Mathematical modeling of structured and Newtonian fluids in associated layer

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Abstract. In this paper, a mathematical model of the process of fluid filtration in underground layered formations is considered and numerically solved as raw material for generating electrical energy. The objects of the filter are anomalously structured and Newtonian fluids. Computational algorithms are built using iteration, direct and streaming differential sweep methods. An analysis of the numerical solution of the problem has been carried out. The number of flows between reservoirs was determined, as well as the position of the boundaries of disturbances, taking into account the dynamics of reservoir development.

1 Introduction

It is known that the issue of energy security of each country has become acute all over the world. In turn, energy security is closely related to the energy supply of the country and it depends primarily on the uninterrupted supply of electricity. If each country has sufficient resources to generate the necessary volumes of electrical energy obtained from wind, solar installations, as well as from hydro-thermal power plants, where the components of the raw material are: wind, sunlight, water from mountain rivers and canals, as well as natural hydrocarbons (gas, oil, gas condensate) produced from underground reservoirs, the scientific and technical development of this country is proceeding at an accelerated pace. The fragility of this system was shown by the energy shortage in European countries and many other countries (including Uzbekistan) during the period of abnormal cold at the end of last year and at the beginning of this year. Consequently, scientists and researchers have faced the priority tasks of providing the energy system with resources, while using automated process systems to manage production processes. natural resources that made it possible to increase and constantly generate electrical energy.

The study of the process of fluid filtration in hydrodynamically connected and unconnected (developed by a single well) porous medium is important in the design, analysis, forecasting and regulation of the development of fields containing fluids (gas, oil, water, gas condensate, etc.) necessary for the functioning of the national economy of any countries. It is due to the fact that the porous medium is multilayered and is a complex geological structure. In real cases, it is sometimes difficult to determine the boundaries

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between interlayers, since there is heterogeneity in spatial variables, and sometimes in temporal variables. In the latter case, the porous medium may be filled with fluids having structural properties, and sometimes the porous medium itself may be structured. In these cases, reservoir characteristics change over time to accommodate the fluid velocity. Works [1, 2] are considered to be the beginning of the study of the process of groundwater filtration in multilayer porous media in simplified formulations. At the same time, the authors neglected the vertical velocity component in well-permeable formations, and thus the flow was considered horizontal and in low-permeable formations, the horizontal component of the velocity was neglected and the flow was assumed to be vertical. Further, a refined scheme was proposed [3, 4] where the vertical velocity component is taken into account in well-permeable reservoirs, and the effect of hydraulic connection between reservoirs was taken into account through the boundary conditions. In [5], a mathematical model was constructed that takes into account the elastic reserve of fluid in low-permeability formations. Later, within the framework of these models, many problems of underground hydrodynamics were solved. Thus, in [6], a mathematical model according to the Hantush scheme for layered reservoirs was considered.

Since when integrating over the variables z in the reservoir, terms appear in the equations - the flow coefficients then for the effective organization of the computational process, in [7] an approximate method for calculating at each time step is proposed, which the authors called intermediate models.

Generalization and substantiation of these works for multilayer oil-gas fields and dedicated work [8].

The study of the filtration process was also devoted to numerous works [9, 10, 11, 12] with assumptions and assumptions regarding the geometry of the layered reservoir and the characteristics of the saturating fluid. Almost all of these studies have assumed that fluid motions follow the linear Darcy law (Newtonian). Some works [6, 7, 8] considered fluid motions as non-Newtonian and mathematical models were built taking into account these assumptions. For structured fluids, there is almost no research in the scientific literature, especially in multilayer systems it has not been considered. It is known that structured fluids include those types of fluids that have a kind of filtration, differing from others, both in kinematic and dynamic properties, affecting their structural structure during filtration. Sometimes the structure of the porous medium itself may have structural characteristics that are not characteristic of ordinary media. The influence of these factors in total can lead to the fact that during the filtration process, physicochemical molecular and structural transformations begin to occur, associated with surface tension forces and other actions, which subsequently can be the causes of anomalous filtration of structured fluids.

Such types of fluids and media behave differently with a destroyed and not destroyed structure, which affects the mobility and filtration rate.

In the process of fluid filtration of this type, various mobility zones with unknown mobile boundaries are formed in the reservoir, such as: creep zone (where the fluid structure is practically not destroyed); a zone of medium (sometimes anomalous) mobility (where the relationship between velocity and pressure gradient is non-linear); zone of maximum mobility (where the relationship between velocity and pressure gradient is almost linear). Between these zones, there may be a critical value of the pressure gradient [13-15].

