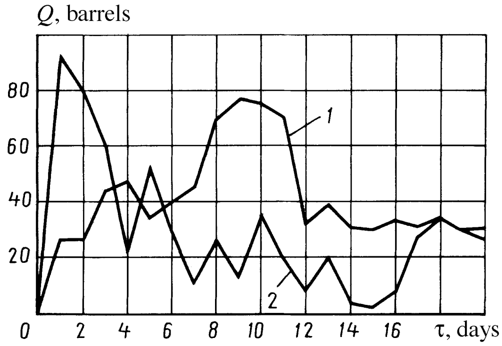


Fig. 5. Dependence of the output Q on time τ for borehole Rust 14B3 after AWS treatment: *1*) oil; *2*) water.

We also performed experiments on the effects of ultrasound on the fluidity of nonnewtonian liquids and the permeability of porous media.

Ultrasound increases the fluidity of oil by a factor of 2–3 (Table 1); also, ultrasound increases the oil filtration rate through the porous medium by a factor of 1.2–1.5 (Table 2). These effects were observed for oils of all types.

The experiments showed indirectly that the low performance of US treatment for heavy crude oil is not related to the lack of effect from ultrasound on the fluidity. It appears that the borehole choking effect in these cases sets in very rapidly. Consequently, there is an increase in borehole flow only when the apparatus works continuously in the borehole, since then the effective viscosity is reduced and acoustic flows occur.

Field Tests on US Equipment in Oil Boreholes

For the field tests, we selected three boreholes at Wyoming deposits in Utah (USA). Further tests were conducted at the Blue Bell deposits on oil boreholes with low flow.

Working conditions in these boreholes: low clearance, porosity, stratal pressure, and temperature.

Stratal geophysical characteristics and borehole parameters:

Diameter	139.7 mm
Perforation interval	12.2–15.8 m
Depth	2347–2363 m
Stratal porosity	8–14%
Permeability	0.25–14 mD
Water content in fluid	72%
Wax content	49.3%
Stratal pressure	172.5 bar (17237.5 kPa)
Stratal temperature	73.3°C

The borehole equipment included a Push-Pull waveguide system and was mounted on the pumping tube and lowered into the borehole, where it remained for six months. The US treatment at a power of 10 kW was applied every day for 3 h, and the daily borehole outflow was recorded.

The previous level of oil output from three boreholes (Rust 14B3; Lotridge Gates 13B3; Ute 16D6) during May–October 2008 was 290 barrels, while with the AWS technology for the same period it was 3766 barrels, i.e., an increase by almost a factor of 13.

The AWS technique applied for six months to the three boreholes produced an increment in output of 13286 barrels. The output of a borehole that had been attained over 4.7 years with the previous extraction conditions was attained in 130 days with the AWS technique.

Figure 5 shows the changes in output for oil and water from a borehole during 20 days from the start of treatment.

TABLE 1

Oil	Tube diameter, mm	Flow time,* min	Viscosity,* mm^2/sec	Relative viscosity change, %
Specimen 1	1.5	2.75/1.33	21.5/10.4	52
Specimen 2		4.82/2.03	40.9/17.3	58
Specimen 3		6.13/2.66	53.5/23.4	56
Oil	4.0	Flow speed, g/min		Relative change in flow speed, %
Specimen 4			120	
Specimen 5		70	195	178
* The top line is without ultrasonic treatment and the bottom line for such treatment (displacement amplitude 3 μm).				

TABLE 2

Oil	Flow speed,* ml/sec	Relative change in flow speed, %
Specimen 1	0.92/1.40	52
Specimen 2	0.71/0.95	34
Specimen 3	0.46/0.57	24
* Top line without ultrasound, bottom line with ultrasound (500 W).		

The tests revealed additional advantages of AWS:
- processing only in zones where necessary;
- simplicity of use;
- low energy consumption; and
- stable operation during entire test period.

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