

Development Of A Computational Algorithm For Solving The Pv Diffusion Problem In The Conditions Of Using A Storey Development System

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Abstract – The development of a computational algorithm to solve the problem of PV diffusion in the context of the use of a layer development system is described in the article. A mathematical model of the management of the underground mixing process in the conditions of a layered system of development has been developed; the dynamics of the reagent concentration and pressure value at different values of the parameters affecting the technological process of underground mixing in the conditions of the layered system of development were studied; a computer model was developed to conduct numerical experiments and visualize the results in two- and three-dimensional graphics; a software package of the underground mixing process was developed to support technological decision-making in the management of the development of mineral deposits in the conditions of a stratified system of development. The developed computational algorithms and computer model can be used in decision-making, analysis and forecasting of parameters of the underground mixing process in order to optimally obtain minerals from real deposits developed in the stratified system of underground mixing.

Keywords – Underground mixing, layered system of development, specific gravity of reagent, hydrodynamics, concentration, computer model, numerical-approximate method, flow drive, variable directional method, control parameters, decision support, control scheme.

I. INTRODUCTION

Let us consider a diffusion problem in the control of PV processes in inhomogeneous media under the conditions of a storey development system, which is solved using two-dimensional equations of convective diffusion with an additional term that takes into account the kinetics of dissolution and the distribution field of the reagent. In this case, we will assume that the filtration rate is known and determined in the previous paragraph, taking into account the specific gravity of the reagent. We also assume that the value of the concentration of the limiting saturation is known C_m , dissolution rate constants, initial, boundary and internal concentration values.

Let us consider a vertical, rectangular heterogeneous ore layer of constant width h . A solvent with a constant concentration of C_1 is supplied through the injection well, as a result of the migration of which a chemical reaction occurs, and the enriched productive solution is pumped out to the surface. If at the beginning the concentration of the useful component in the liquid phase was equal to C_0 , then after injection it is equal to $C(x,z,t)$.

Then we determine the value of the concentration function C in the rectangular region

$$G = \{(x, z, t) / a < x < b, c < z < d, 0 < t \leq T_k\}.$$

The equation is being solved

$$\frac{\partial}{\partial x} \left(D \frac{\partial C}{\partial x} \right) + \frac{\partial}{\partial z} \left(D \frac{\partial C}{\partial z} \right) - \frac{\partial(v_x C)}{\partial x} - \frac{\partial(v_z C)}{\partial z} - \frac{\partial N}{\partial t} = m \frac{\partial C}{\partial t} \quad (1)$$

(here $\frac{\partial N}{\partial t} = -\gamma(C_m - C)$, $N(x, z, 0) = N_0(x, z)$) in domain G with initial

$$C(x, z, 0) = C_0,$$

borderline

$$\left(\bar{\alpha} \frac{\partial C}{\partial n} + (1 - \bar{\alpha}) C \right) \Big|_{\Gamma} = \psi(x, z, t) \quad (2)$$

and internal

$$C(x, z, t) \Big|_{(x,z)=(x_i,z_i')} = C_i, \quad \frac{\partial C}{\partial n} \Big|_{(x,z)=(x_j,z_j')} = 0 \quad (3)$$

conditions.

Problem (1) - (3) will be solved by the method of alternating directions using a monotone scheme for approximating the convective term, i.e. we use an economical difference scheme for equations of parabolic type with mixed derivatives, which were proposed by A.A. Samarskii.

To implement this method, it is necessary to go over to dimensionless variables. In our case, they look like this:

$$\bar{x} = \frac{x}{L_x}; \quad \bar{C} = \frac{C}{C_x}; \quad \bar{v}_x = \frac{v_x}{v_0}; \quad \bar{t} = \frac{t}{t_x}; \quad \bar{v}_z = \frac{v_z}{v_0}; \quad \bar{z} = \frac{z}{L_z}; \quad \bar{D} = \frac{D}{D_x}; \quad \bar{N} = \frac{N}{N_x^*}.$$

Where $L_x, C_x, v_0, L_z, D_x, N_x^*, t_x$ some characteristic values, in what follows, for convenience of writing, we will omit the dashes above the letters

To compose finite-difference equations, we construct in the domain G uniform length and depth mesh with steps $h_x = \frac{L_x}{N_x}$, $h_z = \frac{L_z}{N_z}$, and the time step is taken equal to $\Delta\tau$, Where N_x , N_z – number of nodes.

