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PHYSICAL PROCESSES IN A PRODUCING STRATUM FROM A CONDITIONING SOURCE IN A WELL

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The inventory of methods for increasing the yield of producing strata is enormous. Explosive and vibroseismic low-frequency conditioning of strata [1-4] have gained the most widespread acceptance among forcing methods. A considerable number of papers have been published to date, mainly at the experimental level, and have made successful contributions to increasing the yield of producing strata. However, the physical processes in the producing part of a stratum with a radius r_t much smaller than the radius of the feed loop have not been studied. Whereas explosive conditioning is used to advantage for deep strata (oil and gas-bearing), the vibropercussive technique is most effective for strata at shallow depths with the application of well pneumatic drivers in injection wells. The first attempt at a theoretical schematization of the physical processes in a producing stratum under the influence of elastic oscillations has been undertaken in [5].

In the present article we attempt to substantiate the use of self-organization theory to account for these processes, which lead to restructuring of a stratum and impart new physical characteristics to it in the zone of influence of external disturbances. We also suggest the possible sequence of the processes involved, call attention to the importance of the choice of structural model for the pore space of the stratum, and describe the underlying assumptions and experimental data obtained in the example of vibropercussive conditioning.

1. The theory of self-organization of dissipative structures is used successfully wherever it is required to describe the final stage of the fracture process, i.e., the fissure nucleation mechanism. Consequently, a deformable solid (including a producing stratum) in which a nonequilibrium thermodynamic process with metabolism takes place can be regarded as a dissipative, self-organizing system. The statement of the problem is similar to that in [5]. The volume of the stratum around the well in the range $r_* \le r_i \le r_t$ is partitioned into N zones with variable physical characteristics: the half-length of an opening microfissure l_{*i}, its transverse width d_{*i}, the half-spacing between fissures h_{2i}, the induced porosity Δm_i, the number of fissures n_i, the induced permeability K_{1i}, and the incremental output ΔQ_i (r_* is a characteristic range of the source of disturbance; in vibropercussive conditioning it is interpreted as the distance from the working chamber of the pneumatic driver to the stratum).

Basic governing equations have been derived previously [5] for the specific binding energy per unit mass E_s/dM_i and the specific energy of the disturbance E_Σ/dM_i, which are related to the stratum parameters – the specific energy of formation of new surface γ_*, the elastic modulus E, the velocity of transverse elastic waves c_t, the Poisson ratio ν, the density of the stratum ρ, the modulus of cohesion K_1, and the zone interval dr_i – and also to the parameters of the pneumatic driver – the initial pulse amplitude in its air chamber A_0 and the period T. The stratum restructuring time t_* is determined from the basic equation of self-organization theory relating the process of buildup of excess stresses σ_1 to stressed inhomogeneities of length $L(t)$ and their relaxation at the rate v_* (t is the time) [1]. It has been shown [6] that for a variable strain rate $d\varepsilon/dt$ the solution of the equation governing the evolution of the system (in our case the producing stratum) has a bifurcation character. For $d\varepsilon/dt$ = const the limiting energy density E_* and the external energy of the disturbance E_Σ for the buildup of the limiting stress σ_{1*} in the volume $L^3(t)$ in vibropercussive conditioning does not depend on t, and the solution for t_* has the form

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$$t_{*i} = (L_0/v_*)(E_{*i}/E_{\Sigma i})^{1/3}\times$$
$$\times \ln\left[(\rho g H - \rho c_t^2(d\varepsilon/dt)L_i v_*^{-1})/(\sigma_{1*i} - \rho c_t^2(d\varepsilon/dt)L_i v_*^{-1})\right] \quad (1.1)$$

for $\rho gH << \rho c_t^2(d\varepsilon/dt)Lv_*^{-1}$ and $t_{*i} = \sigma_{1*i}/[\rho c_t^2(d\varepsilon/dt)]$. Here L_0 is the initial value of L, interpreted as the perforation mesh size of the casing filter r_{01}, and g is the acceleration of gravity.