Studies related to mathematical modeling of this direction were also carried out in works [16-18], in one-dimensional and two-dimensional cases for single-layer media, where separate, as well as multi-parameter mathematical models were proposed, including various types of approximation of the functional relationship between the speed of movement and the pressure gradient. Such an interpretation and method of constructing a multiparametric mathematical model with the corresponding parametric boundary conditions made it possible to consider (combine) all existing mathematical models corresponding to certain lawful motions in one model (boundary value problem) [19, 20]. The study of the process of filtration of structured fluids in multilayer reservoirs is also studied in [21, 22], where a layered reservoir is considered and, moreover, in a productive reservoir, the movement occurs horizontally and in the bridges, vertically.

2 Objects and methods of research

Let a two-layer reservoir be given, with the lower one being productive (area Ω_1), with predominant horizontal characteristics, and the other upper layer (area Ω_2) considered to be a bridge and vertical characteristics predominating in it. Therefore, it can be assumed that the fluid motion in the lower region Ω_1, occur horizontally, and the upper region Ω_2 vertically. It is assumed that the region Ω_1 is saturated with structured fluids and the upper region Ω_2 is saturated with non-Newtonian fluids.
Assume that at the initial time the reservoir pressure in both reservoirs is constant and equal. If at the beginning of time $t > 0$ from wells located at the origin of coordinates (area Ω_1) there is a selection, then the process of reservoir filtration is mathematically formulated as follows: It is necessary to find continuous functions $u(x,t)$ and $\upsilon(x,z,t)$ as well as unknown boundaries $R_1(x,t),\ R_2(x,t),\ \Gamma(x,z,t)$ from the following system of differential equations:

$$\frac{\partial}{\partial x}\left(\Phi_1\left(|\nabla u|,\beta_1\right)\frac{\partial u}{\partial x}\right)-\chi\left(|\nabla v|,\beta\right)\frac{\partial v}{\partial z}\Big|_{z=h_1}=M_1\frac{\partial u}{\partial t},\ x\in\left(0;R_1(t)\right),\ t>0, \quad (1)$$

$$\frac{\partial}{\partial x}\left(\Phi_2\left(|\nabla u|,\beta_2\right)\frac{\partial u}{\partial x}\right)-\chi\left(|\nabla v|,\beta\right)\frac{\partial v}{\partial z}\Big|_{z=h_1}=M_2\frac{\partial u}{\partial t},\ x\in\left(R_1(t);R_2(t)\right),\ t>0, \quad (2)$$

$$\frac{\partial}{\partial x}\left(\Phi_3\left(|\nabla u|,\beta_3\right)\frac{\partial u}{\partial x}\right)-\chi\left(|\nabla v|,\beta\right)\frac{\partial v}{\partial z}\Big|_{z=h_1}=M_3\frac{\partial u}{\partial t},\ x\in\left(R_2(t);L\right),\ t>0, \quad (3)$$

$$\frac{\partial}{\partial z}\left(\chi\left(|\nabla v|,\beta\right)\frac{\partial v}{\partial z}\right)=M\frac{\partial v}{\partial t},\quad z\in\left(h_1;\Gamma(t)\right),\ t>0, \quad (4)$$

$$\frac{\partial}{\partial z}\left(\Phi\left(|\nabla v|,\beta\right)\frac{\partial v}{\partial z}\right)=M\frac{\partial v}{\partial t},\quad z\in\left(\Gamma(t);h_2\right),\ t>0, \quad (5)$$

with initial

$$u(x,0)=v(x,z,0)=u_0(x,z), \quad (6)$$

$$R_1(x,0)=R_2(x,0)=0,\ \ \Gamma(x,h_1,0)=0, \quad (7)$$

and boundary

$$\Phi_1\left(|\nabla u|,\beta_1\right)\frac{\partial u}{\partial x}\Big|_{x=R_1-0}=\Phi_2\left(|\nabla u|,\beta_2\right)\frac{\partial u}{\partial x}\Big|_{x=R_1+0}, \quad (8)$$

$$\Phi_2\left(\left|\nabla u\right|,\beta_2\right)\frac{\partial u}{\partial x}\Big|_{x=R_2-0}=\Phi_3\left(\left|\nabla u\right|,\beta_3\right)\frac{\partial u}{\partial x}\Big|_{x=R_2+0}, \quad (9)$$