However, here one should use a scheme that takes into account the sign of the component of the filtration rate, since the sweep method is applicable for sufficiently small grid steps h, when the condition $h|v| < 2D$, where v is, respectively, equal in each direction v_x or v_z . If this condition is not met, then the maximum principle is not met. Therefore, the use of a monotonic scheme eliminates this drawback, since for it the maximum principle is valid for any h. If we use one-sided difference derivatives, then we obtain a monotonic scheme of the first order of accuracy. To obtain a monotonic second-order scheme, it is sufficient to write it as one-sided differences for the derivatives in the equation with perturbed coefficients:

$$m \frac{\partial C}{\partial t} = \tilde{L}C + f, \quad (4)$$

Where
$$\tilde{L} = \tilde{L}_x + \tilde{L}_z, \quad \tilde{L}_x = \chi_x \frac{\partial}{\partial x} \left(k_x \frac{\partial C}{\partial x} \right) + r_x \frac{\partial C}{\partial x} - q_x C + \frac{\gamma}{2},$$

$$\tilde{L}_z = \chi_z \frac{\partial}{\partial z} \left(k_z \frac{\partial C}{\partial z} \right) + r_z \frac{\partial C}{\partial z} - q_z C + \frac{\gamma}{2}.$$

The notation is used here $\chi_x = (1 + R_x)^{-1}$, $R_x = 0,5h_x |r_x| / k_x$,

$$\chi_z = (1 + R_z)^{-1}, \quad R_z = 0,5h_z |r_z| / k_z, \quad k_x = D_x, \quad k_z = D_z, \quad r_x = -v_x, \quad r_z = -v_z,$$

$$q_x = \frac{\partial v_x}{\partial x}, \quad q_z = \frac{\partial v_z}{\partial z}$$

r_x and r_z are represented as the sum

$$r_x = r_x^+ + r_x^-, \quad r_x^+ = 0,5 \cdot (r_x + |r_x|) \geq 0, \quad r_x^- = 0,5 \cdot (r_x - |r_x|) \leq 0;$$

$$r_z = r_z^+ + r_z^-, \quad r_z^+ = 0,5 \cdot (r_z + |r_z|) \geq 0, \quad r_z^- = 0,5 \cdot (r_z - |r_z|) \leq 0.$$

Then, using this, we approximate the expression

$$(r_x C_x) = \left(\frac{r_x}{k_x} (k_x C_x) \right)_i \approx b_{x,i}^+ a_{i+1} C_{x,i} + b_{x,i}^- a_i C_{\bar{x},i},$$

Where
$$b_x^\pm = \frac{r_x^\pm}{k_x}, \quad b_z^\pm = \frac{r_z^\pm}{k_z}, \quad a_x = k_x, \quad a_z = k_z.$$

Using these, we write the difference analogue of the operators $\tilde{L}_x$ and $\tilde{L}_z$:

$$\tilde{L}_x C \approx \Lambda_x C = \chi_x (a_i C_{\bar{x}})_{x,i} + b_{x,i}^+ a_{i+1} C_{x,i} + b_{x,i}^- a_i C_{\bar{x},i} - q_x C, \quad (5)$$

$$\tilde{L}_z C \approx \Lambda_z C = \chi_z (a_j C_{\bar{z},j})_{z,j} + b_{z,j}^+ a_{j+1} C_{z,j} + b_{z,j}^- a_j C_{\bar{z},j} - q_z C. \quad (6)$$

