Journal of Mining Science, Vol. 38, No. 4, 2002

CALCULATION OF FLUID FLOW IN THE OIL WELL UNDER THE ACTION OF POWDER GAS GENERATOR

S. V. Serdyukov, E. N. Sher, and N. I. Aleksandrova UDC 622.235

A numerical algorithm is developed, and the parameters of fluid flow in the oil well under the action of powder charge are calculated. For different combustion conditions, the dependence of gas pressure on the time and the maximum amplitude of fluid rise are found. The value is obtained for decreasing the pressure in the well relative to the hydrostatic pressure in the stratum; the hydrostatic pressure arises in cooling down the gases to the ambient temperature.

Oil well, powder charge, gas pressure

INTRODUCTION

Exploitation of oil deposits is accompanied by deterioration of reservoir filtration properties in the well-bottom zone. To solve the problem on recovery of hydrodynamic well parameters, the widespread methods are used for impulse increasing or decreasing the pressure in the perforated interval of productive stratum. In oil-field practice the impulse increase is created by the pressure of gases forming during the powder charge combustion, while the rapid failure of walls of the hollow down-chamber causes the decrease in pressure. The method combining the mentioned types of action is developed in the Institute of Mining of the Siberian Branch of the Russian Academy of Sciences; it increases the technical and economic indices of well-bottom zone treatment [1], which is achieved by the fact that the packer with built-in check valve ensuring the fluid cross-flow from bottom to top is additionally installed above the powder charge (Fig. 1). When the powder charge is burning, the fluid from under the packer is displaced upwards and partially to the productive stratum (stage 1). At stage 2 the gas cavity cools down and collapses, which causes the decrease in pressure at the well bottom. Due to deep depression effect, an intensive flow of fluid from the productive stratum to the well arises; this flow favors the cleaning and increase in permeability of the well-bottom zone. The calculated model for the first stage of the process is given in this paper.

STATEMENT OF THE PROBLEM

There is an oil well with the depth l and internal diameter D. It is filled with oil and water, and the powder charge is located in the well-bottom zone. At the initial instant of time, combustion of the powder charge is initiated, as a result of which a large amount of hot gas is released. The fluid in the well starts flowing under the action of gas pressure.

INCOMPRESSIBLE FLUID MODEL

Let us consider the problem on the assumption of fluid incompressibility. In this case, its flow in the well with regard for viscous resistance is described by the equation

$$M\ddot{X} = P_1 F - Mg - R\,,$$

Institute of Mining, Siberian Branch, Russian Academy of Sciences, E-mail: sher@misd.nsc.ru, Novosibirsk, Russia. Translated from Fiziko-Tekhnicheskie Problemy Razrabotki Poleznykh Iskopaemykh, No. 4, pp. 38–45, July-August, 2002. Original article submitted August 26, 2002.

1062-7391/02/3804-0344$27.00 ©2002 Plenum Publishing Corporation

where X is the coordinate of gas-fluid boundary; t is the time; P_1 is the gas pressure; $F = 0.25\pi D^2$; $M = Fl\rho$ is the mass of fluid flowing in the well with the density ρ; R is the resistance force of viscous friction; g is the gravitational acceleration.

For the diatomic ideal gases, P_1 is determined by the internal energy of gases E and their volume W [2]:

$$P_1 = \frac{0.4E}{W}. \tag{1}$$

In this case, $W = FX + \dot{m}t/\rho_1$ ($\dot{m}$ and ρ_1 are respectively the mass rate of powder combustion and the powder density).

Let us assume that

$$\dot{m} = \dot{m}_0 H(t_0 - t),$$

where H is the Heaviside function; t_0 is the time of charge combustion.

Suppose that the process is adiabatic, then for E, we have

$$\dot{E} = \varepsilon\dot{m} - FP_1V_1. \tag{2}$$

Here, ε is the specific gas energy after the charge combustion; $V_1 = \dot{X}$ is the velocity of gas-fluid boundary motion.

The force of viscous friction was found by the empirical formula valid for the stationary fluid flow in the pipe with the Reynolds number in the range $3\cdot10^3 - 10^6$ [3]:

$$R(V_1) = 0.1582M\frac{\nu^{0.25}V_1^{1.75}}{D^{1.25}},$$

where ν is the kinematic fluid viscosity.

