WATER-OIL DISPLACEMENT IN FISSURE-POROUS RESERVOIR UNDER NON-STATIONARY ACTION

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ABSTRACT. Oil resources of reservoirs with fissure-porous structure are falling in the category of the hardly-recovered ones. In such layers the oil phase is concentrated in porous blocks and during the reservoir exploitation the fluids filtration occur in the cracks. If blocks are hydrophobic then, as a rule, the standard quasi-stationary water flood can not be effective. In this case the capillary soak mechanism does not act and water goes practically alone through cracks. Special field experiments has evidenced, that cyclical action on the fissure-porous reservoirs considerably decreases the water flooding factor of producing wells. Till now this fact had no its explanation within the two-phase filtration theory. In this paper the mathematical model of unsteady water-oil displacement in fissure-porous reservoirs is offered. The effectiveness of a cyclical action is estimated by means of computational experiments. An optimum of the frequency period, obtained by supposed theory, has good agreement with production data.

1. PHYSICAL SUPPOSITIONS AND MATHEMATICAL THEORY

To concretize the model of the filtration process in fissure-porous reservoir, the determination of relationships for the mass-transfer flows between blocks and cracks is needed. Statement of these relations generally requires a solution of the intricate interior problem connected with two-phase filtration within blocks under elasticity. Non-stationary magnitudes of saturation and pressure in cracks should be given as boundary conditions of such problem and its solution should be found with taking into account of capillary barriers (end effects, see e.g. [Barenblatt *et al.,* 1984]) on boundary between block and cracks. Such approach would reduce in double-level model containing the «exterior» equations of two-phase filtration in cracks with a mass sources which are being obtained as integral characteristics of an «interior» problem solution in the block.

In this work we offer the simplified approach to solution of the specification problem based on following ideas. The mass-transfer flows are caused of two reasons: the first of them is a disturbance of capillary equilibrium and the second one - the change of elastic energy of fluid in medium. In the first case the surface energy minimization takes place at constant medium porosity and fluids density. This is a long-term process of the water-oil capillary redistribution both inside blocks, and between blocks and cracks. At same time *the selective soak* of blocks by the wetting phase occurs. Rather then give back an oil phase, the hydrophobic blocks soak up it, that only hampers the action of considered process. In the second case the mass-transfer flows compensate the elastic energy. Thus the summary water and oil flow coming into cracks from the block per unit time per unit volume of pores medium (the mass-transfer flows intensity) is defined as $q = -\overline{\beta} \cdot \partial P / \partial t$. Hereinafter an upper dash denotes parameters of block, water and oil phases are indexed by 1 and 2 accordingly; t - time; P - pressure identical for both fluids, $\overline{\beta} = \overline{\beta}_1^* \overline{S}_1 + \overline{\beta}_2^* \overline{S}_2$ - an elastic capacity of blocks; $\overline{\beta}_i^* = \beta_c + \overline{m}\beta_i$; β_c and β_i - elastic capacity of the pore medium and i -th phase respectively, $\overline{S}_i$ and $\overline{m}$ - water saturation and porosity of blocks.

The use of hypothesis about local equilibrium between blocks and cracks in respect to pressure is based on special estimations which show that a time of its equalizing in cracks and blocks is negligible in comparison with the frequency pressure periods at non-stationary condition of oil field development. Therefore, in order to describe the process it is possible to assume the pressure in cracks and blocks as identical. The mass-transfer flows intensities of water and oil separately can be defined by relations $q_i = \lambda_i q$, $(i = 1,2)$, where $\lambda_1(S, \bar S)$ - a share of water phase in the summary liquid flow; $\lambda_2 = (1-\lambda_1)$ - a share of oil phase. Note that function $\lambda_1(S)$ depends from direction of the mass-transfer flow: if fluid goes from cracks into blocks then $\lambda_1(S)$ is determined by mobility of water and oil phases in cracks, if from blocks into cracks - by their mobility in the blocks.