Replacing C_i with the right difference approximation, passing from layer n to layer $n + 1$, in two stages we apply the method of alternating directions:

$$m \frac{C^{n+\frac{1}{2}} - C^n}{0,5\tau} = \tilde{\Lambda}_x C^{n+\frac{1}{2}} + \tilde{\Lambda}_z C^n + f^n,$$

$$m \frac{C^{n+1} - C^{n+\frac{1}{2}}}{0,5\tau} = \tilde{\Lambda}_z C^{n+1} + \tilde{\Lambda}_x C^{n+\frac{1}{2}} + f^n.$$

By supplying instead $\tilde{\Lambda}_x$ (5) and instead of $\tilde{\Lambda}_z$ (6), making some transformations, we get the following systems of algebraic equations:

$$A_i^1 C_{i-1,j}^{n+\frac{1}{2}} - \bar{C}_i^1 C_{i,j}^{n+\frac{1}{2}} + B_i^1 C_{i+1,j}^{n+\frac{1}{2}} = -F_{i,j}^1, \quad (7)$$

$$A_j^2 C_{i,j-1}^{n+1} - \bar{C}_j^2 C_{i,j}^{n+1} + B_j^2 C_{i,j+1}^{n+1} = -F_{i,j}^2. \quad (8)$$

Here

$$A_i^1 = \frac{a_i}{h_x^2} (\chi_x - h_x b_i^-), \quad A_j^2 = \frac{a_j}{h_z^2} (\chi_z - h_z b_j^-),$$

$$B_i^1 = \frac{a_{i+1}}{h_x^2} (\chi_x + h_x b_i^+), \quad B_j^2 = \frac{a_{j+1}}{h_z^2} (\chi_z + h_z b_j^+),$$

$$\bar{C}_i^1 = A_i^1 + B_i^1 + \frac{m}{0,5\tau} + \gamma, \quad \bar{C}_j^2 = A_j^2 + B_j^2 + \frac{m}{0,5\tau} + \gamma,$$

$$F_{i,j}^1 = \frac{m}{0,5\tau} C_{i,j}^n + \chi_z \frac{a_{j+1} C_{z,i}^n - a_j C_{\bar{z},j}^n}{h_z^2} + b_j^+ a_{j+1} C_{z,j}^n + b_j^- a_j C_{\bar{z},j}^n + \gamma_m,$$

$$F_{i,j}^2 = \frac{m}{0,5\tau} C_{i,j}^{n+\frac{1}{2}} + \chi_x \frac{a_{i+1} C_{x,i}^n - a_i C_{\bar{x},i}^{n+\frac{1}{2}}}{h_x^2} + b_i^+ a_{i+1} C_{x,i}^{n+\frac{1}{2}} + b_i^- a_i C_{\bar{x},i}^{n+\frac{1}{2}} + \gamma_m.$$

To solve system (7) - (8), it is necessary to add initial, boundary and internal conditions to it. We define a difference analogue of the initial condition (6) in the form

$$C_{i,j}^0 = C_0. \quad (9)$$

Consider the generalized boundary conditions:

$$\left(\bar{\alpha} \frac{\partial C}{\partial n} + (1 - \bar{\alpha})C \right) \Big|_{\Gamma} = \psi(x, z, t).$$

It allows us to consider three cases: for $\bar{\alpha} = 0$ the condition of the first kind is realized; at $\bar{\alpha} = 1$ – condition of the second kind; and at $\bar{\alpha} = 0,5$ – condition of the third kind.

The difference approximation of the boundary condition of the first kind has the form:

$$C_{i,0}^n = \psi, \quad C_{0,j}^n = \psi. \quad (10)$$

Expanding C in a Taylor series in the vicinity of the point under study, we use the following relations for the difference approximation of the boundary condition of the second kind [100]:

$$C_{N,j}^n = \frac{(4 - \alpha_{N-1})\beta_N - \beta_{N-1}}{3 - \alpha_N(4 - \alpha_{N-1})}, \quad (11)$$

$$C_{i,N}^n = \frac{(4 - \alpha'_{N-1})\beta'_N - \beta'_{N-1}}{3 - \alpha'_N(4 - \alpha'_{N-1})}. \quad (12)$$

An approximation of the internal conditions, i.e. well conditions were studied in . In the wells are replaced by points at which their values are set.

