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DEVELOPMENT OF A CONTROL SYSTEM FOR DOWNHOLE HYDRAULIC PRODUCTION

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Abstracts

This research article contains materials on the development of an automated control system for downhole hydraulic production to achieve high technical and economic performance of the process. In recent years, the interest in the hydraulic fracturing method has increased significantly. However, the practical application of this method requires comprehensive studies of the physical and geological conditions of specific deposits, development of production techniques and designs of downhole equipment, as well as development of a mathematical model of the hydraulic fracturing process, and synthesis of a hydraulic fracturing control system based on rock erosion rate control.

Introduction

A review of existing systems showed an insufficient level of automation of the hydraulic scour process. Scour control is mainly performed by the operator, which does not provide the required quality of control and productivity. The synthesis of modern control systems for hydraulic monitoring scour requires the establishment of structural links between the input and output parameters of the object, the correct choice of controlled parameters and control actions.

In this work, it is proposed to control the process of hydraulic monitoring scouring on the basis of controlling the distance between the hydraulic monitor nozzle and the face wall and the rate of rock scouring. Monitoring the change in the size of the extraction chamber over time also provides information on the performance of the scouring process. Modern ultrasonic and laser rangefinders allow for non-contact distance measurement with high accuracy. Their hermetically sealed design and small size allow them to be used in downhole hydraulic applications.

1. Analysis of the process flow chart and existing automatic

control systems

The essence of the borehole hydraulic extraction method.

The technology of deposit development by downhole hydraulic mining is primarily related to the physical and geological conditions of the ore body. A number of natural conditions and properties of ore and host rocks (geological and hydrogeological conditions of the deposit, mechanical and hydraulic properties of ores and host rocks, etc.) have a significant impact on the parameters and mechanism of the extraction process.

Mining using borehole hydraulic extraction creates such advantages over conventional mining methods that allow for a new assessment of both known deposits and newly discovered ones. In addition, borehole hydraulic extraction provides technological, economic and environmental benefits.

Borehole hydraulic extraction of tuffs is an underground mining method based on bringing them into a mobile state at the place of occurrence by hydromechanical impact and their delivery to the surface in the form of a hydraulic mixture.

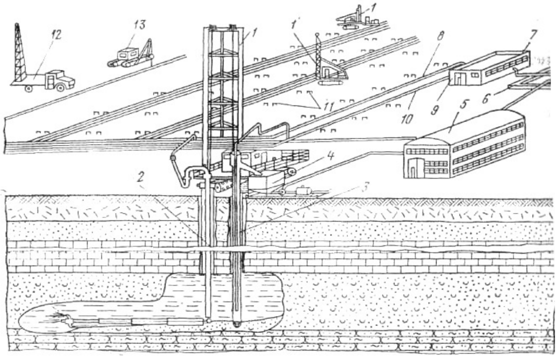


Fig. 1. Technological scheme of downhole hydraulic mining: *1* - hydraulic extraction unit; *2* - downhole hydraulic monitor; *3* - slurry lifting mechanism; *4* - dredge; *5* - processing plant; *6* - water intake basin; *7* - pumping station; *8* - water pipelines; *9* - compressor room; *10* - air pipelines; *11* - production wells; *12* - drilling rigs; *13* - pipe layers

Borehole hydraulic mining is one of the geotechnological mining methods [1], which is the most effective for the development of loose, weakly cemented ore deposits. The mineral component is extracted through specially equipped and prepared wells, with the production well being an opening, preparatory and tapping workings from which tuffs are cleaned. One of the variants of the technological scheme of downhole hydraulic production of shallow deposits through twin wells is shown in Fig. 1.

The methods of fracturing a tuff massif mainly depend on its strength. Particles of loose and weakly cemented tuffs can be detached by creating a filtration flow with the required hydraulic gradient in the formation. The most rational way to fracture cohesive rocks is to use a hydraulic water jet. The destruction process can be intensified by vibration, explosion, chemical or microbiological decomposition of the cementing agent.

The destroyed tuff is fed to the suction of the discharge device either by gravity flows (with a sufficient slope of the chamber sole) or by pressurized water flows. The hydraulic mixture is discharged to the surface using a hydraulic elevator, a submersible dredge, or by creating back pressure by injecting water or air into the deposit.

A distinctive feature of downhole equipment is the stringent conditions for transverse dimensions due to the need for its operation in the well. A hydraulic production unit (Fig. 2) is a combination of a downhole hydraulic monitor and a dispensing mechanism with a lifting and transporting part and a unit for transporting slurry from the unit [2].