Thus, we have the system of equations:

$$M\dot{V}_1 = P_1F - gM - R, \tag{3}$$

$$P_1 = \frac{0.4EF}{FX + \frac{\dot{m}t}{\rho_1}},$$
$$\dot{E} = \varepsilon\dot{m} - FP_1V_1, \quad \dot{X} = V_1. \tag{4}$$

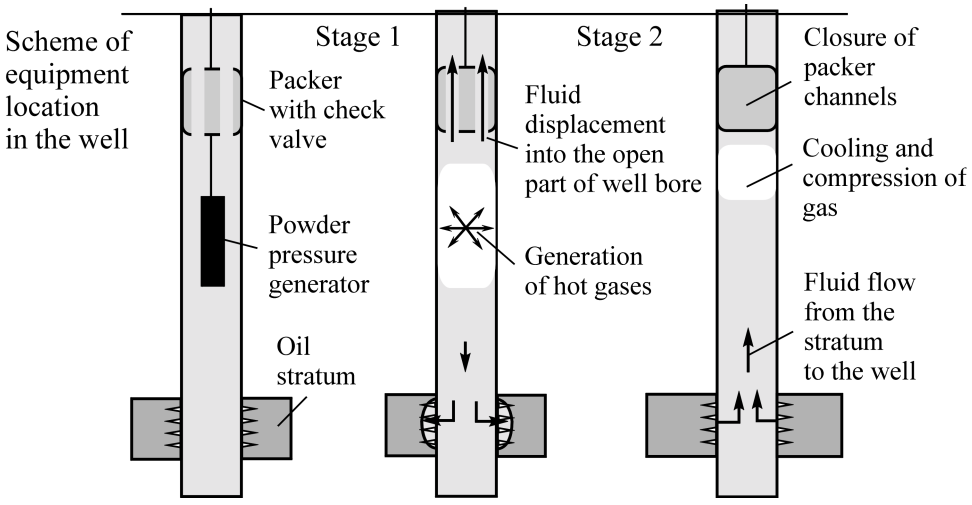

Fig. 1. Method of impulse well treatment

The problem was solved by integrating (3) and (4). As the gas generator, we considered a production powder charge with the following parameters: mass — 7.5 kg; $\varepsilon = 8.4 \cdot 10^6$ J/kg; combustion temperature — 2500°C; $\dot{m}_0 = 0.176$ kg/s; $t_0 = 42.5$ s; and $\rho_1 = 1830$ kg/m^3. The other parameters had the following values: $l = 500 - 2000$ m; $D = 0.14$ m; $\rho = 1000$ kg/m^3; and $\nu = (1 - 100) \cdot 10^{-6}$ m^2/s. The numerical calculations showed that when the powder charge starts burning, the acceleration of fluid column occurs within $1 - 10$ ms, then the regime of uniform fluid rise with a constant gas pressure has set in.

The stationary solution of (3) and (4) is found on the assumption that $\dot{V}_1 = 0$ and $X = V_1 t$. Then,

$$\frac{0.4F\varepsilon\dot{m}}{1.4FV_1 + \dfrac{\dot{m}}{\rho_1}} - Mg - R(V_1) = 0 . \tag{5}$$

When $R(V_1) = 0$, from (4) and (5) it follows:

$$V_1 = \frac{\dot{m}}{7}\left(\frac{2\varepsilon}{Mg} - \frac{5}{\rho_1 F}\right), \quad E = \frac{5}{7}\dot{m}\left(\varepsilon + \frac{\rho g l}{\rho_1}\right)t, \quad P_1 = \rho g l . \tag{6}$$

Figure 2 presents the calculation results of stationary velocity of fluid rise in the well under the action of powder gas generator for $\nu = 0, 1, 10, 100 \cdot 10^{-6}$ m^2/s (curves *1 – 4*). It is obvious that the influence of viscosity is weak, therefore, it can be neglected in more complicated models if the average fluid flow velocities are low.