Taking foregoing formulas for the mass-transfer flows, the balance-mass equations and the motion equations for fluids in cracks, equations describing the change of water and oil saturation in the blocks [Yentov, 1969], system equations of non-stationary filtration in fissure-porous reservoir can be written as

$$\beta\frac{\partial P}{\partial t} + div\vec{\mathbf{V}} = q \ , \quad m\frac{\partial S}{\partial t} + \beta_1^* S\frac{\partial P}{\partial t} + div(f\cdot\vec{\mathbf{V}}) = \lambda q \ , \quad \bar m\frac{\partial \bar S}{\partial t} + \bar\beta_1^* \bar S\frac{\partial P}{\partial t} = -\lambda q \ , \quad (1)$$

$$\vec{\mathbf{V}} = -\frac{k(P)}{\mu_1}k^*\nabla P \ , \qquad \lambda = \begin{cases} f(S), \\ \bar f(\bar S), \end{cases} \text{for} \quad \begin{matrix} \partial P/\partial t > 0 \\ \partial P/\partial t < 0 \end{matrix} \qquad (2)$$

where $\beta = \beta_1^* S + \beta_2^*\cdot(1-S)$, $\beta_i^* = m\cdot(\alpha + \beta_i)$ - elastic capacity of cracks saturated by i-th phase, $k^* = k_1^* + \mu k_2^*$, $\mu = \mu_1/\mu_2$, $f(S) = k_1^*/k^*$, $\bar f(\bar S) = \bar k_1^*/\bar k^*$, k_i^* and μ_i - relative permeability and viscosity of i - phase. The absolute permeability $k(P)$ of cracks generally depends on pressure and should be instituted experimentally.

Note that the phase permeabilities for blocks and cracks essentially differ. It is due to fact that the influence of capillary forces in cracks is being decreased (by virtue of a considerable difference between oil and water viscosity) and the water-oil displacement has the developed jet stream. It leads to linear functions of phase permeability k_i^* in respect saturation [Yentov, 1969]. We shall define also the relative phase permeabilities $\bar k_i^*$ for blocks by usual cubic functions Thus:

$$k_1^* = \begin{cases} 0 \ , & 0 \le S \le S_* \\ (S - S_*)/(1 - S_*), & S_* \le S \le 1; \end{cases} \qquad k_2^* = \begin{cases} 1 - S/S^* \ , & 0 \le S \le S^* \\ 0 \ , & S^* \le S \le 1; \end{cases} \qquad (3)$$

$$\bar k_1^* = \begin{cases} 0 \ , & 0 \le \bar S \le \bar S_* \\ \left((\bar S - \bar S_*)/(1 - \bar S_*)\right)^3, & \bar S_* \le \bar S \le 1; \end{cases} \qquad \bar k_2^* = \begin{cases} \left((\bar S^* - \bar S)/(\bar S^* - \bar S_*)\right)^3, & 0 \le \bar S \le \bar S^* \\ 0 \ , & \bar S^* \le \bar S \le 1; \end{cases} \qquad (4)$$

Here $\bar S_*$, S_* - an irreducible saturation and $\bar S^*$, S^* - a limit saturation for blocks and cracks.

System equations (1) - (4) should be enclosed by the boundary and initial conditions. Let's define an initial state of reservoir by conditions $P\big|_{t=0} = P^0$, $S\big|_{t=0} = S^0 \ge S_*$, $\bar S\big|_{t=0} = \bar S^0 \ge \bar S_*$. In considered case of drilling in we have the multiply-connected solution region because of presence of wells. To simulate the periodic action we shall take boundary conditions on the well of radius r_w as $q(t) = A\cdot(1 - \cos(\omega\cdot t))$ or $P_w(t) = P^0 - A\cdot(1-\cos(\omega\cdot t))$ depending on its operating regime at the given well production $q(t)$ or pressure $P_w(t)$, where $\omega = 2\pi/T_o$, T_0 and A - frequency period and amplitude of cyclical action. In these formulas $A > 0$ for producing wells and $A < 0$ for the injecting wells. On exterior boundary of reservoir the boundary conditions of the first or second kind in respect to pressure can be given.

Proposed new mathematical model (1) - (4) essentially differs from known model of a medium with a double porosity [Barenblatt *et al.*, 1984]. Obtained within this model, the governing equations for the filtration process in cracks and blocks can be written as [Chekalin *et.al.*, 1997]:

$$\beta\frac{\partial P}{\partial t} + div\vec{\mathbf{V}} = q \ , \qquad \overline{\beta}\frac{\partial \overline{P}}{\partial t} + div\vec{\mathbf{V}} = -q \ , \qquad q = -\tilde{\alpha}(P - \overline{P}) \ , \tag{5}$$

$$m\frac{\partial S}{\partial t} + \beta_1^* S\frac{\partial P}{\partial t} + div(f\vec{\mathbf{V}}) = \lambda\, q \ , \quad \overline{m}\frac{\partial \overline{S}}{\partial t} + \overline{\beta}_1^* \overline{S}\frac{\partial \overline{P}}{\partial t} + div(\bar{f}\vec{\mathbf{V}}) = -\lambda\, q \,, \tag{6}$$

where $\tilde{\alpha}$ -a coefficient determining the mass interchanging q_m between cracks and blocks because of a pressure difference P-$\overline{P}$.