The main idea behind the description of the physical processes in the stratum is that the mechanism of absorption of externally admitted energy is associated with the onset of an inhomogeneity of the stressed state of the medium. The inhomogeneities themselves are involved in energy transfer during loading as characterized by A_0, T, the number of disturbances (discharges) N, the loading rate c_t, and the rate $d\varepsilon/dt$ of energy transfer over $L(t)$. Also significant is the ratio of the intervals between discharges Δt and t_*. The existence of L and the dependence $L(d\varepsilon/dt)$ have been confirmed experimentally [7].

According to [1, 5], the value of γ_* upon fulfillment of the equation $\sigma_{1*} = p_1$ in each i-th zone, where p_{1i} is the cold component of the Hugoniot pressure, corresponding to attainment of the value E_s/dM_i of the cold component of the internal energy E_{1i} calculated from the equation of state of the stratum, is adopted as the critical condition for restructuring of the medium. The increment ΔQ is assumed to be formed as a result of the formation of new current tubes (microfissures) adjacent to the zone boundaries, and it is assumed that an pulse with the parameters A_0, T, and f (frequency of the radiation in the pulse) is translated into the fluid filling the well and passes through it to reach the casing, which is equipped with a filter having a mesh perforation size r_{01}, through which the stratum comes into direct contact with the well fluid, imparting hydrodynamic coupling to the system well-stratum. If the stratum is separated from the fluid by a blind casing, an additional condition for decay of the discontinuities at the fluid-casing and casing-stratum interfaces is considered for finding the initial pulse pressure in the stratum A_1 [5].

The instantaneous amplitude $A_i(r_i)$ (r_i is the instantaneous value of the radial coordinate r at the boundary of the ith zone) decays as a result of energy dissipation and spreading of the elastic wave front to a value r_t corresponding to failure of the inequality $E_\Sigma/dM_i > E_s/dM_i$. Consequently, taking the results of [5] and the relation $\gamma_* = K_1^2(1 - \nu^2)/(\pi E)$ into account, we obtain the relations

$$\begin{aligned} E_s/dM_i &= K_1(c_tT)^{1/2}\pi^{-1}2^{-1/4}/(\rho dr_i), \\ E_\Sigma/dM_i &= 0{,}25A_i(r_i)c_tT/(\rho dr_i), \\ A_* &= K_1/[0{,}25\pi(c_tT)^{1/2}2^{1/4}], \qquad A_1 \leqslant A_i \leqslant A_*, \quad r_* \leqslant r_i \leqslant r_t, \end{aligned} \quad (1.2)$$

where A_* corresponds to the value r_t. We assume that $A_i(r_i) = \text{const}$ within each zone, the volume $8h_{2i}^3$ contains one arbitrarily oriented fissure, and the permeability coefficient depends on the porosity Δm_i. Because of the difference between the pulse pressures and the stratum pressure p_i, the well fluid initially enters the stratum by natural initial fissures.

Restructuring of the stratum begins once σ_{1*} builds up to the value p_1 in each zone after a time t_{*i} according to (1.1). Since the lifetime t_1 of the wave fields in the zone r_t is calculated in milliseconds, usually $t_1 << t_{*\max}$. The injected well fluid then releases at once through the stratum with its new physical characteristics as a result of ordinary depression $(p_+ - p_-)$ (p_- is the face hydrostatic pressure at depth H in the well fluid). New microfissures are contained in a volume V_{1i}, which is a part of the volume V_{0i} and is determined from the Rosin–Rammler law [8]. If the maximum length l of the initial fissures is greater than l_{*i}, the Rosin–Rammler law gives $V_{1i} \to V_{0i}$. For definiteness we can set $V_{1i} = V_{0i}$. Calculations and a comparison with experiment show that this assumption is valid for vibropercussive action ($A_0 \approx 10$ MPa) and for gunpowder pressure generators ($A_0 \approx 150$ MPa) [2].

The influence of the gas cloud and its pulsations after air discharge in vibropercussive action or the influence of the explosion products in explosive action on the possible additional opening of natural fissures in the stratum is disregarded.