CALCULATION OF FLUID FLOW WITH REGARD FOR ITS COMPRESSIBILITY

Assuming that the fluid flow velocities are low, let us use the linearized Euler equations. In this case, the fluid flow is described by the equation:

$$\frac{\partial^2 \varphi}{\partial t^2} = c^2 \frac{\partial^2 \varphi}{\partial x^2}, \tag{7}$$

where φ is the velocity potential; c is the velocity of acoustic wave propagation in fluid; x is the coordinate.

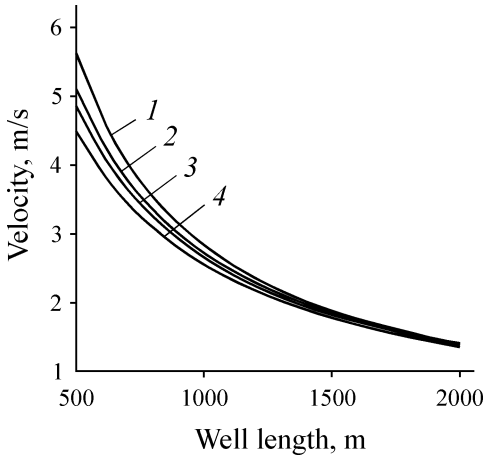

Fig. 2

For φ, the boundary conditions are determined by the absence of pressure at the upper end $x = l$ of the well:

$$\frac{\partial \varphi}{\partial t} = 0 \tag{8}$$

and by the continuity of pressures, as well as gas and fluid velocities at the lower end $x = 0$:

$$P - \rho \frac{\partial \varphi}{\partial t} = P_1, \quad V_1 = \frac{\partial \varphi}{\partial x}, \tag{9}$$

where $P = \rho g l$ is the hydrostatic fluid pressure near the charge.

Gas generation is described by Eqs. (4). The influence of viscosity is neglected. Let us consider the initial conditions of two types. The first ones correspond to the combustion from the moment $t = 0$:

$$X^0 = 0, \quad E^0 = 0. \tag{10}$$

From here on, the superscript "0" denotes the initial values.

Let us obtain the analytical solution on the interval $0 < t < 2l/c$ for (10). The solution of (7) for the wave moving in the positive direction: $\varphi = f(ct - x)$. For boundary conditions (9), the velocity of gas

$$V_1 = f'(ct) = \frac{P_1 - \rho g l}{\rho c}. \tag{11}$$

Substituting (11) into (4), we have the equation relative to V_1:

$$0.4\varepsilon \dot{m}_0 - (\rho c V_1 + \rho g l)\left(1.4 F V_1 + \frac{\dot{m}_0}{\rho_1}\right) = \dot{V}_1 \rho c \left(FX + \frac{\dot{m}_0 t}{\rho_1}\right). \tag{12}$$

Since $X^0 = 0$, then for $t = 0$, according to (12), $V_1^0 = V_1^+$, $P_1^0 = P_1^+$ or $V_1^0 = V_1^-$, $P_1^0 = P_1^-$, where

$$V_1^{\pm} = \frac{1}{2}\left(-\frac{gl}{c} - \frac{5\dot{m}_0}{7F\rho_1} \pm A\right), \tag{13}$$

$$P_1^{\pm} = \frac{\rho c}{2}\left(\frac{gl}{c} - \frac{5\dot{m}_0}{7F\rho_1} \pm A\right), \quad A = \sqrt{\left(\frac{gl}{c} - \frac{5\dot{m}_0}{7F\rho_1}\right)^2 + \frac{8\varepsilon \dot{m}_0}{7F\rho c}}. \tag{14}$$

Since $P_1^- < 0$, $P_1^+ > 0$, we hereinafter assume $P_1^0 = P_1^+$, $V_1^0 = V_1^+$. Thus, at $t < 2l/c$

$$V_1 = V_1^+, \quad P_1 = P_1^+, \quad E^+ = \frac{5}{7}\dot{m}_0 \left(\varepsilon + \frac{P_1^+}{\rho_1}\right) t. \tag{15}$$

