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DETERMINATION OF HYDRODYNAMIC LOAD ON THE WALL OF A WELLBORE FORMED BY AN ELECTRIC DISCHARGE

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Hydrodynamic processes in the discharge chamber of a device intended to increase the fluid conductivity of the porous medium in the well bottom zone are studied. Spatial and temporal characteristics of the pressure waves resulting from an electric discharge in a fluid are determined. The effect of the performance of the electric-discharge device and the wellbore fluid pressure on the dynamic load acting on the wellbore wall are determined.

The hydrodynamic processes in the chamber of an electric-discharge device (EDD) used to treat oil wells to improve the filtration characteristics of their bottom zones are studied using a mathematical model.

A diagram of the discharge chamber of the EDD is shown in Fig 1. Here 1 and 2 are electrodes, 3 is a polyethylene electric insulator, 4 is a "window" of the device, 5 is a wellbore wall, 6 is a discharge channel, and 7 is a boundary of the gap between the EDD and the wellbore wall. The principle of operation of the EDD is as follows. An electric discharge between the electrodes leads to formation of a cavity filled with a plasma (discharge channel), in which the pressure can reach 10^9 Pa, which is much higher than the ambient fluid pressure [1]. As a consequence, the cavity begins to expand. The resulting compression wave and its attendant fluid flow through the "window" of the device reach the wellbore wall. The hydrodynamic load acting on the wall gives rise to radial cracks in the bottom zone, which increase the permeability of the bed. In addition, the load leads to relative motion of the matrix and the fluid, which facilitates an increase in the permeability of the matrix [2]. The effect of the hydrodynamic load depends on pressure-wave parameters. Therefore, the main goal of the studies performed was to determine the hydrodynamic load on the wellbore wall.

In constructing a mathematical model for the process considered, we adopted the following assumptions: the discharge chamber is axisymmetric; the walls of both the chamber and the well are absolutely rigid; at the initial time, the cavity produced by the electric discharge has the shape of a right circular cylinder whose height is equal to the interelectrode spacing and whose symmetry axis coincides with the symmetry axis of the EDD and the cavity; the wellbore wall is impermeable; the well is filled with an ideal compressible fluid, and the discharge channel is filled with an ideal plasma.

In accordance with the adopted assumptions, the mathematical formulation of the problem was as follows. In the region whose inner boundary is the plasma–water discontinuity (discharge channel wall) and whose outer boundary is an immovable rigid wall (surface of the well and the EDD) and the boundaries of the gap between the EDD and the wellbore wall (Fig. 1), it is necessary to solve the following system of two-dimensional nonlinear gas-dynamic equations written in cylindrical coordinates and expressing the laws of conservation of mass, momentum, and energy [3]:

$$\frac{\partial(rF_1)}{\partial t} + \frac{\partial(rF_2)}{\partial z} + \frac{\partial(rF_3)}{\partial r} = F_4,$$

$$F_1 = [\rho, \rho v_r, \rho v_z, e]^{\rm t}, \quad F_2 = [\rho v_z, \rho v_z v_r, \rho v_z^2 + p, (e+p)v_z]^{\rm t}, \tag{1}$$

$$F_3 = [\rho v_r, \rho v_r^2 + p, \rho v_r v_z, (e+p)v_r]^{\rm t}, \quad F_4 = [0, p, 0, 0]^{\rm t},$$

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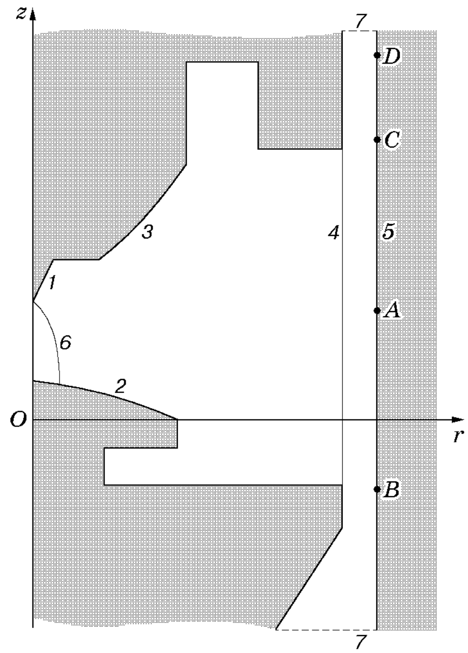

Fig. 1

which is closed by the equation of state in two-term form [3]

$$\varepsilon = [p - c_0^2(\rho - \rho_0)]/[\rho(æ - 1)]. \qquad (2)$$

Here t is time, r and z are cylindrical coordinates, v_r and v_z are the fluid-velocity components along the Or and Oz axes, respectively, p is the pressure, ρ is the density, $e = \rho[\varepsilon + (v_r^2 + v_z^2)/2]$, ε is the specific internal energy, $æ = 7.15$, ρ_0 and c_0 are the density of the unperturbed fluid and the speed of sound in it.