$$\chi\left(\left|\nabla v\right|,\beta\right)\frac{\partial v}{\partial z}\Big|_{z=\Gamma-0}=\Phi\left(\left|\nabla v\right|,\beta\right)\frac{\partial v}{\partial z}\Big|_{z=\Gamma+0}, \quad (10)$$

as well as the boundary conditions

$$\alpha_1\Phi_1\left(\left|\nabla u\right|,\beta_1\right)\frac{\partial u}{\partial x}\Bigg|_{\substack{x=0\\ z=h_1}}+\gamma_1 b_1 U\Big|_{\substack{x=0\\ z=h}}=q_0\left(t\right),\ t>0, \quad (11)$$

$$\alpha_2\Phi_3\left(\left|\nabla u\right|,\beta_3\right)\frac{\partial u}{\partial x}\Big|_{x=L}=0,\ t\geq 0, z=h_1, \quad (12)$$

$$\alpha_3\Phi\left(\left|\nabla v\right|,\beta\right)\frac{\partial v}{\partial x}\Big|_{z=h_2}=0,\ t\geq 0, \quad (13)$$

Here: Function $\Phi_l=\dfrac{K(x)}{\eta_l}A_l\left(\left|\nabla u\right|,\beta_l\right),\ l=\overline{1,3}$;

$K(x)$ permeability, η_l coefficients, dynamic viscosity corresponding to three filtration zones; $A_l\left(\left|\nabla u\right|,\beta_l\right)$- functions expressing the mobility of the fluid in these zones and takes a specific form corresponding to the indicator curves of the fluid velocity. β_l-coefficients relative to the critical values of the shear gradients.

$\chi\left(\left|\nabla v\right|,\beta\right)=\dfrac{K_1(z)}{\mu}\left(1-\dfrac{\beta\gamma_0}{\left|\nabla v\right|}\right)$ at $\left|\nabla v\right|>\beta$, where μ is the viscosity value in the anomalous filtration zone. $\gamma_0=1-0,41142135\dfrac{\mu}{\nu}$, [21], ν is the dynamic viscosity of the fluid at low $\left(\left|\nabla v\right|<\beta\right)$ pressure gradients. $\Phi\left(\left|\nabla v\right|,\beta\right)=\dfrac{K_1(z)}{\nu}\ \dfrac{\left|\nabla v\right|}{\beta+\left|\nabla v\right|}$, at $\left|\nabla v\right|<\beta$, describes one of the non-linear motions in the region of small pressure gradients in the bulkhead.

$M_l=M_l\left(x,t,u\right),\ \ l=\overline{1,3},\ \ M=M\left(x,z,t,\upsilon\right)$ well-known functions depending on the filtration regime and the types of fluids under consideration (water, gas, oil, condensate, etc.) as well as on the structure of the porous medium itself.

$\alpha_l\ \ (l=\overline{1,3})$ constants depending on the width and height (length) in the layers balancing the dimensions of the equations.

Problem (1)-(13) is generally non-linear and therefore it is difficult and even impossible to construct an analytical solution. Under certain assumptions and assumptions regarding the parameters and functions, it is possible to construct approximately analytical solutions [16].

Problem (1)-(13) is solved by the flow version of the finite difference method [21-23]

We introduce notation

$$W_e\left(x,t\right)=\Phi_e\left(\left|\nabla u\right|,\beta_e\right)\frac{\partial u}{\partial x},\ e=\overline{1,3} \quad (14)$$

$$\omega_r\left(x,z,t\right)=x\left(\left|\nabla v\right|,\beta\right)\frac{\partial v}{\partial z},r=\overline{1,2} \tag{15}$$

(at $r=1,\chi=\chi,$ at $r=2,\ \chi=\Phi$).
Then problem (1)-(6) takes the form.

$$\frac{\partial W_e}{\partial x}-\omega_1\Big|_{z=h_1}=M_e\frac{\partial u}{\partial t},\quad e=\overline{1,3}; \tag{16}$$

$$\frac{\partial \omega_r}{\partial z}=M\frac{\partial v}{\partial t},\quad r=\overline{1,2}; \tag{17}$$