If the inequality $gl/c >> 5\dot{m}_0/7F\rho_1$ is satisfied, then (13) and (14) are simplified:

$$V_1^+ \approx \frac{1}{2}\left(-\frac{gl}{c} + A\right), \quad P_1^+ \approx \frac{\rho c}{2}\left(\frac{gl}{c} + A\right), \quad A = \sqrt{\left(\frac{gl}{c}\right)^2 + \frac{8\varepsilon \dot{m}_0}{7F\rho c}}.$$

At $\varepsilon \dot{m}_0 c << F\rho g^2 l^2$

$$V_1^+ \approx \frac{2\varepsilon \dot{m}_0}{7F\rho g l}, \quad P_1^+ \approx \rho g l + \frac{2\varepsilon \dot{m}_0 c}{7Fgl}. \tag{16}$$

The second type of the initial conditions corresponds to the explosion of part of the charge. Let the volume of charge, which can burn for the time t_1, detonate first and combustion to the moment $t_0 - t_1$ take place later on, then the initial conditions will take the form:

$$X^0 = 0, \quad E^0 = \varepsilon \dot{m}_0 t_1, \quad P_1^0 = 0.4\varepsilon \rho_1, \tag{17}$$

and the gas pressure will be determined by the formula

$$P_1 = \frac{0.4E}{FX + \dfrac{\dot{m}(t+t_1)}{\rho_1}}. \qquad (18)$$

For the boundary conditions of the second type, the problem solution at $0 < t < 2l/c$ is found numerically by integrating Eqs. (4) with regard for (11) using the Euler method. Figure 3 presents the dependencies of gas pressure on time at different t_1 (0.5 s — *1*; 2 s — *2*; 5 s — *3*; 10 s — *4*; 20 s — *5*; 40 s — *6*). The dotted line corresponds to $P_1^+ = 17.4$ MPa. The other parameters have the following values: $\varepsilon = 8.4 \cdot 10^6$ m^2/s^2; $\dot{m}_0 = 0.176$ kg/s; $\rho_1 = 1830$ kg/m^3; $c = 1500$ m/s; $\rho = 1000$ kg/m^3; $l = 1500$ m; $F = 0.015$ m^2; $R = 0$; and $P_1^0 = 6.15 \cdot 10^9$ Pa. It is seen from Fig. 3 that in the course of time the gas pressure tends to P_1^+ with a velocity depending on the mass of detonated part of the charge.

When $t \to \infty$, the asymptotic estimates of fluid rise velocity and gas pressure correspond to the stationary solution for incompressible fluid (6). The solution of nonstationary problem described by Eqs. (4) and (7)–(9) on the whole time interval is obtained by the finite-difference method using the explicit scheme of the "cross" type. For (7), the digitization steps with respect to time τ and space h were chosen from the Courant stability condition $c\tau \le h$ and numerical dispersion minimization $c\tau = h$. For the initial conditions of the first type, the calculation can be performed since the moment $t = 0$; for the conditions of the second type, this method is unacceptable at the initial stage due to the necessity of using small τ and h. Thus, to integrate (4), we use analytical solution (11) on the interval $0 < t < 2l/c$ and the method of finite differences in conjunction with the Euler method at $t > 2l/c$.

On detonation, when the pressure wave is reflected from the free surface, the wave moving in the inverse direction with a very high negative pressure on the front arises. As a result of it, a fluid part close to the free surface separates. Let us determine the column length of such part after the first reflection. Assume that the separation is possible if $P < P_0 = -2$ MPa. The pressure at the point with the coordinate x at the instant of time t after one reflection

$$P = -\rho \frac{\partial \varphi}{\partial t} + \rho g y = P_1\left(\frac{2y}{c} + \tilde{t}\right) - P_1(\tilde{t}) + \rho g y,$$

where $y = l - x$; $\tilde{t} = t - (l + y)/c$.

