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Аннотация. In the development of oil fields with anomalous oil, it is necessary to start up and shut down the wells and change the amount of produced fluid from the formation. The data of the listed works give rise to a new regime in the reservoir that manifests itself in the redistribution of reservoir pressure and the flow rates of filtration flows that change over time. Under the given conditions, the features of the filtration processes depend on the effect of the elasticity of the oil-bearing and aquifers themselves and on the elasticity of the liquids that saturate them. Therefore, the main goal of this paper is to identify the peculiarities of the motion of a compressible viscous-plastic fluid in the formation during its development.

Ключевые слова: filtration flow, pressure, fluid density, boundary conditions, compressibility, filtration.

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Annotation. In the development of oil fields with anomalous oil, it is necessary to start up and shut down the wells and change the amount of produced fluid from the formation. The data of the listed works give rise to a new regime in the reservoir that manifests itself in the redistribution of reservoir pressure and the flow rates of filtration flows that change over time. Under the given conditions, the features of the filtration processes depend on the effect of the elasticity of the oil-bearing and aquifers themselves and on the elasticity of the liquids that saturate them. Therefore, the main goal of this paper is to identify the peculiarities of the motion of a compressible viscous-plastic fluid in the formation during its development.

Keywords: filtration flow, pressure, fluid density, boundary conditions, compressibility, filtration.

Mathematical methods for solving the process of movement of an elastic fluid in a reservoir are necessarily reduced to the integration of differential equations under various boundary and initial conditions.

It is known that the anomalous properties of compressible fluids create additional difficulties for solving practical problems of field mechanics. This is facilitated by the information provided on the results of field observations and research, tables and graphs compiled according to calculation formulas. A detailed analysis of literary sources allows us to give a theoretical substantiation of the features of the motion of a compressible viscoelastic fluid in a porous medium, which plays a significant role in regulating the development process [1–6].

Theory. The behavior of an oil reservoir during the development process depends on the methods of influence on it and on multiple natural factors. Methods for influencing reservoirs with abnormal oils are associated with various methods of placement and sequential commissioning of production and injection wells, fluid withdrawal rates, the position and size of well bottoms in a productive reservoir, methods of opening the reservoir and various methods of treating the bottom-hole zone of the well.

Filtration of liquid and gas in the reservoir during the development process occurs both through the use of the potential energy of the reservoir in various forms, and due to additional external energy sources [7].

At the same time, it should be noted that the elastic drive mode is characterized by the following features: the pressure in the pressure reservoir must be higher than the saturation pressure in order to ensure single-phase oil filtration. Then the movement of oil to each well begins due to the use of the potential energy of the elastic deformation of the oil. Practice shows that with a decrease in reservoir pressure, the volume of compressed oil should increase, and the volume of the pore space should decrease. This physical phenomenon contributes to the displacement of oil from the reservoir into the well [8, 9].

The piezo metric lines are practically in the form of logarithmic curves, the initial points of which are located on the wall of the perturbing well, and the end points move away from this well over time, but they are always located below the initial static piezo metric level.

This feature of the redistribution of reservoir pressure gives grounds to use a technique that makes it possible to apply the method of successive change of steady states. This technique is reduced to the conditional division of the entire reservoir into two areas: perturbed and unperturbed. In this case, it should be emphasized that the inner boundary of the disturbed area is located on the borehole wall, and the outer, expanding one serves as the inner boundary of the undisturbed area. We accept that in the entire perturbed region, the pressure is distributed in the same way as in the case of steady fluid motion, where the outer boundary of the region serves as a feed contour.

The radius of the outer boundary of the disturbed area is denoted as the reduced radius of influence of the well. The perturbed area is called the reduced area of influence of the well. Then, using this calculation scheme for an incompressible fluid, it is possible to obtain a calculation method for a compressible viscous-plastic fluid. At the same time, we note that the flow rate and bottom-hole pressure in the well correspond to the steady filtration of this fluid.

The velocity of a viscous-plastic fluid, according to the law of filtration, in the case of plane-radial motion can be determined as follows:

$$v = -\frac{k}{\eta}\left(\frac{dP}{dr} - i_0\right), \quad (1)$$

where v – filtration rate, m/s; k – permeability coefficient, m^2; η – dynamic viscosity, Pa*sec; P – pressure, MPa; r – radius, m; i_0 – initial shear gradient, Pa/m.

The pressure gradient for isothermal conditions can be defined as [5]:

$$\frac{dP}{dr} = \frac{1}{\beta\rho}\frac{d\rho}{dr}, \quad (2)$$

where β – coefficient of volumetric elastic expansion of a liquid; ρ – density, kg/m^3.

Substituting this expression into the filtration equation, we have

$$v = -\frac{k}{\eta}\left(\frac{1}{\beta\rho}\frac{dP}{dr} - i_0\right). \quad (3)$$

The «–» sign in expression (3) shows that the pressure value decreases along the filtration path. This loss is due to the emergence of resistance forces. In other words, the filtration rate is directed in the direction of pressure reduction – from the circuit to the well.