Conditions (8)-(10) will be written as

$$W_1\left(x,t\right)\Big|_{x=R_1-0}=W_2\left(x,t\right)\Big|_{x=R_1+0}, \tag{18}$$

$$W_2\left(x,t\right)\Big|_{x=R_1-0}=W_3\left(x,t\right)\Big|_{x=R_1+0}, \tag{19}$$

$$\omega_1\left(x,z,t\right)\Big|_{z=\Gamma-0}=\omega_2\left(x,z,t\right)\Big|_{z=\Gamma+0}. \tag{20}$$

Relations (11)-(13) will take the form:

$$\alpha_1W_1\left(x,t\right)\Big|_{x=0}+b_1U\Big|_{x=0}=q_0, \tag{21}$$

$$\alpha_2W_3\left(x,t\right)\Big|_{x=L}=0, \tag{22}$$

$$\alpha_3W_2\left(x,z,t\right)\Big|_{z=h_2}=0. \tag{23}$$

Problem (16)-(18) is solved as follows:

Integrating (16), on the interval $\left[x_{i-\frac{1}{2}},x_{i+\frac{1}{2}}\right]$ and applying the mean value theorem for the time derivative, we obtain

$$W\left(x_{i+\frac{1}{2}},t\right)-W\left(x_{i-\frac{1}{2}},t\right)=M_i\frac{\partial u_i}{\partial t}h_i+\left(\omega_r\right)_i h_i \tag{24}$$

We integrate relation (17) on the interval $\left[z_{j+\frac{1}{2}},z_{j-\frac{1}{2}}\right]$ and also performing the same operations as with (16) we have

$$\omega\left(x_i,z_{j+\frac{1}{2}},t\right)-\omega\left(x_i,z_{j-\frac{1}{2}},t\right)=M\left(x_i,z_j,u_{ij}\right)\frac{\partial v_i}{\partial t}\overline{h_j}, \tag{25}$$

where $h_i = x_{i+\frac{1}{2}} - x_{i-\frac{1}{2}}$, $\overline{h_j} = z_{j+\frac{1}{2}} - z_{j-\frac{1}{2}}$.

In order to save the amount of work, we do not write down the fully obtained ratio in the future, but state the verbal form of the work done. In expression (24), passing to the difference relations over (equivalent to integration (24) over the variable t on the segment $\left[t_k, t_{k-1}\right]$), we write (24) and (25) as

$$W_{i+\frac{1}{2}} - W_{i-\frac{1}{2}} - c_i u_i = -d_i \ , \quad i = 1,2,\ldots,N-1,$$

$$\omega_{j+\frac{1}{2}} - \omega_{j-\frac{1}{2}} - \tilde{c}_i \upsilon_{j,k} = -d_j \ , \quad j = 1,2,\ldots,N-1,$$

where $W_{i+\frac{1}{2}} = W\left(x_{i+\frac{1}{2}}, t_k\right)$, $u_i = u\left(x_i, t_k\right)$.

In the future, the course of the constructed computational formulas will be presented in a descriptive form:

We integrate from the beginning [23, 24] equality (24) and (25) with respect to the variable t on the interval $\left[t_k, t_{k-1}\right]$ and also (14) on the interval $\left[x_{i-1}, x_i\right]$ (15) to $\left[z_{j-1}, z_j\right]$ obtain a system of grid difference equations for the flows and sought functions with the corresponding initial and boundary and also boundary flow conditions.

The constructed flow-difference boundary value problems are solved using the flow version of the difference sweep [8, 21–28].

The sweep coefficients are determined using the appropriate equation and boundary conditions.

The obtained algorithms make it possible to calculate the value of both the desired functions and the flow at the nodes of the grid area.

On the boundaries of the zones $R_i\left(t_k\right)$ and using the conditions of equality of flows, $\Gamma\left(z_j, t_k\right)$ the sweep coefficients are determined and then it is possible to calculate the boundaries of these zones and the moving unknown boundary of the upper layer. In this case, the accuracy of computational schemes in the limit $o\left(h^2 + \tau\right)$.

