ANALYTICAL DETERMINATION OF THE CRITICAL VALUE OF WELL FLOW RATE DURING FLOWING OPERATION

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Abstract

The purpose of this study is to propose a methodology for determining the critical flow rate in flowing wells to prevent the collapse of the productive formation, taking into account the homogeneity of the rocks. The method of operating wells, in which the rise of hydrocarbons from the bottom of the well to the surface occurs due to natural (reservoir) energy, is called flowing. Flowing of oil wells occurs due to hydrostatic pressure or the energy of compressed gas, as well as due to the energy of compressed rocks. The influx of oil to the bottom of wells occurs due to the difference between reservoir and bottomhole pressure. In the case when the pressure of the liquid column (to the wellhead of the filled well) is less than the reservoir pressure, the well will flow. Flowing well production is a method of hydrocarbon production in which the pressure in the formation is high enough to cause the product (such as oil or natural gas) to spontaneously rise to the surface without the additional use of artificial pumps or other devices. Basic concepts of flowing include:

1. Hydrostatic head: The natural pressure created by the hydrostatic column of fluid in a formation allows production to rise to the surface.

2. Compressed Gas Energy: In some cases, the presence of compressed natural gas in the formation can provide additional energy to lift production.

3. Energy of compressed rocks: During fracturing or other geological processes, additional dynamic conditions may be created that promote flow.

The influx of oil or gas to the bottom of wells occurs due to the pressure difference between the formation and the bottom. When reservoir pressure exceeds pressure at the bottom, this can lead to flowing - raising production to the surface. Maintaining flowing conditions can be an important aspect of well operation, and engineering efforts may include pressure control, calculations of optimal production rates, use of water injection techniques (If there is water in the formation), and other techniques to ensure efficient production.

Most often, in the flow of wells the gas contained together with oil in the formation plays the main role, including in cases where the gas under reservoir conditions is completely dissolved in oil and a homogeneous liquid moves through the formation. The structure of productive formations can be different, including layered and heterogeneous formations. This can lead to uneven hydrocarbon production and problems with water cut in permeable layers. For successful oil or gas production from such reservoir formations, the difference between the reservoir pressure and the pressure at the bottom of the well plays a key role. If the pressure in the liquid column is lower than the reservoir pressure, the well may begin to flow. Often the gas contained together with oil in the formation plays an important role in the flow of wells. Even if gas is completely dissolved in oil and a homogeneous liquid moves through the reservoir, its presence can significantly affect the pressure and dynamics of production. For example, when the pressure at the bottom decreases, gas can be released from the solution, increasing the volume and pressure inside the well and promoting its flow. Effective management of the production process includes not only pressure control, but also evaluation of gas factors, optimization of production rates and use of water injection technologies to minimize the negative effects of heterogeneity of formations and ensure the most efficient production of hydrocarbons. Flowing of an oil well can occur depending on the operating mode of the energy source, *including hydrostatic pressure or expansion energy of the gas contained in the oil. In some cases, gushing can occur simultaneously due to both energies. Hydrostatic pressure created by the column of oil and other fluids in the formation can be the main source of energy for a blowout. If the formation pressure is high enough and has good permeability, oil can rise to the surface under the influence of this pressure. If the oil contains dissolved gas, its release and expansion when reaching the surface can also contribute to blowout. Gas expansion creates additional pressure inside the well, which can increase the flow of oil and gas to the surface. When both of these mechanisms operate simultaneously, this can lead to more intense flowing and increased hydrocarbon production. However, control over this process is important to avoid unwanted consequences such as oil spills or loss of hydrocarbons into the environment. In this context, engineers and well operators actively monitor and adjust production parameters to ensure safe and efficient operation.*

Keywords: oil and gas condensate field, bottomhole pressure, operating methods, hydrostatic head, acceleration of gravity, fluid filtration, back pressure at the wellhead, stress state, hydrostatic head

I. Introduction

However, most often the main role in the flow of oil wells is played by natural gas contained together with oil in the reservoir. This applies even to situations where gas is completely dissolved in oil and movement through the formation occurs as a homogeneous liquid.

In this case, all the gas is in a dissolved state in the oil, and the bottomhole pressure is determined as the pressure of a column of homogeneous liquid filling the well, according to the formula

$$P_{b.h.} = H\rho g + P_{fr} + P_w \quad (1)$$

where, $P_{b.h.}$ pressure, MPa; H – well depth, m; ϱ – liquid density, kg/m^3; g-free fall acceleration, m/s^2; P_{fr} – hydraulic pressure loss due to friction during fluid movement in pipes, MPa; P_w – back pressure at the wellhead, MPa. Friction pressure losses are determined using the Darcy-Weisbach formula:

$$P_{fr} = \frac{\lambda \cdot L}{d} \cdot \frac{v^2}{2} \cdot \rho \quad (2)$$

where λ is the coefficient of hydraulic resistance; d – diameter of pump-compressor (lifting) pipes, m; ν – speed of fluid movement in the rising pipes, m/s; L – length of the lifting pipes, m. The numerical value of λ is determined depending on the surface roughness of the lifting pipes and the Reynolds criterion:

$$\lambda = \frac{64}{\mathrm{Re}} \;\; when \; \mathrm{Re} = \nu \cdot d/\upsilon < 2320 \quad (3)$$

$$\lambda = \frac{0,3164}{\sqrt[4]{\mathrm{Re}}} \text{ when } \mathrm{Re} > 2320 \quad (4)$$

where υ is the kinematic viscosity of the liquid, m^2/s.