On the inner boundary of the calculation domain, we specify the pressure determined by solving the equation of energy balance in the discharge channel [1]:

$$\frac{1}{\gamma - 1}\,\frac{d(p_{\rm ch}V_{\rm ch})}{dt} + p_{\rm ch}\,\frac{dV_{\rm ch}}{dt} = N(t). \qquad (3)$$

Here $\gamma = 1.26$, $p_{\rm ch}$ and $V_{\rm ch}$ are the discharge-channel pressure and its volume, respectively, and $N(t)$ is the rate of energy input into the discharge channel.

On the immovable rigid wall, we impose the nonpenetration condition [3]

$$v_n = 0, \qquad (4)$$

where v_n is the normal component of the fluid velocity.

On the boundaries of the gap between the EDD and the well wall, the fluid pressure is set equal to the wellbore hydrostatic pressure: $p = p_{\rm h}$. The boundaries of the gap are located at a distance such that the pressure waves from the discharge channel do not reach them over the period of time considered (analog of an infinite boundary).

The initial conditions are formulated as follows:

— the values of the hydrodynamic characteristics correspond to the unpertubed state of the fluid;

— the rate of channel expansion is equal to zero and the channel radius is equal to 0.1 mm;

— the discharge channel pressure is 1 MPa higher than the ambient fluid pressure.

System (1), (2) is solved by Godunov's finite-difference method [3] using a movable computational grid constructed taking into account the shape of the inner surface of the discharge chamber and the expansion of the discharge channel. The pressure $p_{\rm ch}$ is determined from Eq. (3) by Euler's two-step method. The volume of the discharge channel $V_{\rm ch}$ and its time derivative are calculated from the coordinates of the channel surface and the rate of its expansion, obtained by solving the problem of decay of an arbitrary discontinuity [3] on the plasma–fluid interface. The algorithm used to solve the interior problem of hydrodynamics for an electric discharge in water is given in [4].

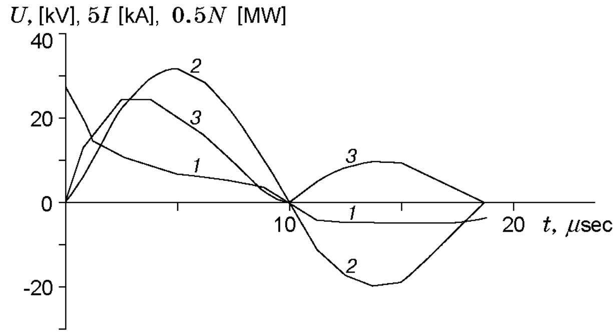

Fig. 2

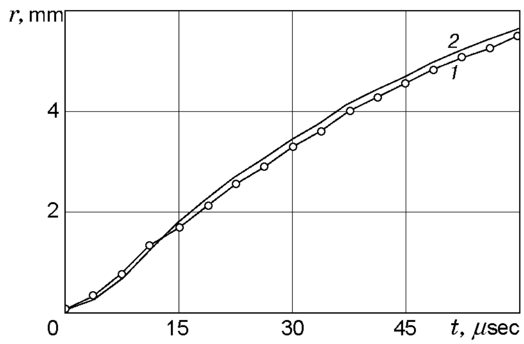

Fig. 3

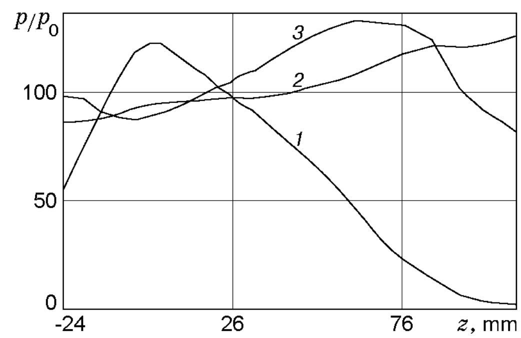

Fig. 4

The function $N(t)$ in Eq. (3) is determined from the formula $N(t) = U(t)I(t)$, where $U(t)$ and $I(t)$ are the voltage and current in the discharge channel. The functions $U(t)$ and $I(t)$ are obtained from data of an experiment in an EDD whose discharge chamber is shown schematically in Fig. 1. The initial voltage of the capacitor bank of capacitance 2.4 μF is 30 kV, the electric circuit inductance is 3 μH, and the electrode spacing is 0.025 m. The dependences $U(t)$, $I(t)$, and $N(t)$ obtained for a hydrostatic pressure $p_{\rm h} = 0.1$ MPa are given in Fig. 2 (curves 1–3, respectively).