3 Results and their discussion

The sequence of calculation of the developed algorithms is as follows: From the beginning with respect to non-linear terms, linearization is carried out using the iteration method;

Since at the beginning of the calculations the value of the flow from the bridge to the reservoir is unknown, then within one time step we proceed as follows: first, we consider there is no flow and solve the problem in the reservoir. Next, the problem is solved on the jumper and, using the known value of the flow, the problem is again solved in the reservoir. In further time steps in the solution process in the area, Ω_1 the flow value from Ω_2 is taken from the value from the previous time step. In this case, at each time step , the position of the zone boundary in the region is determined Ω_1 by comparing the magnitude of the flows on the left and right in each zone boundary. In the region, Ω_2 too, at every step along t_k border is defined $\Gamma(t_k)$ by comparing the flows in the direction of the variable z . To improve the accuracy of perturbation boundary values, it is proposed to use the "shuttle" iteration method [21] or the simple iteration method. To test the model and establish the performance of computational algorithms, hypothetical data of the form: $q_0 = 50$ t/ s ; 100 t/s ; $\mu = 0;\ 0,01;\ 0,1;\ 0,3.\ k = 0,005;\ 0,01;\ 0,02:$

$$v = 0,018,\ m_1 = 0,017,\ m_2 = 0,27.\ u_0 = 1\ \ (100atm)$$

Separate fragments of the results are shown in Figures 1- 4 as well as in tables 1 and 2.

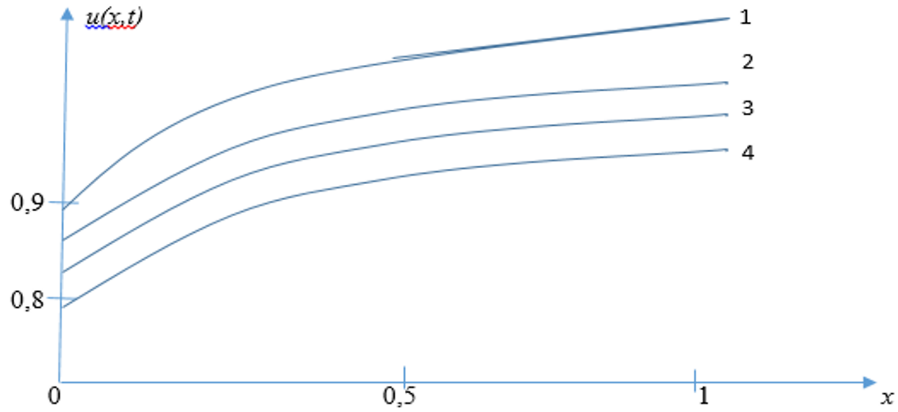

Fig. 1. Distribution of pressure in the reservoir $t = 0.1; t = 0.2; t = 0.3; t = 0.5$ for Newtonian fluids

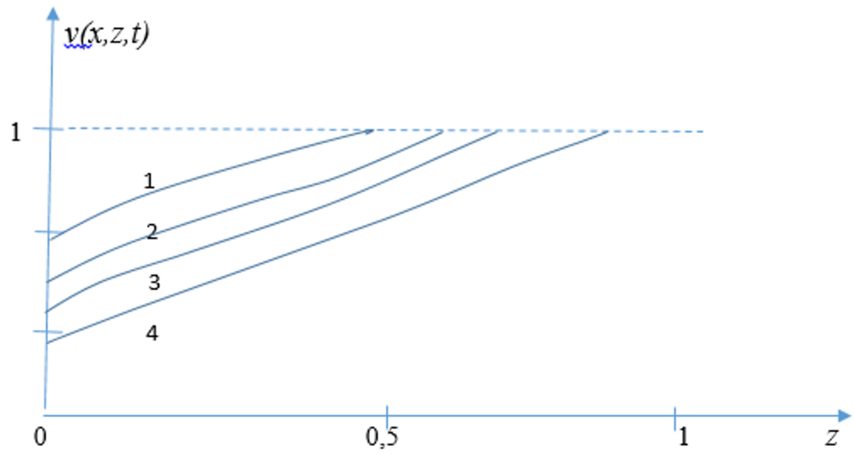

Fig. 2. Pressure distribution in the bulkhead at $t = 0.1; t = 0.2; t = 0.3; t = 0.4$.