In this case, in order not to complicate the calculations, we will use the well point approximation.

Thus, the solution of problem (1) - (3) is reduced to the following algorithm.

First, the system (7) is solved with the appropriate conditions, applying the sweep method, we obtain the values $C_{i,j}^{n+\frac{1}{2}}$. Then, using the obtained values at a fractional step, system (8) is solved with the appropriate conditions, and as a result, we obtain the values of the desired function at the full time step $C_{i,j}^{n+1}$ for all i, j .

At the initial stage, the direction along x is implicit, and along Z is explicit, therefore the sweep is carried out with a fixed direction along Z ($j=1, N_z-1$). And in the next stage, the solution is explicit in x , and implicit in Z , therefore, we fix ($i=1, N_x-1$).

As a result of using a step-by-step solution of the system along and across, we obtain the values of the desired function (concentration) at all nodes of the considered region.

According to the proposed algorithm, a program was compiled in the modern algorithmic language Delphi 7. In order to check the reliability of the results obtained, the computational algorithm was tested by the method of trial functions [69]. As an exact solution, the function

$$C(x, z, t) = \exp(t \cdot x \cdot z(x-1)(z-1)), \quad (13)$$

odds

$$\begin{aligned} f = & (m x z(x-1)(z-1) - D_x t^2 (z(z-1)(x-1) + xz(z-1))^2 - 2D_x tz(z-1) - \\ & - D_z t^2 (z-1)(x-1)x + xz(x-1))^2 - 2D_z tx(x-1) + v_x t(z(x-1)(z-1) + \\ & + v_z t(x(x-1)(z-1) + xz(x-1) + \gamma) \cdot \exp(t x z(x-1)(z-1)). \end{aligned}$$

with initial $C(x,z,0)=1$ and at the boundaries of the concentration value is equal to one.

The following hypothetical values were taken as the initial data:

$$C=5,0014; N=50; N_x=N_z=50;$$

$$C_m=5001,4; C_s=0; m=0,2; \gamma=10^{-8};$$

$$\Delta\tau=1; h_x=h_z=0,02, D=0.001.$$

Figure 1 shows the results of calculating the exact (Tx) solution by formula (13) and the approximate (Px) solution by the alternating direction method using a monotonic scheme to approximate the convective term. As a result of comparing solutions, you can see the similarity of solutions with accuracy $O(h^2 + \tau^2)$. This means that the algorithm can be used to solve practical problems of control over PW processes in heterogeneous environments under the conditions of a storey development system.