Bottomhole pressure is determined from the basic equation of fluid inflow to the bottom of the well:

$$P_{b.h.} = P_c - \sqrt[n]{Q/C} \quad (5)$$

where Q is the well flow rate m^3/day;
C – productivity coefficient, this is the ratio of well flow to depression: m^3/(day MPa);
P_c – contour or reservoir pressure, MPa;
n – coefficient equal to 1, when a straight indicator line leaves the origin; if the movement of fluid in the formation obeys Darcy’s law, then the speed of fluid movement in the formation is directly proportional to the pressure drop;
n<1, when the line is convex relative to the pressure drop axis;
n>1, when the line is concave relative to the pressure drop axis

Substituting values (2) and (5) into equation (1), the pressure at the wellhead is determined taking into account n=1:

$$P_w = P_{for.} - Q/C - H \cdot g \cdot \rho - \lambda \cdot L/d \cdot \nu^2/2 \cdot \rho \tag{6}$$

In this case, the bottomhole pressure will be determined as follows;

$$P_{b.h.} = P_c - \frac{Q}{C} \tag{7}$$

II. Statement and solution of the problem

It is known that when the operating mode of oil and gas wells is chosen incorrectly, formation collapse occurs, i.e. a critical stress state arises in the formation. Therefore, solving this problem is very important for preventing emergency situations [1÷5].

Let us consider the stressed state of the bottomhole part of the well, taking into account fluid filtration in the formation. Rocks are accepted as an isotropic body. The stress state of the near-wellbore is characterized by the following equilibrium equation (Lame parameters):

$$\frac{d\sigma_r}{dr} + \frac{1}{r}\left(\sigma_r - \sigma_\varphi\right) = 0 \tag{8}$$

r de σ_r, σ_φ - radial and circumferential stress, respectively

It is known that the production rate of wells, i.e. the influx of fluid to the bottom of wells occurs due to the difference between the reservoir and bottomhole pressure. The internal (bottomhole) pressure of the well will take the value as (5).

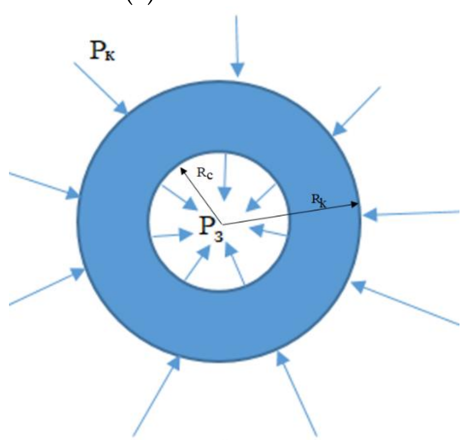

Figure 1: *Stress state at the bottom of the well*

In the case under consideration, the boundary conditions have the form;
at r=R_c; σ_r=$P_{b.h.}$; at r=R_c; σ_r=-P_c. Then the general solution to equation (8) will take the form:

$$\begin{cases} \sigma_r = \dfrac{-R_w^2 P_3 - R_c^2 P_c}{R_c^2 - R_w^2} + \dfrac{R_c^2 R_w^2 (P_{b.h.} + P_c)}{R_c^2 - R_w^2} \cdot \dfrac{1}{r^2} \\ \sigma_\varphi = \dfrac{-R_w^2 P_3 - R_c^2 P_c}{R_c^2 - R_w^2} - \dfrac{R_c^2 R_w^2 (P_{b.h.} + P_c)}{R_c^2 - R_w^2} \cdot \dfrac{1}{r^2} \end{cases} \tag{9}$$

R_w is the radius of the well, R_c is the radius of the formation contour.

Considering that the maximum stress occurs in the inner wall of the well, i.e.

$$\text{at } r = R_c \qquad \sigma_r = P_{b.h.}; \qquad \sigma_\varphi = -P_{b.h.} - \frac{2R_c^2}{R_c^2 - R_w^2}\, P_c \tag{10}$$

The failure condition for isotropic rocks has the form;

$$\sigma_r^2 + \sigma_\varphi^2 = 2\sigma_t^2 \tag{11}$$

where σ_t is the rock strength limit.

If (10) is taken into account in (11), we obtain the following expression;

$$P_{b.h.}^2 + m^2 P_c P_{b.h.} + 0{,}5 m^4 P_c^2 - \sigma_t^2 = 0 \tag{12}$$

where- $m^2 = \frac{2R_c^2}{R_c^2 - R_w^2}$

Considering that the radius of the formation contour R_c compared to the well radius R_w is too large, therefore $m^2 = \frac{2R_c^2}{R_c^2 - R_w^2}$ will take the value $m^2 \approx 2$

The solution of equation (12) with respect to $P_{b.h.}$ determines the critical value of the bottomhole pressure

$$P_{b.h.} = -P_c \pm \sqrt{\sigma_t^2 - P_c^2} \tag{13}$$

For real solutions, equation (12) must satisfy the following condition:

$$\sigma_t^2 - P_c^2 \geq 0 \tag{14}$$

Conditions (14) are satisfied for any rock.

From (13) we determine the critical value of bottomhole pressure;

$$P_{cr} = \left| -P_c + \sqrt{\sigma_t^2 - P_c^2} \right|$$

If we assume that the movement of fluid in the formation obeys Darcy's law, then the speed of fluid movement in the formation is directly proportional to the pressure drop, i.e. n=1, then for the critical value of the well flow rate Q_{cr}, taking into account the homogeneity of the rocks, we obtain the following expression;

$$Q_{cr} = P_c K \left(2 - \sqrt{\left(\frac{\sigma_t}{P_c}\right)^2 - 1} \right)$$

III. Conclusions

1) A method for calculating the stress state at the wellbore is proposed and the critical value of the bottomhole pressure is determined.

2) Based on this method, the critical value of the well flow rate was determined at which a formation collapse may occur.

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