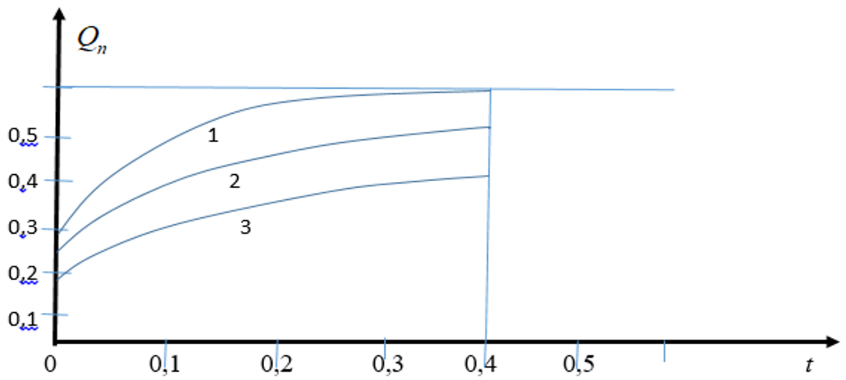

Fig. 3. Change in the flow function at $t = 0.1; t = 0.2; t = 0.3$.

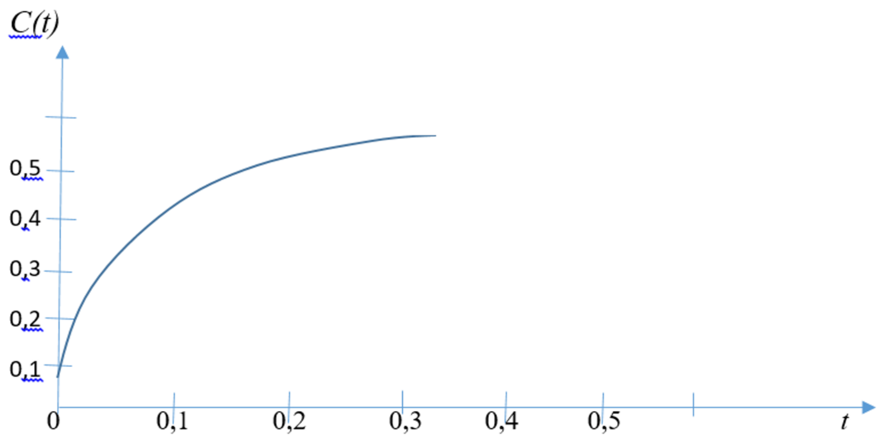

Fig. 4. Change of the perturbation boundary in time t in the upper layer (Ω_2) with non-linearity of the law of motion

Table 1 shows the change in pressure in a well-permeable reservoir during Newtonian fluid filtration: where $\beta_i = 0$; $q_0 = 50\frac{t}{s}$; $\mu = 0; m = 0.27$; $\mu = 0.01\frac{g}{sm^2 sec}$.

Table 1.

t_x	0	0.1	0.2	0.3	0.4
0.1	0.8253	0.8043	0.9315	0.9605	0.9702
0.2	0.7614	0.8218	0.8721	0.9012	0.9171
0.3	0.7072	0.7615	0.8130	0.8615	0.8816

Below in table 2 for $m = 0,2,\ \beta = 0,5 \cdot 10^{-5};\ 10^{-3},\ \mu = 0,3,\ m = 0,18,\ x = 0,005,\ \alpha = 1.$
$b = 5m,\ \ h = 80m.\ \ q = 50$ t/s, $u_0 = 1$
given changes in pressure in Ω, for different β points $x = 0$ in time:

Table 2.

t	$\beta = 0$	$\beta = 10^{-5}$	$\beta = 10^{-2}$
0.01	0.98150	0.97502	0.92163
0.05	0.95261	0.93121	0.89121
0.2	0.92110	0.90422	0.87125
0.15	0.89216	0.87134	0.84786
Flow value			
0.01	0.12143	0.10346	0.08732
0.05	0.18314	0.16342	0.11425
0.1	0.21210	0.19121	0.16522
0.15	0.25146	0.22751	0.19344

4 Conclusions

Numerical experiments show that when $\frac{K_1}{K} < 10^{-4}$ extracting fluid from a dam, using a well-permeable formation does not give the desired effects.

With a nonlinear law of filtration in the area for a zone with a large pressure gradient, a rapid increase in the amount of overflow from Ω_1 the bridge is characteristic, and for an anomalous zone, this value directly depends on the degree of anomaly. By controlling the values of the flow, as well as the perturbation gradients, depending on the rate of production from a well-permeable reservoir, it is possible to achieve the highest recovery of the reservoir being developed. Thus, the constructed mathematical model of the filtration of structured fluids in a two-layer reservoir, as well as the developed computational algorithms, can be used to develop hydrocarbon deposits with a similar geometry proposed in this model, which allows continuous delivery through pipelines for CHP generating electrical energy.

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