Designing of distributed systems of hydrolithosphere processes parameters control for the efficient extraction of hydromineral raw materials

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Abstract. Using methods developed for systems with distributed parameters allows us to optimize processes of hydromineral raw materials production in practice. In accordance with the theory of distributed systems, formation of control actions on each well of a complex of production wells requires taking into account a state of the entire complex of wells, which ensures better dynamics and accuracy of a control process. The methodology of constructing distributed control systems for controlling the entire complex of wells involves the use of dynamic and static characteristics of an exploited aquifer. In this connection, a problem of mathematical description (identification) of the processes under consideration arises, which can be realized, for example, using the methods and formulas of Theis-Jacob. Using the Theis-Jacob formulas for the identification of the processes under consideration assumes an availability of information about parameters of hydrolithosphere processes (piezoelectric conductivity, overflow coefficients, etc.). The calculation of the considered parameters is a rather laborious task. The article proposes a methodology for constructing approximation models of the processes under consideration based on experimental studies using 2 wells of a field. Based on the obtained approximation model, a synthesis of the system for the hydrolithosphere processes parameters control was implemented.

1. Introduction
Hydrolithosphere processes belong to the class of objects with distributed parameters [1,2]. The problem of a mathematical description of hydrolithosphere processes was investigated in the works of C.L. Maroney and C.R. Rehmann [3], D.A. Pervukhin and Y.V. Ilyushin [4], Asadulagi M.M. and Pervukhin D.A. [5]. The study of groundwater pumping impacts on real stream networks was carried out by Zipper S.C., Dallemagne T., Gleeson T., Boerman T.C. and Hartmann A. [6]. Developments in the field of a synthesis of control systems for hydrolithosphere processes was carried out by Ilyushin Y.V., Pervukhin D.A., Afanaseva O.V. [7,8], Martirosyan A.V. and Martirosyan K.V. [9], Asadulagi M.M., Ioskov G.V., Tronina E.V., Vasilkov O.S. [10,11]. However, an identification of hydrolithosphere processes presupposes an availability of information about their parameters. Obtaining these parameters is quite a costly and time-consuming task. The article proposes the methodology for constructing approximation models of the hydrolithosphere processes based on a modal representation of distributed objects and...
experimental studies using 2 wells of a field. The methodology of an analysis and synthesis of control systems for objects with distributed parameters [2,12,13] is also successfully used in the gas producing complex [14-16], for automation of the technological process of the paraffin oil production [17], for thermal processes control [18,19].

2. Physical scheme of the process

Figure 1 shows a diagram of a mineral water deposit. Production is carried out from one producing well, which implements an imperfect water intake. The production well flow rate $Q_r$ is 1100 m$^3$/day. At a distance of $\Delta x_s = 20$ m (see figure 1) there is a control well. The production and control wells are equipped with devices that measure heads at given points $A(x_0, y_0, z = (z_1 + z_2) / 2)$ and $B(x_0 + \Delta x_s, y_0, z = (z_1 + z_2)/2)$ of the aquifer.

3. Determination of static and dynamic characteristics of the hydrolytosphere process

The experimental research procedure is as follows:

1. A step change in the flow rate of the production well from $Q_r$ to $Q = Q_r + 100$ m$^3$/day was done, and the level change at predetermined points relative to the steady state was determined. The graphs based on the results of experimental studies are shown in figure 2.

Figure 2. Response of the object to the step change in the production rate

2. The static transmission coefficient of the control object $K_1$ was determined as a division of the level change in the steady state by the subtraction between the input impact and the production rate (in m$^3$/day): $K_1 = 0.506 / 100 = 0.00506$, $K_2 = 0.229/100 = 0.00229$.

3. The response of the object to the dynamic input $Q = Q_r + 100 \cdot \sin(\omega_1 \cdot \tau)$, $\omega_1 = 0.0001$ 1/s = 8.64 1/day was determined. Figure 3 shows the graphs of the level change at the consideration point under the harmonic input action.
Figure 3. Response of the object to the dynamic input action

4. The phase shift of the output signal relative to the input signal (the oscillation period of the input signal is 17.453 hours) was determined:
\[ \phi = -2\pi \cdot \frac{2.31}{17.453} = -0.831 \text{ rad.} \]

4.  Methodology for determining parameters of an approximating link

In the case under consideration, there is one input impact (the flow rate of the production well) and two outputs.