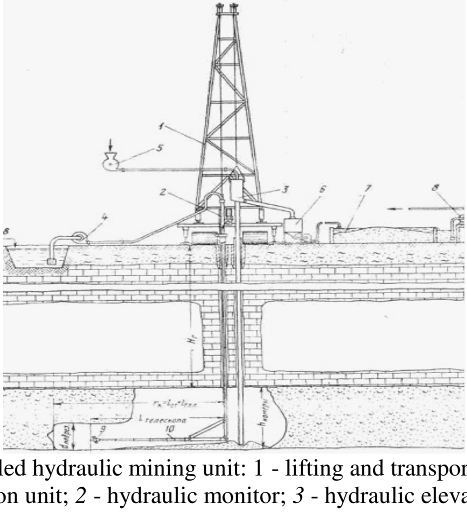


Fig. 2. Self-propelled hydraulic mining unit: 1 - lifting and transporting part of the hydraulic extraction unit; *2* - hydraulic monitor; *3* - hydraulic elevator; *4* - pump; *5* - compressor; *6* - dredge with a sump; *7* - warehouse; *8* - water supply pump; *9* - rotating hydraulic monitor head; *10* - telescopic barrel of the hydraulic monitor

The extraction process is controlled from the surface by changing the use and pressure of water, as well as the places of exposure to the working agent and selection of the useful component.

The choice of parameters of the technological process of downhole hydraulic production is determined by the geotechnological property of the useful component and the physical and geological situation [3].

The existing model of the downhole hydraulic production unit and the placement of measuring devices to control its main parameters.

Fig. 3 shows the existing automation scheme of the downhole hydraulic production process.

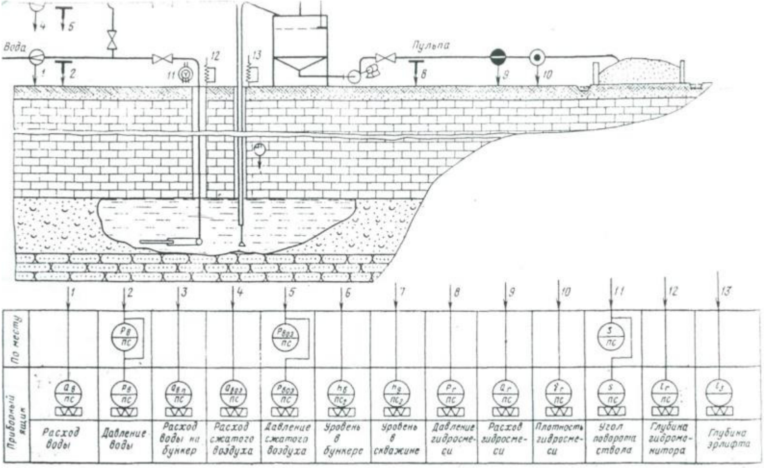


Fig. 3. Scheme of the downhole hydraulic production unit and placement of instrumentation to control its main parameters

This scheme was developed in the early 80s and is quite outdated, as it is very energy-intensive and does not control the quality of the process itself [4]. The operator's work is only partially automated. The sensors used are unreliable, with a significant measurement error, which affects the rational use of energy resources and material costs, and are "disposable" because they do not tolerate dismantling and transportation.

Equipment of production wells. Production wells to the productive horizon are drilled in the same way as conventional oil and gas wells. No curvature of the wells is allowed, which makes it difficult to lower the production tubing, especially in fractured and karstic rocks. To prevent curvature, drilling should be done with a reduced load on the bit. High mechanical drilling speed and troublefree operation can be ensured only with the correct flushing regime. Based on the results of the core study, a geological section of the well is drawn up. To study and test the core, half of it is transferred to the laboratory. After the discovery of the useful component, the well is cased and cemented. Only after the cement has hardened does drilling continue to the full extent of the deposit with a small amount of overburden.

Anchoring. The well casing process is divided into two stages:

- lowering casing;
- cementation.

Casing in the well is subjected to complex stresses (external rock pressure, internal pressure of flowing water, longitudinal tension and bending under its own weight) and, in some cases, temperature. The pipes have external threads at both ends. Cementing production wells is one of the main aspects of preparing a well for operation. Well-executed cementation outside the tubular space ensures tightness and, accordingly, the success of the well in producing the useful component. Filling outside the tubular space is performed with a conventional cement mortar.

Well pressurization. A conventional well leakage test is performed in two stages:

- testing the tightness of casing pipes;
- esting the tightness of the cementation.

The first one is performed after the cement has hardened but before the cement shoe is broken. At a shallow well depth of 100-200 meters. The casing is tested under a pressure 2-3 times higher than the pressure of the working agent during development. The second stage is carried out after the cement shoe has been broken and under the casing string. The test pressure is equal to twice the pressure of the working agent.