We note that the sufficient condition for the formation of a single microfissure in external loading is $\sigma_{1*} = p_2$, where p_2 involves the critical displacement $u_* = \varepsilon_* r_-$, where ε_* is the critical strain, and r_- is a characteristic length of the medium [9]. For the steel casing (drill column) investigated in [9] r_- is interpreted as the thickness of the casing wall, and the value $\varepsilon_* = 2.38\cdot10^{-3}$ has been determined experimentally [10]. The value of ε_* is usually unknown for a stratum, and the condition $\sigma_{1*} = p_1$ is therefore used [5]. The agreement of the calculated results for ΔQ with the experimental under this condition indicates the thermodynamic relationship of the equation of state of the stratum and the basic self-organization theory principles used to solve the problem. For the stratum it is assumed that $r_- = c_tT$. If the number of zones is N_1, the following relations are valid:

$$\Delta A = (A_1 - A_*)/N_1, \quad A_i(r_i) = A_1 - \Delta A i, \qquad i = 1, 2, \ldots, N_1. \tag{1.3}$$

For a spherical elastic wave propagating from a filter perforation into the stratum we postulate the decay law [11]

$$A(r) = A_1 r_*/r. \tag{1.4}$$

From Eqs. (1.2) and (1.4) we obtain

$$r_+ = 0{,}25\pi r_* A_1 (c_t T)^{1/2} 2^{1/4} K_1^{-1}. \tag{1.5}$$

The determination of the increment of K_{1i} after vibropercussive action is based on the selection of a structural model of the pore space [12]. The Coseni equation is well recommended for soil calculations, and the Coseni–Kármán equation for dense rock. In addition, the Darcy equation is assumed to be valid in the subcritical regime after vibropercussive conditioning [5].

We note that, in contrast with the critical loading of a structure, for a stratum p_1 must exceed the rock pressure and, rather than a single fissure, it is necessary that n_i fissures open in the ith zone. It follows from Eqs. (1.2) and (1.5) that the principal reference stratum characteristics influencing ΔQ do not depend on the shape of the stratum. It is evident from calculations and from practical experience [3, 4] that the main factor affecting ΔQ is the first face zone, $i = 1$. It follows from the last equation (1.1) that the choice of L_0 does not influence t_*. It is customarily assumed that $L_0 = r_{01}$. The interference of waves from the base and roof of the stratum is ignored, because the influence of the wave process on ΔQ is insignificant. If $\Delta t < t_{*\max}$, each successive pulse is generated along the stratum with the old initial data, and Δm_i, K_{1i}, and n_i increase identically. If, on the other hand, $\Delta t > t_{*\max}$, each successive pulse is generated along the stratum with new physical characteristics. According to the Coseni–Kármán equation, the number of bursts can be decreased as the cube root to obtain the same ΔQ_N in this case.

The stated problem is solved by the following general algorithm:

1) The effective characteristics of a stratum having a specified mineralogical composition are calculated, and the ranges of the parameters of the external disturbance, the well fluid, and the overlying rock are given as input.

2) The quantities A_1, r_+, and A_* are determined with the decay of the discontinuity at the contact boundaries of the stratified medium taken into account according to the procedure in [5].

3) For each zone $E/dM - E$ is computed from the calculated equation of state of the stratum, and p_{1i} is determined.

4) The new physical characteristics of the stratum after a single action are calculated from p_{1i}.

5) The increments ΔQ are summed over the zones after a single burst, and ΔQ_N is determined.

6) The time t_* is calculated in the interval $d\varepsilon/dt = (10^{-2}\text{-}10^{-6})\ \text{sec}^{-1}$ [5]. Note that fracture (and hence restructuring of the stratum) is impossible for $L(d\varepsilon/dt) < \sigma_{1*}v_*/(\rho c_t^2)$ [13]. Accordingly $(d\varepsilon/dt)_{\min} = p_{1*}v_*/(\rho c_t^2 L_i)$.

