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ROCK FAILURE

CRACK DEVELOPMENT UNDER PULSE HYDRAULIC FRACTURING OF ROCKS

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The calculation scheme is developed for describing the hydraulic fracturing of rocks by explosion of charge in well. The investigation is conducted within the quasi-static approach to the analysis of crack propagation in the productive stratum.

Hydraulic fracturing, oil well, explosion, crack, fluid

One of the methods increasing the oil recovery is hydraulic fracturing of the productive stratum. Usually it is carried out by injecting the fluid into the well, which results in formation of extended crack within the stratum. Besides, there are the hydraulic fracturing technologies which use the pulse increase in the well pressure due to either explosion of charge located in the well [1] or operation of submerged powder gas-generator [2].

Currently, the theoretical simulation of pulse hydraulic fracturing is insufficiently developed. This is governed by the complexity of describing the process dynamics. In this paper, the approximate calculation scheme of hydraulic fracturing in the dynamic statement is proposed. The basic simplifying assumption is substantiated in [3]: the fluid filling the well and causing the hydraulic fracturing is considered ideal and incompressible.

PROBLEM STATEMENT

In a well with the depth H and the cross-section area S, packer *1* is installed at the height z_p from the face (Fig. 1). Explosive charge *2* of the length L_c is located under the packer. To pump out the oil from productive stratum *3*, the perforated section of the length W adjoins the bottom part of the well. It is assumed that the stratum thickness is equal to W. Hydraulic fracturing crack *4* is of the same height; it propagates symmetrically about the well in the productive stratum and does not penetrate into enclosing rocks. As is shown in [4], this is possible if the productive stratum is bounded by plastic rocks. In this case, the crack opening is constant relative to height.

The pulse hydraulic fracturing occurs in the following way. After the charge initiation, a gas-filled cavity forms. Under the gas pressure, the fluid from below the packer starts flowing into the crack of the initial length $2L_0$ thus expanding it. When the stress intensity coefficient K_I is equal to the critical value K_{IC}, the crack begins propagating with the velocity $\dot{L}$ determined by the dynamic crack resistance. If K_I becomes lower than K_{IC}, the growth in crack and filling it with fluid cease. Then, under the action exerted by the elastic forces and lithostatic pressure, the fluid flows into the well in backward direction and stops when the gas compression becomes maximal. Later on, such flow

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continues periodically; its attenuation depends on the fluid viscosity and elastic wave radiation in the stratum. In the present paper, these effects are not taken into account, the calculations are carried out before the termination of the first half-period of steady oscillations.

CALCULATION SCHEME

In order to describe the dynamics of fluid flow under the pulse hydraulic fracturing, we use the energy conservation law $T+\Pi+G=\Pi_0$, where T is the kinetic energy of fluid and stratum rock; Π_0 and Π are the initial and current potential energies, respectively; G is the energy spent for the crack formation.

Deformation of the productive stratum is investigated in the approximate quasi-static statement, which is governed by the small velocities of crack development and opening. The value of opening in the horizontal cross-section is obtained from the solution of the elastic plane problem for the single linear cut loaded by internal pressure. The crack edges form an ellipse with the major $2L$ and minor $2u$ axes. The parameters of fluid flow in the crack were calculated on the assumption that the crack opening h is constant with respect to length, and the volume is equal to that one of elliptical shaped crack $V=4hLW=\pi uLW$, where L is the half-length, and $h=\pi u/4$. The values of h and L are accepted as generalized coordinates. The fluid velocity v_z in well is associated with the change in crack dimensions. Within the interval $W<z<z_k$ (z_k is the coordinate of gas-fluid interface), it is constant:

$$v_z=v_b=\frac{4W(\dot{h}L+\dot{L}h)}{S}. \tag{8}$$

In the reservoir zone, at $0<z<W$ the fluid flows into the crack through the holes in casing pipe along the well. Assuming that filling of the crack is uniform over the whole stratum thickness, we obtain the equation for v_z along the well:

$$v_z=\frac{v_b z}{W}. \tag{9}$$

According to (8) and (9), the kinetic energy of fluid with the density ρ flowing in the well is determined by the relation:

$$T_1=\frac{\rho SWv_b^2}{2}\left(\frac{z_k}{W}-\frac{2}{3}\right). \tag{10}$$

From the condition of incompressibility, we have $z_k=z_p-L_c-4hLW/S$.