Before the drilled wells are equipped, it is necessary to carry out a cycle of geological and hydrogeological works to test the productive horizon. Geophysical testing of wells is mandatory to determine the physical and refine the hydrogeological characteristics of the productive formation. Since each formation has certain physical properties: electrical conductivity, hardness, radioactivity, which depend on the lithological composition of the rocks, their porosity and permeability.

Production well equipment means lowering production tubing strings into the well, specially manufactured for the production process. Each geotechnological method requires a specific production well equipment.

Calculation of flow and pressure characteristics of pumps. The characteristics of the pump show the dependence of its performance indicators (head, impeller speed, pump power) and efficiency (efficiency) on the flow rate [2,3,4]. The passport characteristics of the pump are given in its technical documentation, indicating the density and temperature of the liquid for which they were obtained, as well as the diameter and speed of the impeller. The actual performance of the pump is calculated according to the passport characteristics, taking into account changes in operating conditions (diameter and impeller speed) and taking into account the influence of the particle size distribution and fractional composition of the transported material (Table 1)

$$W = W' A_E A_F, \tag{1}$$

where W - is the actual value of the pump indicator;

W' - is the passport value of the pump's performance;

A_E - is a coefficient that takes into account changes in operating conditions;

A_F - is a coefficient that takes into account the influence of the granulometric and fractional composition of the transported material.

The calculation of the flow and pressure characteristics of centrifugal pumps pumping a hydraulic mixture of polydisperse materials of different fractions is carried out according to the following algorithms (Fig. 4, Fig. 5);

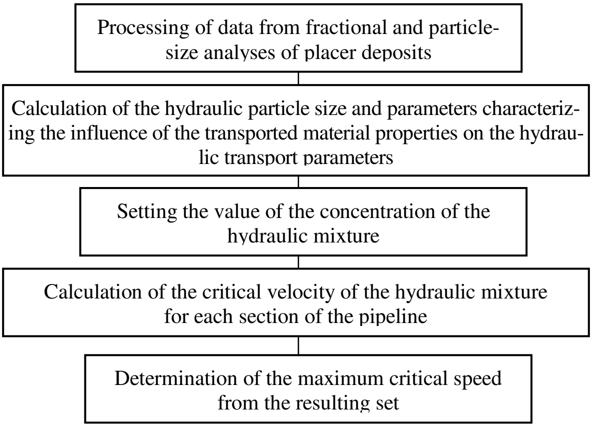


Fig. 4. Block diagram of the algorithm for calculating the critical speed for a hydraulic transport complex for hydraulic transportation of polydisperse materials of different fractions

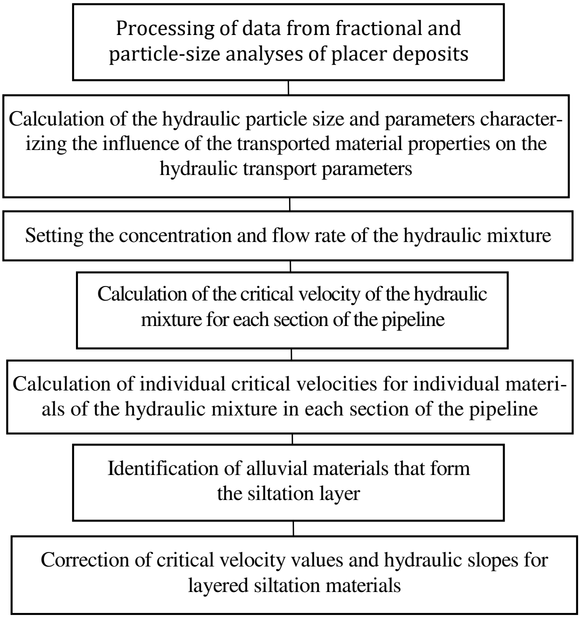


Fig. 5. Block diagram of the algorithm for calculating hydraulic slopes for a hydraulic transport complex for hydraulic transportation of polydisperse materials of different fractions

Table 1

Formulas for calculating conversion factors

Indicator	Formulas for calculating coefficients	
	A_E	A_F
Submission	$\frac{n}{n'}\left(\frac{D_p}{D'_p}\right)^{1.57}$	1
Pressure	$\left(\frac{n}{n'}\right)^{2}\left(\frac{D_p}{D'_p}\right)^{2.46}$	$\left(1-k_pk_zk_*\sum_{l=1}^{m}\alpha_lA_l\sum_{j=1}^{k}\psi_jk_{jl}\beta_jS\right)\rho$
Power	$\left(\frac{n}{n'}\right)^{3}\left(\frac{D_p}{D'_p}\right)^{3.9}$	$1+\sum_{i=1}^{3}\sum_{j=1}^{N(i)}a_j^{(i)}S_j^{(i)}$
Efficiency	$\left(\frac{D_p}{D'_p}\right)^{0.31}$	$\left(1-k_pk_zk_*\sum_{l=1}^{m}\alpha_lA_l\sum_{j=1}^{k}\psi_jk_{jl}\beta_jS\right)\rho$