The studies presented in [2] show that the following structure of the approximating link is recommended to describe dynamic characteristics of hydrolytosphere processes:

\[ W_s(s) = \frac{G_1}{s + G_1} \cdot \exp(-\beta \cdot \Delta x), \beta = \left(\frac{s}{a} + G_1\right)^{1/2}, \quad (1) \]

where \( s \) is the Laplace operator; \( G_1, K, a \) are determined parameters.

Let us describe the procedure for determining the parameters of the approximating link:

1. Assuming in (1) \( s = j\omega = 0 \) and equating the static gain of the approximating link to the values of \( K_1 \) and \( K_2 \), we obtain:

\[ \begin{align*}
K_1 &= \frac{K}{\beta} \cdot \exp(-\beta \cdot \Delta x), \\
K_2 &= \frac{K}{\beta} \cdot \exp(-\beta \cdot \Delta x), \beta = \left(G_1\right)^{1/2}. \quad (2)
\end{align*} \]

Substituting the initial data: \( K_1 = 0.00506; K_2 = 0.00229; \Delta x = 0.2 \) (well radius [2]); \( \Delta x_s = 20 \), we get:

\[ \begin{align*}
0.00506 &= \frac{K}{\beta} \cdot \exp(-\beta \cdot 0.2), \\
0.00229 &= \frac{K}{\beta} \cdot \exp(-\beta \cdot 20), \beta = \left(G_1\right)^{1/2} \quad (3)
\end{align*} \]

Solving the system of equations (3), we arrive to the following result:
The static transmission coefficient of the object in question is written as:

$$W_a(s) = \frac{0.000205}{\beta} \cdot \exp(-\beta \cdot x), \beta = (0.00161)^{\frac{1}{2}}, \Delta x \leq x. \quad (4)$$

Figure 4 shows the graph of the change of the static transmission coefficient with change $x$.

Figure 4. Static gain graph

2. Assuming in (1) $s = j\omega = j\omega_1$, we write the relation for determining the phase of the approximating link:

$$\Delta \phi_1 = -\text{Im}(\beta) \cdot \Delta x_1 \cdot \arctan(\text{Im}(\beta)/\text{Re}(\beta)), \beta = \left(\frac{j\omega}{a} + G_1\right)^{\frac{1}{2}}. \quad (5)$$

Substituting the initial parameters: $\Delta \phi_1 = -0.8316$ rad; $K = 0.00020576$; $G_1 = 0.00165163$; $\omega_1 = 0.0001$ in (5) and solving numerically, we determine the value of the parameter $a = 0.00547$.

The approximating link describing the hydrolytosphere process has the following transfer function:

$$W_a(s) = \frac{0.0002048}{\beta} \cdot \exp(-\beta \cdot x), \beta = \left(\frac{s}{0.00547 + 0.001609}\right)^{\frac{1}{2}}. \quad (6)$$

Replacing the value of $x$ with $r$, $r \geq \Delta r$ in (6) (where $r = \Delta r$ is the radius of the producing well $\Delta r = \Delta x$, see figure 5), the hydraulic model of the hydrolytosphere process under consideration in an operator form was obtained:

$$W_a(s) = \frac{0.0002048}{\beta} \cdot \exp(-\beta \cdot r), \beta = \left(\frac{s}{0.00547 + 0.001609}\right)^{\frac{1}{2}}, r \geq \Delta r. \quad (7)$$

Figure 5. Well location
When constructing the model under consideration (7), the results of experimental studies of the control object were used.

5. Design of control systems for hydrolytosphere processes

Let us formulate the synthesis problem. For the object whose transfer function is written in the form (7) we need to synthesize a controller that implements a proportional-integral-differential control law. At the same time, the following restrictions are imposed on the stability margins of the open system in modulus (ΔL), phase (Δφ), and on parameter Δ: Δ L ≥ 11db, Δ φ ≥ π/3, Δ = 1.47. Using a standard software package for calculating parameters of a controller, the following controller was obtained:

\[ R(s) = \frac{1.937 + 0.00322}{s + 0.000682} \cdot s. \]

6. Analysis of the closed-loop control system

The output function of the system is \( H_2(x_0, y_0, z = (z_1 + z_2)/2, \tau) \). The input action on the control system was formed as \( H_2(x_0, y_0, (z_2 - z_1)/2, \tau = 0) - 2\cdot(\tau/(2 + \tau)), \) where \( \tau \) is the time. Based on the test results of the control system (figure 6), graphs of transient processes were obtained (figure 7).

![Figure 6. Block diagram of the control system](image)

![Figure 7. Graphs of the transient processes](image)

The test results of the closed-loop control system show that the regulator effectively controls the hydrolytosphere process.
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