2. Calculations have been carried out by the above-described algorithm on an IBM PC/386 personal computer for two injection wells and a producing stratum comprising sandstone and morainal pebble–gravel deposits. To determine the influence of the conditioning regime on ΔQ_N and r_+, the values of A_0 and T are varied over the ranges $A_0 = 1\text{-}10$ MPa and $T = (2\text{-}6)\cdot 10^{-2}$ sec. The initial data of the strata are determined from [14, 15], since conditioning was not preceded by preliminary geophysical studies. As postulated, the contribution to ΔQ_N from the first zone ($i = 1$) is predominant (96-98%), and the width of the zone is $dr_1 = 10^{-1}\text{-}10^{-2}$ m.

For both wells ($i = 1$) $t_{*\max} = 207\cdot 10^3\text{-}5.3$ sec (for the adopted interval of variation of $d\varepsilon/dt$, which exceeds the specified interval Δt by 1 sec and 4 sec). Consequently, the condition $\Delta t < t_{*\max}$ is established.

For $A_0 = 10$ MPa the range of variation of r_+ is equal to 3.62-29.2 m for both wells. Taking into account the possible variations of A_0, T, d_e, r_*, K_1, and N, our analysis of the reported calculations indicates the following qualitative relative impact of these parameters in diminishing order of influence: r_+ by A_0, r_*, T, K_1^{-1}; ΔQ_N by A_0, r_+, r_*, T, d_e, N. The range of variation of $(d\varepsilon/dt)_{\min}$ is $0.625\cdot 10^7\text{-}8.6\cdot 10^{-6}\ \text{sec}^{-1}$. Consequently, the values of $(d\varepsilon/dt)_{\min}$ differ very little from those determined in [5]. The increase in temperature for the computed values of $p_{1\max}$ according to the equation of state of the strata

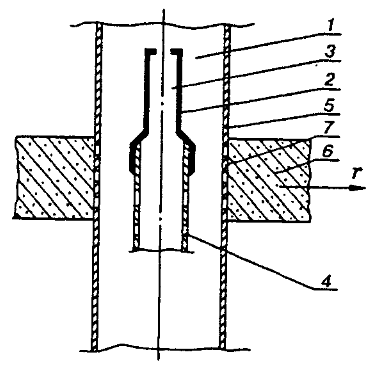

Fig. 1

is negligible, and $p_{1\max} \approx 10^8$ Pa, which generally agrees with the data of [5] for calcite. The discrepancy of ΔQ_N with the experimentally determined value is not greater than 5-10%.

To prevent the discrepancy from becoming too large, it is essential to conduct preliminary geophysical studies in the well, along with a laboratory investigation of the physicochemical properties and a sieve analysis of the face zone of the stratum, which is the zone contributing predominantly to ΔQ_N, since the handbook data for any rock or soil fluctuate over wide ranges [14, 15].

Here the ratio $(Q_0 + \Delta Q_N)/Q_0 = 2.5\text{-}2.67$ after pneumatic conditioning of both wells. Calculations show that during the existence of elastic wave fields in the stratum for a time $t_1 << t_*$, despite the slight increase in the porosity and fissility, the increment of the influx as a result of this factor is zero. If the height of the filter is less than the height (strength) of the stratum, then $\approx 90\%$ of ΔQ_N is associated with the producing part of the stratum next to the filter for steel casings. However, this does not extend to the polyethylene casings used in geotechnological wells [15].

3. We now describe experimental data in support of certain assumptions underlying the theoretical scheme set forth above. The customary positioning of well pneumatic drivers in an injection well for vibropercussive action is shown in Fig 1. The pneumatic driver 2 with discharge openings 4 is placed in the well fluid (water) 1 inside the casing 5, which is equipped with the filter 7. Compressed air is pumped into the interior volume of the working chamber 3 of the pneumatic driver. The filter usually overlaps the height (strength) of the producing stratum 6.