New model (1) - (4) avoids the main foible of model (5), (6) for the double-porosity medium: there is no need to identify the coefficient $\tilde{\alpha}$ (at present time the experimental field methods for measurement of this parameter are absent). However, from our viewpoint, the account of the pressure distinction and the interchanging coefficient, connected with this magnitude, can not misrepresent the qualitative nature of the water-oil displacement in the fissure-porous reservoir. It was proved by our special investigations. To solve models (1)-(4) and (5)-(6), the corresponding numerical methods and algorithms were developed. We'd like to note also that the new model has considerable advantage: it can be solved by more simple numerical methods. On base of these methods the software development was done. These programs gave possibility to carry out the variant computational experiments.

2. PRESENTATION OF COMPUTATIONAL EXPERIMENTS

Let's consider the influence of the cyclical action under the fissure-porous reservoir. In this case most interest is correspond to a radial filtration in neighborhood of the injecting or producing well, operated in the periodic regime, when on the exterior boundary of the solution area ($r = R$) the pressure P_R is given. In presented below computational experiments the following values of parameters were used: $\mu_1 = 1$ mPa$\cdot$c, $\mu_2 = 20$ mPa$\cdot$c, $r_w = 0.1$ m, $k = 0.5$, $R = 250$ m, $m = 0.02$, $\overline{m}$=0.2, $S_* = S^0 = 0.02$, $S^* = 0.95$, $\overline{S}_* = \overline{S}^0 = 0.2$, $\overline{S}^* = 0.8$, $A = 25\ m^3 \cdot day^{-1}$, P^0=18 MPa, P_R = 18.01 MPa,. The calculations was being ended when the water-flooding factor θ of the well was reached of 96 % («the end of the reservoir development»).

2.1. Influence of the frequency period on oil recovery. In Table 1 some results of calculations are presented for various values of frequency period T_0 (in hours) at the end time of reservoir development. The first line corresponds to the steady state of reservoir exploitation. The third column contains values of the exploitation time t (in days), the fourth - a dimensionless time $\tilde{t}$, expressed in a share of the pore volume of reservoir ($\tilde{t}$ = 1 is a time needed to produce (inject) the liquid in amount of one pore volume). In the fifth, sixth and seventh column the values (in %) of the oil-recovery factor η, $\overline{\eta}$ and η_Σ of the cracks, the blocks and reservoir are presented accordingly.

Table 1

N	T_0	t	$\tilde{t}$	η	$\bar{\eta}$	η_Σ
1	-	921	0.53	75.3	0.1	8.3
2	720	1290	0.75	80.0	2.6	11.1
3	192	2072	1.2	78.6	9.7	17.2
4	96	2932	1.70	74.6	16.2	22.6
5	48	3454	2.00	72.5	20.2	25.9
6	24	3663	2.12	72.1	20.8	26.4
7	18	3650	2.11	72.4	20.1	25.8