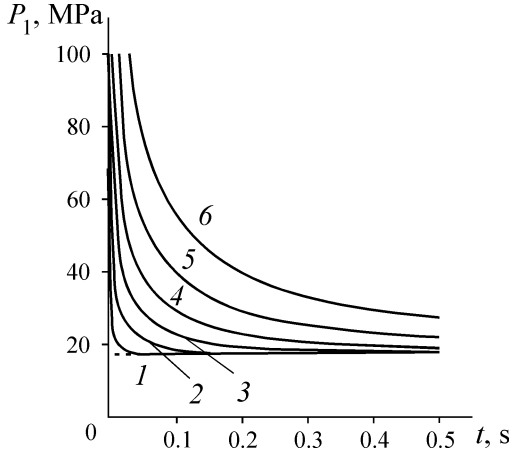

Fig. 3

Hence, for $\tilde{t} > 0$ and $0 < y < l$, the inequality

$$P_1(\tilde{t}) < P_1\left(\frac{2y}{c} + \tilde{t}\right) + \rho g y - P_0$$

must be satisfied in order to prevent the separation.

The function $P_1(\tilde{t})$ is substituted into this inequality. Assuming $\tilde{t} = 0$, we determine the minimum value of y at which the inequality is violated, and the length of first separated fluid column y_1. Let us find the length of the second column y_2 at $\tilde{t} = y_1/c$. Then we assume $\tilde{t} = (y_1 + y_2)/c$, etc. The fall of separated fluid column is not considered. Finally, the height of fluid in the well turns out equal to $l - y_s$ (y_s is the sum of lengths of all separated parts).

As in Fig. 3, the calculation results with the same values of parameters are given in Figs. 4–7. Curves *1* and *2* correspond to the calculation with the initial conditions of the first ($t_0 = 40$ s) and second ($t_0 = 20$ s, $t_1 = 20$ s) types.

The dependencies $P_1(t)$ are shown in Fig. 4. When the whole charge is burnt (curve *1*), the initial pressure insignificantly exceeds the hydrostatic one (the dotted line). When detonating half the charge, the initial pressure is high, but it rapidly decreases to the hydrostatic value. The difference in hydrostatic pressures is explained by fluid separation in the well in case of detonation of part of the charge. The high-frequency oscillations are governed by acoustic vibrations of the fluid column, and the low-frequency ones — by vibrations of the fluid column as incompressible massive body supported by gas pressure. The oscillation range depends on the charge operating conditions determined by the relation between t_0 and t_1. The maximum rarefaction relative to the initial hydrostatic level is reached after the first pressure peak; for the case of complete combustion, it is 2 MPa, and for combustion of half the charge — 7 MPa. The period of low-frequency oscillations is about 10 s.