Special experiments have been performed to determine how loading influences the structure of the well and the stratum. The technological basis for the design of the recording instrumentation was the ASP-S instrument package developed at the All-Russian Scientific-Research, Planning, and Design Institute of Explosion Geophysics (VNIPIvzryvgeofizika). The package includes well and above-ground apparatus plus devices for the initiation, measurement, and recording of signals. Initiation is achieved by pneumatic drivers with working chambers of various volumes and outside diameters. The pulse amplitudes in the media (water and the stratum) were measured by strain-gauge pressure transducers calibrated for the range 2.5-29 MPa in conjunction with an N-117 multichannel CRT oscilloscope. Real-time, on-line monitoring of the amplitude variations was achieved by means of a digital pulse-signal amplitude recorder using a Topaz-3 strain-gauge amplifier with an Agat dc power pack. The triggering of the oscilloscope was synchronized with the firing of the pneumatic driver by an electropneumatic valve.

The ASP-S instrumentation was set up on the ground near the well, and the pressure transducers were placed in the well at a fixed distance of 0.1-0.5 m below the discharge openings of the pneumatic driver, making it unnecessary to allow for the attenuation of the signal along the vertical coordinate in the well fluid. If p^0 and p^{00} are the pulse amplitudes near the filter and in the blind casing without the filter, a decrease in the quantity $1 - p^0/p^{00}$ indicates low or zero output in the stratum, whereas an increase in this quantity indicates high yield from the given depth interval of the stratum for uniform motion of the pneumatic driver along it. The well-site experiments were accompanied by bench experiments inside a steel pipe, which simulated the filter-equipped casing and was filled with water. The pipe was also immersed in water up to a depth of 15 m. The recording system provided a flat frequency response for the recording of pulse pressures in the range 3-500 Hz.

The results of pneumoimpulsive logging by means of the above-described ASP–S instrumentation are shown in Fig. 2 for NGDU Chekmagushneft' well N22342/7 with two sandstone water-bearing strata 3, calculated in Sec. 2 before (line 1) and after (line 2) pneumatic conditioning of the strata. The filters completely spanned the strata 3. The permeability of the working intervals of the filters increased significantly after conditioning; prior to conditioning, the upper stratum had a lower

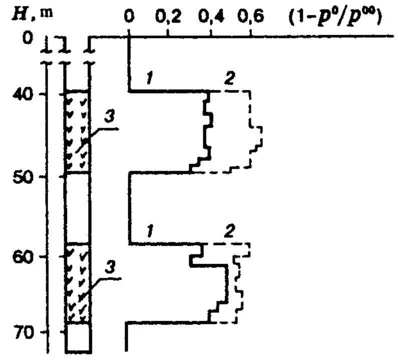

Fig. 2

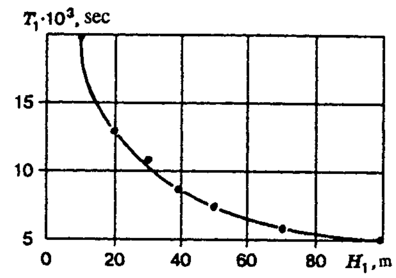

Fig. 3

permeability than the lower stratum. It is evident from Fig. 2 that p^0 remains constant in the filter for the above-described pneumatic conditioning technology. This means that the assumption used in the theoretical scheme regarding the maximum initial pulse amplitude $A_1 = \text{const}$ in the volume V_0 ($i = 1$) of the stratum is indeed valid. We have confirmed the validity of interpreting the stratified medium in which a pulse with the initial amplitude A_0 propagates as air–water–stratum in the presence of the filter and as air–water–casing–stratum in the presence of a blind casing.

An investigation of the behavior of the postdischarge gas cavity in the bench experiments shows that the period T_1 of the first pulsation of the gas cavity depends strongly on the inside diameter of the steel pipe (0.115 s for a diameter of 0.2 m and $55 \cdot 10^{-3}$ sec for a diameter of 0.36 m). In free-standing water using the same pneumatic driver $T_1 = 3 \cdot 10^{-2}$ sec at a submersion depth $H_1 = 15$ m. In this case the volume of the working chamber was $0.5 \cdot 10^{-3}$ m^3. The maximum radius of the gas cavity is equal to 0.15 m ($H_1 = 15$ m) or 0.1 m ($H_1 = 100$ m) for $A_0 = 10$ MPa. If the working chamber is replaced by a gas cavity of the same volume ($0.5 \cdot 10^{-3}$ m^3) with a radius of 0.05 m, the implication is that a point on the surface of a spherical cavity oscillates with an amplitude of 0.1 m ($H_1 = 15$ m) or 0.05 m ($H_1 = 100$ m). In free-standing water the amplitude is reduced by one fourth at the corresponding submersion depth of the pneumatic driver H_1. Since the experiments show that the filter has scarcely any influence on the pulsations, they were subsequently conducted in free-standing water. The pulse parameters were recorded at pneumatic chamber submersion depths $H_1 = 10\text{-}100$ m, i.e., at various hydrostatic pressures p_-.