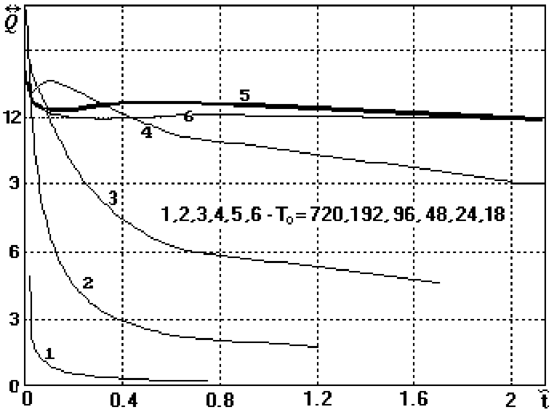

Figure 1

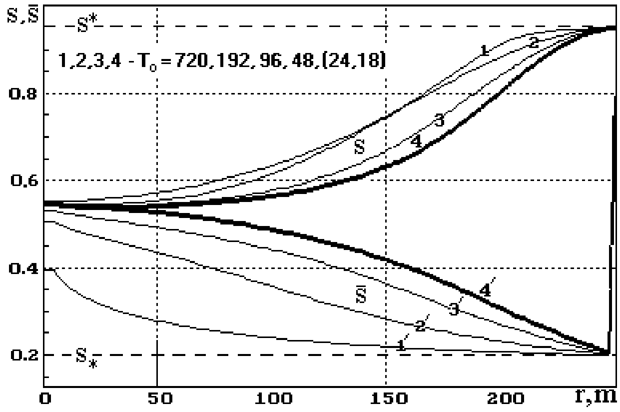

Figure 2

An analysis of the experiments has shown that the water-free exploitation time and the water-free oil-recovery factor both under stationary and under cyclical action remain rather small because of the fast breakthrough of water through the cracks into well. However, in the course of time the mass transfer between cracks and blocks arises along almost all length of reservoir in consequence of non-stationary. It leads to the delayed growth of the water-flooding factor θ of well. The drop of the water-flooding factor is a long-term process rising considerable the oil-recovery factor η_Σ of the fissure-porous reservoir (see Table 1). With lessening of the frequency period T_0 the magnitude η_Σ is being increased, but the summary fluids production $\tilde{t}$ simultaneously rises also; one can easily see it in the fourth column. For example, at T_0 = 24 hours the value $\tilde{t}$ is four times greater, and the oil-recovery factor η_Σ - about three times greater than same parameter of the steady state regime. Naturally, the augmentation of this factor occurs because of the blocks; the oil-recovery factor of cracks η is even being decreased a little. This effect is explained by the mass interchanging between cracks and blocks, taking place along all length of reservoir, and the oil phase coming out blocks diminishes the oil recovery of cracks. Factor η_Σ has maximum when T_0 is equal to 24 hours. Note, that a spectrum of T_0, where the oil-recovery factor η_Σ is close to maximal, is rather wide. It is interesting, that such diapason of optimum cycles is established also by field experiments.

The magnitude of frequency period T_0 has an essential influence not only on the basic parameters of the field development, but also on the behavior of filtration process. The time dependencies of the overall flow $\vec{Q}$ characterizing the interchanging between cracks and blocks are demonstrated in Fig.1 for various values of T_0. The magnitude of $\vec{Q}$ is defined as an integral function along the reservoir length. It is easy to see, that at T_0 = 18 hours the intensity of the flow $\vec{Q}$ is less, than at T_0 =

24 hours. Just it has reduced to a drop of the oil-recovery of reservoir. The saturation distribution S and $\overline{S}$ in cracks and blocks along the reservoir at the end point of its exploitation are presented in Fig.2. Here the curves 4 and 4' correspond to T_0 = 18, 24 and 48 hours giving practically conterminous saturation distributions. We'd like to note that in neighborhood of well the saturation values in the blocks and cracks are almost identical only for these variants. With increasing of magnitude T_0 the water saturation of blocks is being sharply diminished. It is interesting also that in neighborhood of the exterior boundary $r = R$ where water enters reservoir the oil displacement in the blocks remains insignificant at any values of frequency period T_0. This fact takes place because on the contour $r = R$ the constant pressure is supported and elastic forces do not practically act on process.

***2.2.* Comparison of models**. With the aim to compare the models (1)-(4) and (5), (6) the special computational investigations were carried out. It was shown that behavior of saturation and basic parameters of the oil development are qualitatively coincides. However, quantitative results of calculations differ a little. In this case, the magnitude of coefficient $\tilde{\alpha}$ in model of the double-porosity medium has not essential influence on the qualitative behavior of solution, but noticeably changes the quantitative results. Thus, the indeterminacy in identification of parameter $\tilde{\alpha}$ complicates an estimation of effectiveness of a cyclical filtration process in the fissure-porous reservoir.

3. CONCLUSIONS

First of all, an analysis of the computational experiments establishes, that the cyclical action increases the oil-recovery of fissure-porous reservoir. Firstly, it is due to intensification of the mass transfer between cracks and blocks under action of the elastic forces. Secondly, because of distinction of the relative phase permeabilities in the blocks and cracks an interesting phenomenon comes into being: with pressure boost the water predominantly goes into the blocks, and with pressure suppression the oil is predominantly forced out into cracks. The proposed new mathematical model has allowed to study non-stationary processes of water-oil-displacement, to estimate an effectiveness of cyclical action on fissure-porous reservoir and to find an optimum value of frequency period concordant with field experimental data.

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