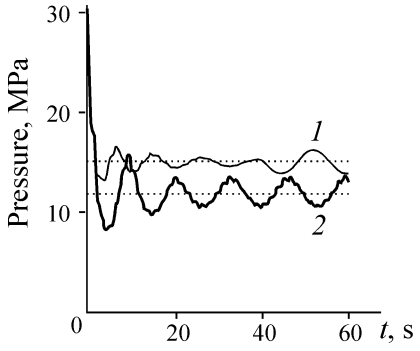

Fig. 4

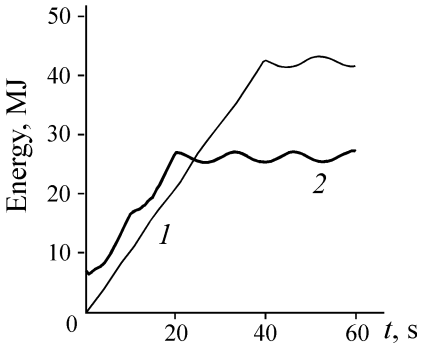

Fig. 5

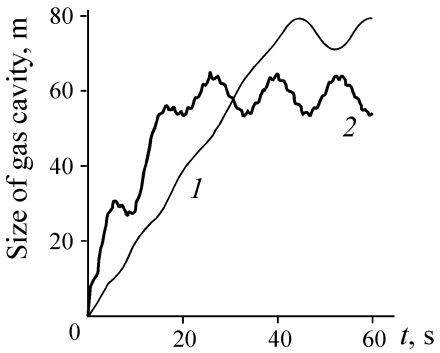

Fig. 6

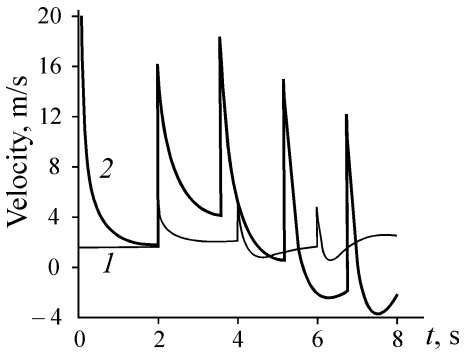

Fig. 7

The time dependencies of the internal gas energy and gas cavity sizes (the largest values are observed in case of whole charge combustion) are shown in Figs. 5 and 6; the dependencies $V_1(t)$ are presented in Fig. 7. The moments of approaching the cavity filled with gases reflected from the fluid surface of the pressure waves are clearly seen (Fig 7). On partial charge detonation, the velocity amplitude is much higher, and the period of oscillations is somewhat shorter due to the fluid separation in the first reflected wave in the well adjoining the surface.

More complete calculation data are shown in Table 1, where the maximum values of fluid rise (determined with regard for the fluid compressibility $\max X$ and incompressibility X_s), gas temperature on cessation of the charge combustion T, and minimum gas pressure $\min P_1$ in combustion are given for different values of detonated part of the charge ($t_1 = 0 - 20$ s).

It is obvious from Table 1 that the gas temperature is maximal under complete charge combustion ($t_1 = 0$). The value of fluid rise is the largest if $t_1 = 2$ s ($l = 1000$ m) and $t_1 = 10$ s ($l = 1500$ m). Rarefaction in gas is maximal, when $t_1 = 20$ s. The comparison between $\max X$ and X_s shows that the calculations performed for the incompressible fluid model at $t_1 \le 5$ s are satisfactorily consistent with the calculations taking into account compressibility; however, they give overstated results if the values of this parameter are great. This is explained by the influence exerted by fluid separation.

For the stage of gas cooling in the well with the volume conservation after the valve actuation in the packer (Fig. 1), the initial gas temperature and gas pressure are of importance. Rarefaction (excess of hydrostatic pressure in the stratum over gas pressure in the well) possible in this case increases with the growth in temperature and decrease in the initial pressure. According to the calculations, the latter is determined by hydrostatic pressure at the moment of valve actuation. In the model for ideal gas, the rarefaction

$$\Delta p = \rho g \left[l - (l - y_s) \frac{T_0}{T} \right],$$

where T_0 is the medium temperature at a depth of productive stratum.

From Table 1 it follows that at $l = 1500$ m the rarefaction is maximal for $t_1 = 5$ s and is 14.8 MPa, which is greater than the rarefaction reached dynamically by a factor of 2. To determine precisely the dependence $\Delta P(t)$, it is required to consider thermodynamics of gas cooling in the well with regard for heat transfer and phase transformations.

TABLE 1

l, m	t_1, s	max X, m	X_s, m	T, deg	y_s, m	min P_1, MPa
1000	0	119.8	112.5	1870	0	8.192
	2	128.3	123	1821	78	7.232
	5	124.7	120	1704	108	7.234
	10	133.2	135	1538	233	7.236
	20	109.1	200	1168	290	7.238
1500	0	79.7	74.9	1870	0	12.915
	2	77.9	76.4	1782	51	11.952
	5	82.1	91.8	1714	146	10.431
	10	73.9	105	1519	162	9.853
	20	64.7	150	1178	314	8.042

CONCLUSIONS

1. The actuation of powder charge in the oil well leads to the considerable rise of fluid. Closure of the valve preventing its reverse flowing favors the decrease in pressure in the well-bottom zone by the value of the order of 10 MPa.

2. The combination of explosion and combustion is an optimum operating regime for the powder charge.

REFERENCES

1. M. V. Kurlenya, S. V. Serdyukov, and Kh. B. Tkach, "Method of productive stratum treatment in the well-bottom zone and the packer for its realization. The Russian Federation Patent No. 2172400," *Byull. Izobret.*, No. 23 (2001).
2. N. E. Kochin, I. A. Kibel', and N. V. Roze, *Theoretical Hydromechanics. Part II* [in Russian], Izd. Fiz.-Mat. Lit., Moscow (1963).
3. V. V. Berdnikov, *Applied Theory of Hydraulic Circuits* [in Russian], Mashinostroenie, Moscow (1977).