Figure 3 shows the experimental dependence of T_1 on H_1 for a pneumatic chamber with a working volume of $0.2 \cdot 10^{-3}$ m^3 for $A_0 = 10$ MPa. A comparison of the above data on T_1 in free-standing water for a larger chamber volume ($0.5 \cdot 10^{-3}$ m^3) shows that T_1 is shorter for the smaller volume (Fig. 3). The experimental data on the amplitudes of the cavity oscillations in the presence of a filter show that they are always smaller than the distance from the discharge site to the stratum for the usual industrial pneumatic driver modifications. This means that the gas cloud does not enter the stratum in vibropercussive conditioning, and the assumption to that effect in the theoretical scheme is valid.

The oscillograms of the pressure pulses show that they are roughly sinusoidal with a maximum initial amplitude. The first compression wave is followed by an alternating compression and rarefaction determined by the pulsation of the gas cavity. The duration of the wave train is calculated in milliseconds and is shorter than Δt, validating the fact that the algorithm operates with only the first wave front with amplitude A_1 in the zone $i = 1$. Experimental studies of the propagation of impulsive pressure waves show that it is consistent with the acoustical approximation of shock wave theory. This validates the attenuation law (1.4) used in the calculations.

On the whole, wave methods of investigation of the system well–stratum lead to the conclusion that the application of low-frequency ($f \leq 40$ Hz) vibropercussive conditioning of strata is well recommended in practice. It is evident from the experiments that T_1 and, hence, the values of A_1, r_+, and ΔQ_N increase when the working volume of the pneumatic chamber is increased (r_* is decreased) for a constant well diameter. On the other hand, according to the analysis of the calculations in Sec. 2, an increase in r_* tends to decrease the attenuation of the pressure in the stratum and causes r_+ and ΔQ_N to increase. The competition between these two opposing patterns of influence of r_* suggests the existence of an optimum value of r_* in each specific instance, corresponding to a particular pneumatic driver modification.

A comparatively less sparse grid of existing wells working the same producing stratum has been used to make a preliminary study of the behavior of wave propagation in the stratum. The experimental procedure called for an impulsive burst to be generated in one well and recorded in others at various distances from it. The monitored quantity was the piezoelectric intensity in the target wells, measured by means of remote ultrasonic level meters. The correspondence of the recorded signals with the transmitted signals was tested using the burst-transmission time code. The pneumatic chamber with a volume of $0.5 \cdot 10^{-3}$ m^3 was triggered by a synchronizing transducer simultaneously with the recording electronics of the ultrasonic level meter.

The experimental well ran to a depth of 180 m, opening water-bearing fissile limestones of the Klyaz'ma or Kasimov level. The results exhibit the low-frequency (0.05-0.06 Hz) pattern of the recorded oscillations within ranges of up to 105 m from the pneumatic-source well, which exceeds the above-calculated values of r_+ for a single well. It should be borne in mind, however, that the radius r_+ has been calculated for strata having a different mineralogical composition and is interpreted as the producing part of the stratum for the same well where the pneumatic driver was placed in the case of a single-shot discharge. For the target wells, of course, the values of ΔQ_N are lower. Many series of pneumatic bursts were used in the above-described experiments, so that the energy E_* in the stratum after a long conditioning time can be assumed to be cumulative to much greater distances than r_+ from the source well. This interpretation of the results of our preliminary experiments is consistent with the ideology of the basic tenets of self-organization theory [16] and confirms its applicability to the stated problem.

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