Multiplying the left and right parts of expression (3) by the formation cross-sectional area, i.e. $F = 2\pi rh$, define

$$2\pi rhv = -\frac{k}{\eta}2\pi rh\left(\frac{1}{\beta\rho}\frac{d\rho}{dr} - i_0\right), \quad (4)$$

From here it is possible to determine the volume flow

$$Q = \frac{k}{\eta}2\pi rh\left(\frac{1}{\beta\rho}\frac{d\rho}{dr} - i_0\right). \quad (5)$$

We solve this equation for density gradients, we find:

$$\frac{Q\eta}{2\pi kh}\frac{1}{r} = \frac{1}{\beta\rho}\frac{d\rho}{dr} - i_0, \quad (6)$$

or

$$\frac{Q\eta}{2\pi kh}\frac{1}{r} + i_0 = \frac{1}{\beta\rho}\frac{d\rho}{dr}. \quad (7)$$

To solve this problem, the boundary conditions are formed as follows:

$$r = R_w;\ \rho = \rho_w;\ r = R_c;\ \rho = \rho_c, \quad (8)$$

where ρ_w – density of the liquid on the well contour with radius R_w, kg/m^3;
ρ_c – density of the liquid on the circular feed contour with radius R_c, kg/m^3.

$$\beta dr\left(\frac{Q\eta}{2\pi kh}\frac{1}{r} + i_0\right) = \frac{d\rho}{\rho}. \quad (9)$$

From here we obtain

$$\frac{Q\eta}{2\pi kh}\beta\frac{dr}{r} + i_0\beta dr = \frac{d\rho}{\rho}. \quad (10)$$

Substituting the boundary conditions, we have

$$\frac{Q\eta}{2\pi kh}\beta\int_{R_w}^{R_c}\frac{dr}{r} + i_0\beta\int_{R_w}^{R_c}dr = \int_{\rho_w}^{\rho_c}\frac{d\rho}{\rho}, \quad (11)$$

and

$$\frac{Q\eta\beta}{2\pi kh}\ln\frac{R_c}{R_w} + i_0\beta(R_c - R_w) = \ln\frac{\rho_c}{\rho_w}. \quad (12)$$

We solve this problem with respect to the volumetric flow rate of the liquid:

$$\frac{Q\eta\beta}{2\pi kh}\ln\frac{R_c}{R_w} = \ln\frac{\rho_c}{\rho_w} - i_0\beta(R_c - R_w), \quad (13)$$

or

$$Q = \frac{2\pi kh}{\beta\eta\ln\frac{R_c}{R_w}}\left[\ln\frac{\rho_c}{\rho_w} - i_0\beta(R_c - R_w)\right]. \quad (14)$$

This equation makes it possible to determine the effect of viscous-plastic properties and compressibility on the volumetric flow rate of the liquid. It should be noted that a viscous-plastic fluid or the Shvedov-Bingham model is a non-Newtonian medium, the inherent characteristic of which is the presence of a yield point [9].

If the fluid is Newtonian, then $i_0 = 0$

$$Q = \frac{2\pi kh}{\beta\eta\ln\frac{R_c}{R_w}}\ln\frac{\rho_c}{\rho_w}. \quad (15)$$

Considering that $\ln\frac{\rho_c}{\rho_w} = \beta(P_c - P_w)$ and η = μ we get the Dupy's equation

$$Q = \frac{2\pi kh}{\mu\ln\frac{R_c}{R_w}}(P_c - P_w). \quad (16)$$

Let's decompose the expression $\ln\frac{\rho_c}{\rho_w}$. It should be noted that when solving problems, in practice they are limited to the first member, then:

$$\ln\frac{\rho_c}{\rho_w} = \frac{\frac{\rho_c}{\rho_w} - 1}{\frac{\rho_c}{\rho_w}} = \frac{\frac{\rho_c - \rho_w}{\rho_w}}{\frac{\rho_c}{\rho_w}} = \frac{\rho_c - \rho_w}{\rho_c}. \quad (17)$$

There fore

$$Q = \frac{2\pi kh}{\mu\ln\frac{R_c}{R_w}}\frac{\rho_c - \rho_w}{\rho_c}. \quad (18)$$

In special case, when

$$\rho_c - \rho_w = \rho_0\beta(P_c - P_w)(1 + \beta\overline{P}), \quad (19)$$

then

$$Q = \frac{2\pi kh}{\mu\ln\frac{R_c}{R_w}}\frac{\rho_0}{\rho_c}\beta(P_c - P_w)(1 + \beta\overline{P}). \quad (20)$$

It was determined that , when the volumetric elastic expansion coefficient of the liquid is taken into account, the liquid flow rate increases. The difference, compared with the values obtained for calculations without taking into account the coefficient is about 20 %.

Dividing the left and right parts of this equation by the cross-sectional area of the formation, we find the radial filtration rate of a compressible viscous-plastic fluid:

$$v = \frac{Q}{2\pi rh}, \quad (21)$$

or

$$v = \frac{1}{2\pi rh}\frac{2\pi kh}{\beta\eta\ln\frac{R_c}{R_w}}\left[\ln\frac{\rho_c}{\rho_w} - i_0\beta(R_c - R_w)\right]. \quad (22)$$

After reducing

$$v = \frac{1}{r} \frac{k}{\beta\eta \ln\frac{R_c}{R_w}} \left[\ln \frac{\rho_c}{\rho_w} - i_0\beta(R_c - R_w)\right]. \quad (23)$$

Considering that $\ln \frac{\rho_c}{\rho_w} = \beta(P_c - P_w)$, we get

$$v = \frac{1}{r} \frac{k}{\beta\eta \ln\frac{R_c}{R_w}} [\beta(P_c - P_w) - i_0\beta(R_c - R_w)], \quad (24)$$

or

$$v = \frac{1}{r} \frac{k}{\eta \ln\frac{R_c}{R_w}} [(P_c - P_w) - i_0(R_c - R_w)]. \quad (25)$$

If the fluid is Newtonian, i.e. $i_0 = 0$, then taking the structural viscosity equal to the dynamic viscosity:

$$v = \frac{1}{r} \frac{k}{\mu} \frac{P_c - P_w}{\ln\frac{R_c}{R_w}}. \quad (26)$$

Conclusions

1. An expression was obtained to determine the effect of viscous-plastic properties and compressibility on the volumetric flow rate of a liquid.
2. When taking into account the coefficient of volumetric elastic expansion of the liquid, the flow rate of the liquid increases.

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