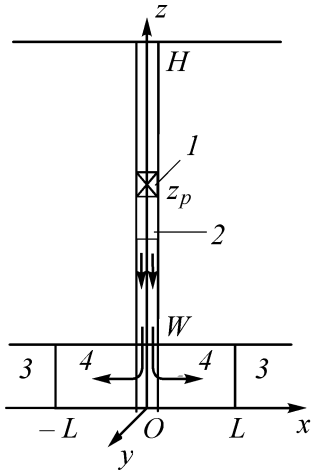

Fig. 1

The fluid flow in the crack cavity can be expressed in terms of the potential φ:

$$\varphi(x, y, z, t) = a(t)x + b(t)(x^2 - y^2), \tag{11}$$

where (x, y, z) is the Cartesian coordinate system (Fig. 1); a and b are the arbitrary functions of time to be found from the boundary conditions for the velocities.

On the crack edges, $v_y = \dot{h}$ provided $y = \pm h(t)$. At $x = L$ along the crack front, $v_x = \dot{L}$, and when $x = 0$ along the well, $v_x = \dfrac{v_b S}{4hW}$.

In the coordinate system, the origin of which is displaced along the x-axis by $L/2$, relation (11) satisfying the boundary conditions takes the form:

$$\varphi = \frac{v_x(0) + \dot{L}}{2} x - \frac{\dot{h}(x^2 - y^2)}{2h}. \tag{12}$$

The kinetic energy of fluid in the crack is expressed by the contour integral:

$$T_2 = \frac{1}{2} \rho W \oint \varphi \frac{\partial \varphi}{\partial n} ds,$$

where n is the normal to the crack surface.

Substituting (12) and (8) in the equality above, we find:

$$T_2 = \rho hLW \left[\left(\dot{L} + \frac{\dot{h}L}{2h} \right)^2 + \frac{1}{3} \dot{h}^2 \left(1 + \frac{L^2}{4h^2} \right) \right]. \tag{13}$$

The crack growth in the productive stratum leads to its deformation. A part of work of detonation product gases in the well converts into the kinetic T_3 and potential U_1 energies. The value of T_3 is estimated on the basis of change in volume of the crack cavity according to the solution of static problem on deformation of sphere under the action of internal pressure in the elastic space. In the quasi-static approximation, we obtain the expression:

$$T_3 = \frac{2\pi \rho_1 SW}{9} \left(\frac{3}{4\pi} \right)^{\frac{5}{3}} V^{-\frac{4}{3}} \dot{V}_c^2, \tag{14}$$

where ρ_1 is the rock density, $V_c = SW + 4hLW$ is the cavity volume. The total kinetic energy value $T = T_1 + T_2 + T_3$.

Let us calculate the potential energy U_1 of stratum deformation using the solution of static problem on linear cut loaded by internal pressure in the elastic plane:

$$U_1 = \frac{4h^2 EW}{\pi} + 4hLWP, \tag{15}$$

where E is Young's modulus; P is the lithostatic pressure.

On the assumption of adiabatic expansion and compression of detonation product gases, we find their potential energy U_0:

$$U_0 = \frac{p_0 V_0}{\gamma - 1} \left(\frac{V_0}{V} \right)^{\gamma - 1}, \tag{16}$$

where p_0, $V_0 = SL_c$, and $\Pi_0 = \dfrac{p_0 V_0}{\gamma - 1}$ are the initial pressure, volume, and energy of gases after the charge initiation, respectively; γ is the adiabatic exponent; $V = SL_c + 4hLW$ is the current value of gas volume.

In this accordance, $\Pi = U_0 + U_1$. The energy G consumed for the formation of new surfaces of hydraulic fracturing crack satisfies the differential equation [5]:

$$\dot{G} = \frac{(1-\nu^2)K_I^2 \dot{L}}{E}, \tag{17}$$

where ν is Poisson's ratio. For the isolated crack in static approximation [5]:

$$K_I = \frac{2hE}{\sqrt{\pi L}}. \tag{18}$$

From (10), (13) – (15), and the law of energy conservation, it follows:

$$T_1 + T_2 + T_3 + U_0 + U_1 + G = \Pi_0. \tag{19}$$

Expressing all the terms in (19) through h and L, we can find the equation for $\dot{h}$:

$$\dot{h} = \frac{\sqrt{k_2{}^2 - k_1 k_3} - k_2}{k_1}, \tag{20}$$

where

$$k_1 = L^2\left(a_1 + \frac{2}{3}a_2\left(1 + \frac{h^2}{L^2}\right)\right); \quad k_2 = hL\dot{L}(a_1 + a_2), \quad k_3 = h^2\dot{L}^2(a_1 + 2a_2) + a_3;$$

$$a_1 = \frac{8W^3}{S}\left[\left(\frac{z_p - L_c}{W} - \frac{2}{3} - \frac{4hL}{S}\right)\rho + \left(\frac{3}{4\pi}\right)^{2/3}\frac{\rho_1 S^2}{3(SW + 4hLW)^{4/3}}\right]; \quad a_2 = \frac{\rho LW}{h};$$

$$a_3 = G + 4hLWP + \frac{4h^2 EW}{\pi} + \frac{p_0 V_0}{\gamma - 1}\left[\left(\frac{V_0}{V}\right)^{\gamma - 1} - 1\right].$$

The value $\dot{L}$ is determined by the dynamic crack resistance of medium being failed; in this paper, it is approximated by the dependence [6]:

$$\dot{L} = \begin{cases} 0, & K_I \le K_{IC}, \\ v_m\left(1 - e^{-\alpha\left(\frac{K_I}{K_{IC}} - 1\right)}\right), & K_I > K_{IC}, \end{cases} \tag{21}$$

where v_m is the maximum velocity of crack propagation; α is the empirical parameter.

The numerical solution of the problem obtained makes it possible to find the laws of both the crack length time-variation and the crack opening in hydraulic fracturing.

CALCULATION RESULTS

System of (18), (20), and (21) was calculated at the following parameters: $\rho = 1000$ kg/m^3, $\rho_1 = 3000$ kg/m^3, $E = 50$ GPa, $\nu = 0.3$, $\alpha = 1$, $K_{IC} = 10^6$ Pa$\cdot$m$^{0.5}$, $v_m = 650$ m/s, $p_0 = 200$ MPa, $\gamma = 1.3$, and $S = 0.0154$ m^2. Some parameters varied: $P = 5 - 30$ MPa, $z_p = 100 - 1000$ m, $L_c = 0.5 - 2$ m, and $W = 10 - 30$ m. For safety of casing pipe, the charge parameters were chosen with respect to the condition of using the small capacity explosives with the energy of 10^8 J/m, which is equivalent to the explosion of ammonite with the consumption of 2.5 kg/m.

The calculation results are presented as curves of $h(t)$ and $L(t)$ in Figs. 2 – 5. The functions $L(t)$ increase monotonically until the moment of crack growth cessation. The greatest value of $L = L_m$ is governed mainly by the lithostatic pressure (Fig. 2*a*), the energy of charge (Fig. 3*a*), and the thickness of productive stratum (Fig. 4*a*). The parameter L_m is independent of z_p (Fig. 5*a*); however, it affects the increase in the time T_m of the crack development at the maximum length. The similar variations take place in T_m with decrease in P and increase in L_c.

The dependences $h(t)$ have an oscillatory character similar to that one illustrated by curves *2* and *3* in Fig. 2*b*. The other graphs in Figs. 2*b* – 5*b* are shown at the initial time period until the moment when the cracks begin opening at the constant value $L = L_m$; they repeat symmetrically every half-period $T_p / 2$ between the moments of minimal h(t) and the previous termination of the crack opening. In the variants calculated, the values T_m and T_p turned out changeable within 0.4 – 5 and 1.2 – 12 s, respectively. For the productive stratum at the occurrence depths of 330 and 1000 m (the pressure is 10 and 30 MPa), the maximum dimensions of cracks formed by hydraulic fracturing were equal to 200 and 80 m, and the amplitudes of opening — 0.18 and 0.11 mm, respectively.