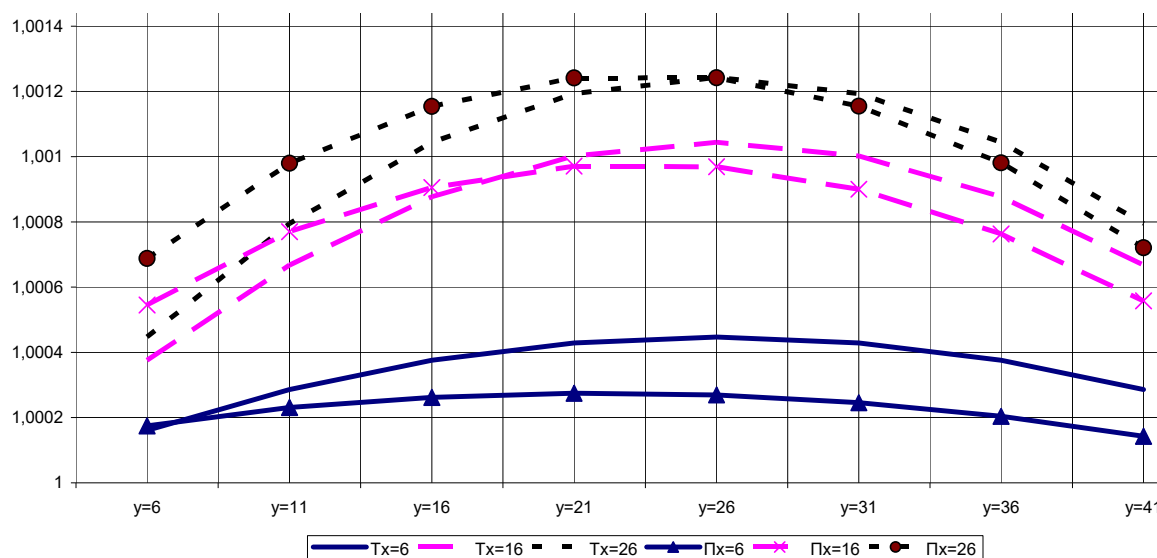


Figure 1. Comparison of exact (Tx) and approximate (Px) results.

Now we will consider the application of this algorithm to the test object PW, which is given in the previous paragraph.

To determine the field of concentration of minerals using the above algorithm, we first select the fields of ore-bearing zones. In the conditions of a storey development system, the filtration and ore-bearing zones have their own separate boundaries. In other development systems, these boundaries were considered the same.

Now let's look at the following test case.

Let us be given an ore layer, which is developed by the PV method in the conditions of a storey development system. Two injection wells and one production well were involved. Geological and hydrogeological data are given in table. 1. The layout of the ore-bearing layer is shown in Fig. 2.

Fig. 2 it can be seen that the thickness of the horizon differs from the thickness of the ore-bearing zone, and also their boundaries are different. Injection well filters are located on top of the ore-bearing zone. Production well filters are located at the bottom of the ore-bearing zone. The injected solutions, flowing through the ore-bearing zone, capture useful components, move towards the production well.

Using the algorithm described above, results are obtained at different points in time based on test data corresponding to a real object. Let's analyze the results obtained.

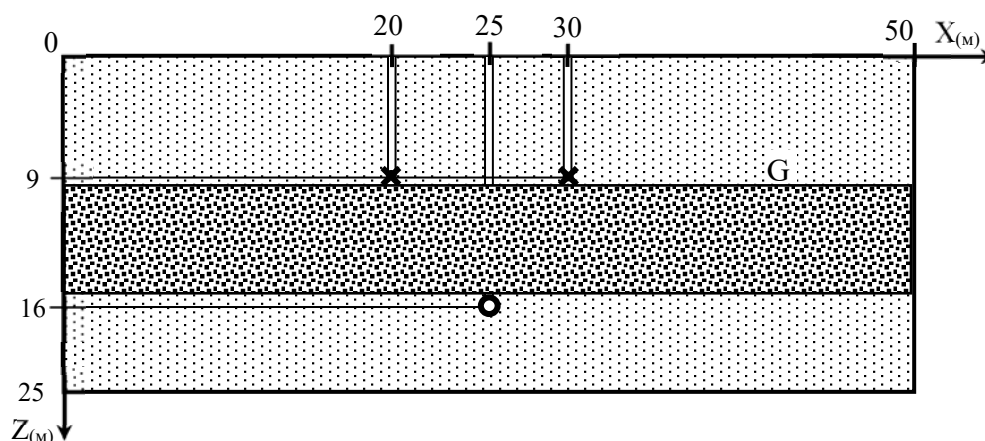


Figure 2. Layout of the ore-bearing layer

 - extra-ore filtration zone,
  - ore layer

It is known that over time, the value of the concentration of the mineral increases due to the injected leaching agent in the ore-bearing zone. In fig. 3 shows the changes in isolines of concentration values in the ore-bearing zone.

If we pay attention to fig. 3 (A, B, C, D), the concentration value is higher near the injection wells than in the distance. This shows that the process spreads mainly in the ore-bearing zone, which corresponds to the physical process.

Fig. 4 shows that the change in concentration takes place only in the ore-bearing zone. And this also corresponds to the physical essence of the PV process.