The adequacy of the present mathematical model to real process was verified by comparing experimental and calculated data. Figure 3 gives time dependences of the discharge channel radius in the equatorial plane obtained experimentally (curve 1) and by solving problem (1)–(4) (curve 2).

The time of arrival of the compression wave produced by the electric discharge at different regions on the wellbore wall and the wave intensity are determined by the distance from these regions to the discharge channel and the shape of the region occupied by the fluid. The wave front first reaches the wall in the plane of the midsection of the discharge channel (point A in Fig. 1) [5]. Then, the perturbation gradually spreads over the entire surface. The nonsimultaneuos arrival of the compression wave at different regions leads to a nonuniform pressure distribution along the wall in the initial period (period of main loading). With time, the pressure distribution along the wellbore wall becomes more uniform. The curves given in Fig. 4 characterize this distribution in the direction from the point B to the point D (see Fig. 1) at the times $t = 50$, 100, and 150 μsec (curves 1–3, respectively).

Curves of pressure versus time at the points A, B, C, and D (see Fig. 1) are shown in Fig. 5 (curves 1–4, respectively). In the region of the wellbore wall between the points C and D, the pressure variation is qualitatively the same but the rate of pressure rise decreases with distance from the discharge channel.

At all points on the wellbore wall located near the "window" of the EDD, after reaching the maximum value due to arrival of the compression wave from the discharge channel, the fluid pressure can have additional maxima from the waves reflected form the EDD surface. These maxima, however, are much smaller than the first, and, therefore, the hydrodynamic load on the wellbore wall is determined to a larger extent by the first pressure pulse. After the attainment of the largest value, the time variation of the wellbore wall pressure is satisfactorily approximated by the dependence

$$p = p_{\max}[1 - s_m \sin(2\pi t/\tau_s)] \exp(-t/\tau_e), \qquad (5)$$

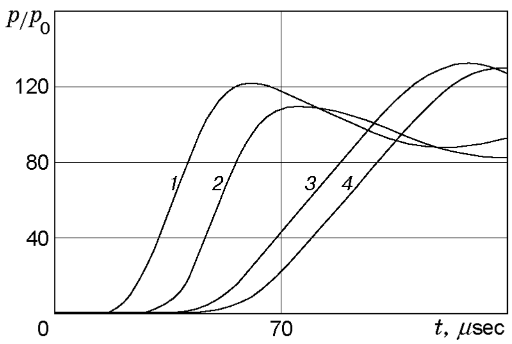

Fig. 5

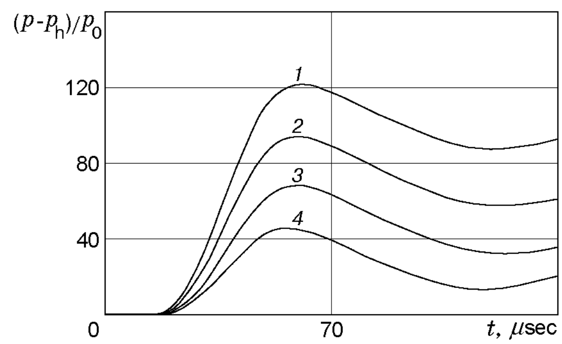

Fig. 6

where $p_{\max}$ is the maximum pressure on the wellbore wall; the period of change in the sinusoidal component (τ_s) the exponent constant (τ_e), and the maximum value of the sinusoidal component (s_m) are approximation parameters.

Relation (5) is conveniently used when one need to know the hydrodynamic load on the wellbore wall over a long period of time, in particular, in studying the processes in the well bottom zone [2].

Commercial oil beds can be located at depths reaching 5 km. The wellbore hydrostatic pressure can be as high as 50 MPa. Therefore, in studies of hydrodynamic processes in a well during an electric discharge, it is necessary to estimate the effect of hydrostatic pressure. Calculation results are given in Fig. 6, which shows the variation of the excess pressure on the wellbore wall in the midplane of the discharge channel (point A in Fig. 1) for values $p_{\rm h} = 0.1$, 5, 10, and 15 MPa (curves 1–4, respectively). These results indicate that an increase in hydrostatic pressure leads to a decrease in the amplitude and pulse of the excess pressure on the wellbore wall and over the entire volume of the fluid. The rate of expansion of the discharge channel, the volume of the channel, and the period of pulsations also decrease, i.e, an increase in the depth of immersion of the EDD reduces the effect of the electric discharge on the well bottom zone.

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