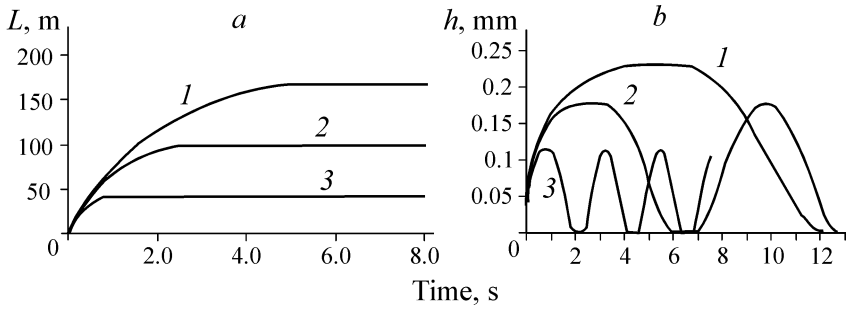

Fig. 2. Curves *1*, *2*, and *3* correspond to the pressure P = 5, 10, and 30 MPa

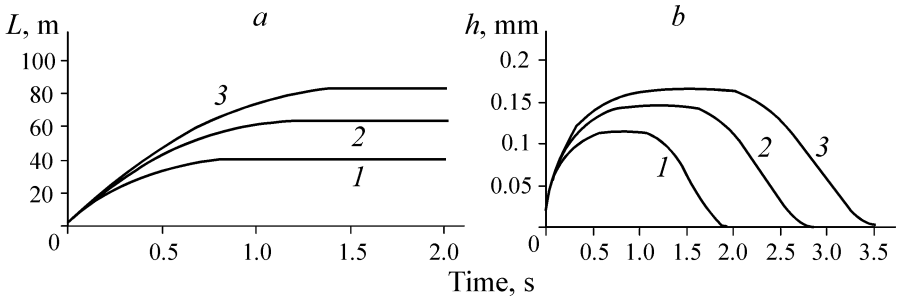

Fig. 3. Curves *1*, *2*, and *3* correspond to the charge lengths L_c = 1, 2, and 3 m

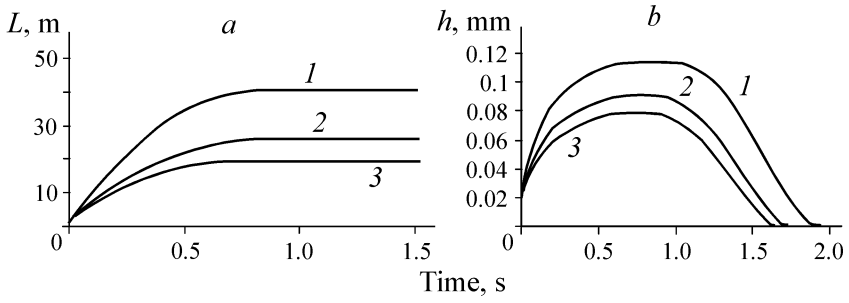

Fig. 4. Curves *1*, *2*, and *3* correspond to the stratum thickness W = 10, 20, and 30 m

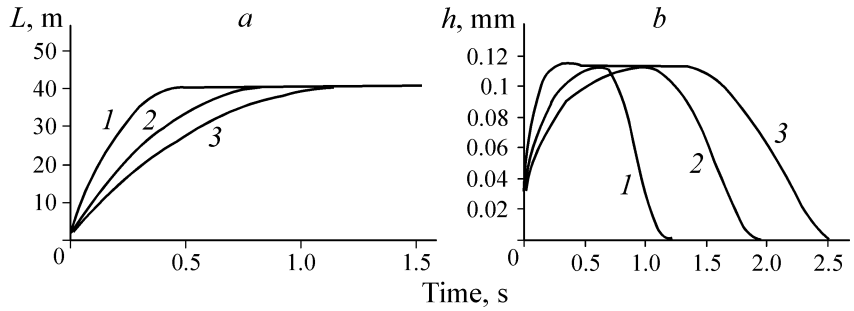

Fig. 5. Curves *1*, *2*, and *3* correspond to $z_p = 100$, 500, and 1000 m

CONCLUSIONS

The calculations show that the explosion of charge with a mass of approximately 2.5 kg in the oil well equipped with the packer leads to the hydraulic fracturing of the productive stratum in perforated interval zone and the formation of crack 80 – 200 m in length with regard for the stratum occurrence depth. As a result of the explosion, the low-frequency oscillatory process of periodic fluid flow takes place in the *well – hydraulic fracturing crack* system; it can be employed both for cleaning the reservoir and exerting the vibration action on the enclosing productive stratum.

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