Figure 5 shows a graph of changes in the concentration value at different depths of the reservoir over time. Here, the 1st line reflects the concentration values near the injection wells when it is at its highest. The 2nd and 3rd lines represent the concentration values at different distances from the injection wells, and the 4th line reflects the concentrations at points outside the ore zones. Here you can see that the 4th line does not change and has its initial constant value.

Over time, the concentration value in the developed formation near the injection wells is higher than in the distance. This fully corresponds to the physical state of the process taking place in the reservoir.

To check the reliability of the developed algorithm, consider a homogeneous reservoir, in which injection wells are located symmetrically. In this case, the advancement of the injected solutions also changes symmetrically over the formation.

The results show that the developed algorithm gives the correct result when solving the problem.

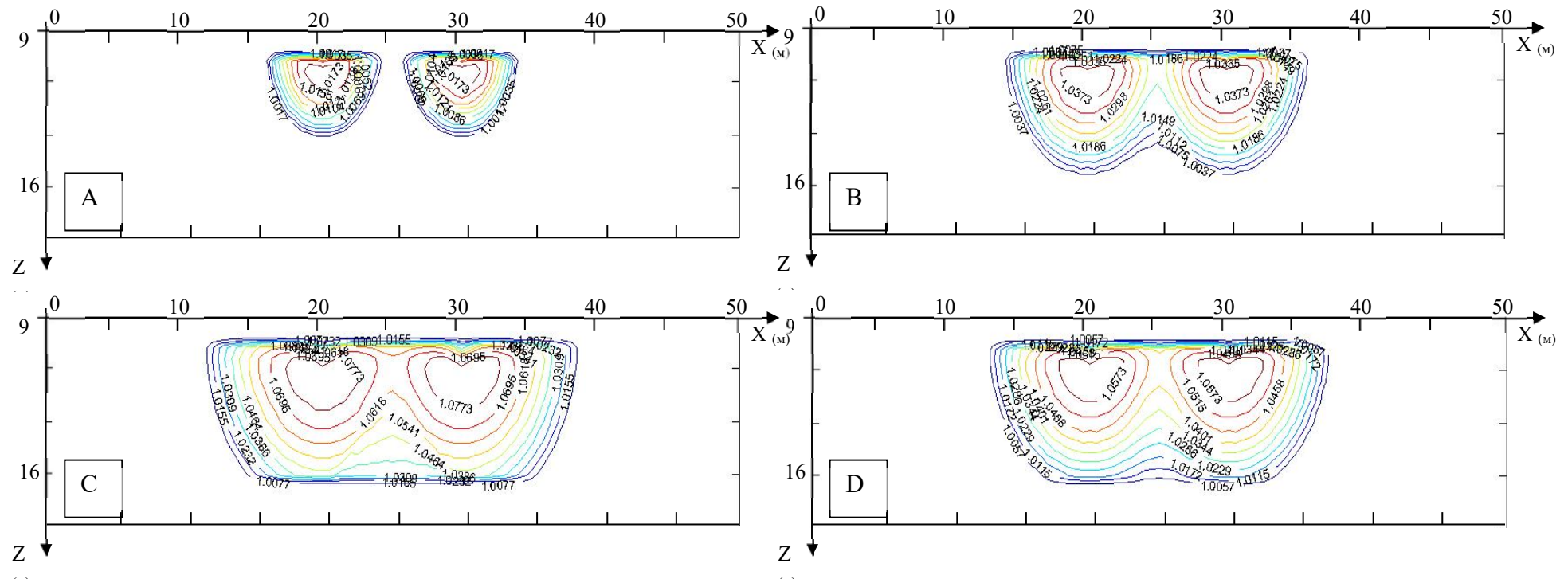


Figure 5. Dynamics of changes in concentration over time:

A - 10 days; B - 20 days; C - 30 days; D - 40 days.

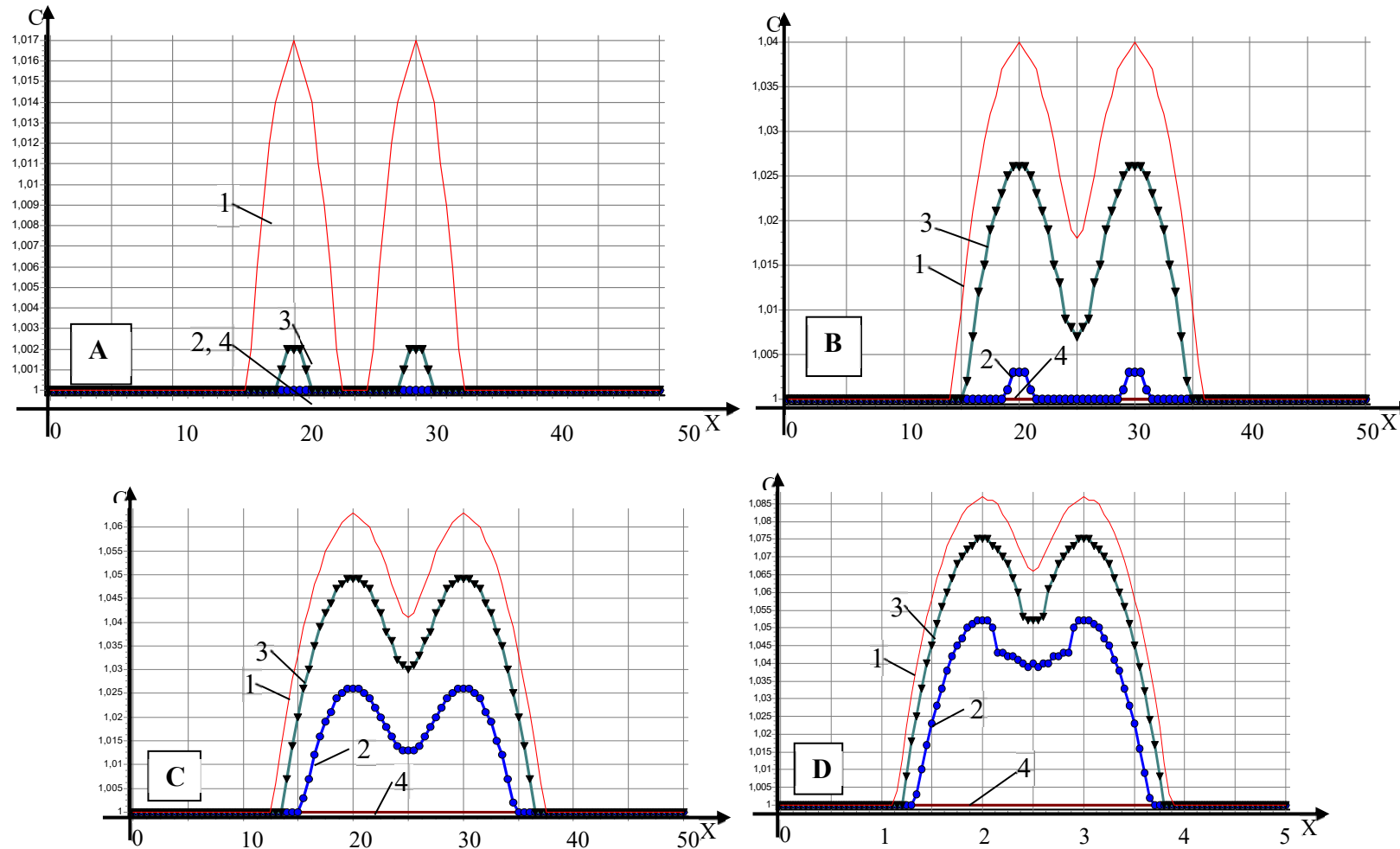


Fig. 6. Dynamics of changes in the concentration value in the depths of the reservoir 10 m (curve 1), 12 m (2), 14 m (3) and 7 m (4)
(A - 10 days; B - 20 days; C - 30 days; D - 40 days.)

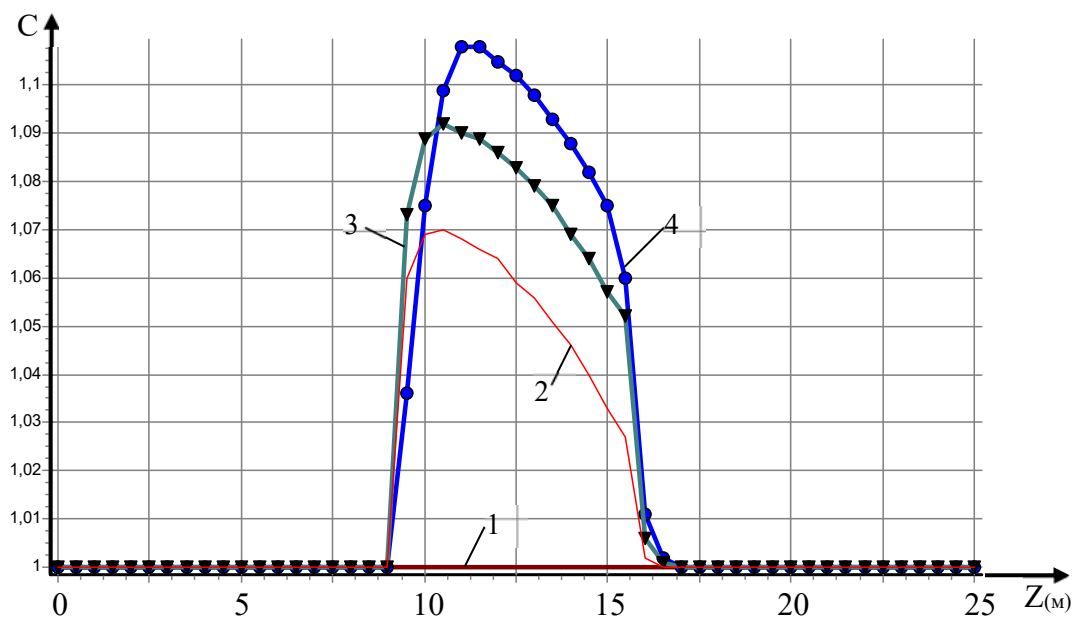


Fig. 7. Distribution of concentration for 40 days at points:

1 - $x = 10$ m; 2 - $x = 14$ m; 3 - $x = 16$ m; 4 - $x = 20$ m.

Figure 7 shows the dynamics of changes in the concentration value at various points in the formation.

Concentration values near the injection well (curve 4) are higher than in other points of the formation. This graph once again confirms the results of the above analysis and corresponds to the real description of the physical process of PV in the conditions of a storey development system.

Thus, we can conclude that the developed mathematical model and computational algorithm are fully consistent for solving problems of control of PV processes in the conditions of a storey development system. And they can be used to make technological decisions on the management of PV processes in real objects.

Conclusion/Recommendations

The main results of this work consist of the following:

an effective computational algorithm has been developed for solving a one-dimensional hydrodynamic problem of the PV process in relation to the conditions of a storey development system, when the force factor of gravity must be taken into account;

computational experiments were carried out to verify the reliability of the developed computational algorithm using the method of trial functions for solving a one-dimensional hydrodynamic problem of the PV process under the conditions of a storey development system, taking into account the specific gravity of the reagent;

an effective computational algorithm has been developed for solving a two-dimensional hydrodynamic problem of control of PV processes in a multi-storey development system, taking into account the specific gravity of the reagent;

computational experiments were carried out to solve the hydrodynamic problem of the PV process under the conditions of a storey development system to check the reliability of the developed computational algorithm using the corresponding test data of a real object;

an effective computational algorithm has been developed for solving a two-dimensional diffusion problem, taking into account the kinetics of dissolution, in order to control the PV processes in the conditions of a storey development system;

the structure of the software for controlling the PV processes in heterogeneous environments is described, which develops in the conditions of a storey development system, data types are given, a description of the structure of the data file and the result file is given.

Screen forms of results presentation are developed, a brief explanation of the software product operation is given.

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