The following notations are used in Table 1

$$A_l=\frac{Ar_l}{1+\sum_{i=1}^{3}\sum_{j=1}^{N^{(i)}}a_j^{(i)}S_j^{(i)}}; \qquad (2)$$

$$k_{jl}=0.15Ar_j+0.561\lg\frac{d_{il}}{D_p}+1.813; \qquad (3)$$

$$k_p=1.94-1.68\frac{Q}{Q_H}+0.74\left(\frac{Q}{Q_H}\right)^2; \qquad (4)$$

$$k_z=0.546+0.159z-0.011z^2; \qquad (5)$$

$$k_*=1.215-0.0077\gamma; \qquad (6)$$

$$\rho=S\sum_{l=1}^{m}\sum_{j=1}^{k}\left(1-\psi_{jl}\right)Ar_j\sigma_{jl}; \qquad (7)$$

$$\psi_{jl}=\begin{cases}1 & k_{jl}>0\\ 0 & k_{jl}\le 0\end{cases} \qquad (8)$$

where k_p - is a coefficient that takes into account the influence of the pump operating mode [4];

k_z - is a coefficient that takes into account the influence of the number of impeller blades [4];

k_* - is a coefficient that takes into account the influence of the impeller blade exit angle[4];

γ - the angle of the impeller blade exit;

z - is the number of impeller blades;

Q_H - is the nominal flow rate of the pump;

n, n' - new and passport value of the impeller speed;

D_p, D'_p - the new and passport value of the impeller diameter.

The following types of polynomials are recommended for approximating the flow and pressure characteristics of centrifugal pumps.

It is recommended to approximate the dependence of the pump head and efficiency on the flow rate with second-order polynomials

$$H(Q) = C - BQ - AQ^2; \tag{9}$$

$$\eta(Q) = E - FQ - GQ^2, \tag{10}$$

and the dependence of the pump power on the flow rate by a third- order polynomial

$$N(Q) = V + RQ + UQ^2 + XQ^3; \tag{11}$$

where *C,B,A,E,F,G are the* coefficients of approximation of the pump's flow and pressure characteristics.

Calculation of an airlift device for downhole hydraulic production of zeolite-smectite tuffs. As a rule, when calculating the airlift, the following parameters are set: hourly productivity Q, lifting height H, static or relative water level in the well h_{cm}($\alpha = \dfrac{H}{h_{cm} + H}$).

Then the purpose of the calculation is to determine the compressed air parameters and select the compressor, diameters of the air and slurrylifting pipes, and nozzle design parameters. The following calculation procedure is used for this purpose.

1. Compressed air consumption

$$V_0 = \frac{Q \cdot H \cdot \gamma'_г}{23 \cdot 60 \eta_{із} \lg\left(\dfrac{h}{w \cdot 10} + 1\right)} \tag{12}$$

where $\gamma'_г$ - is the relative density of the hydraulic mixture, kg/m^3.

$$\gamma'_г = \frac{\gamma_в}{\gamma_г};$$

$\gamma_{в}, \gamma_{г}$ - are, respectively, the densities of water and mud, kg/m^3; h - is the dynamic level in the well, m; $\eta_{iз}$ - is the isothermal efficiency of the airlift:

$$\eta_{iз} = \frac{H \cdot \gamma_{г}^{'}}{23 \cdot q \cdot \lg \cdot \left(\frac{h}{w \cdot 10} + 1 \right)}, \tag{13}$$

where q - is the specific consumption of compressed air for lifting 1 m^3 of the hydraulic mixture, m^3/m^3.

At Q=50-300 m^3/h and H= 80-300 m, the optimal value of $\eta_{iз}$ can be taken depending on the values of α

α	0,10-0,15	0,15-0,25	0,25-0,35	0,35-0,50
$\eta_{iз}$	0,25	0,32	0,36	0,40

2. The diameter of the air pipe

$$d_{air} = \frac{0{,}000125 \cdot \beta \cdot R \cdot T \cdot G^2 \cdot l}{\Delta p p_m}, mm, \tag{14}$$

where p_m - is the average compressed air pressure in the pipe, MPa; Δp - is the pressure loss, assumed to be 5% of p_m; R - is the universal gas constant: $R=29{,}27$ kgm/kg C° (R=0,0821 atm/mol$\cdot K$); T - is the average absolute temperature in a given section of the pipe $T=t°C+273°K$; l - is the reduced length of the air network, m, i.e. the length consisting of the actual length plus the length equivalent to the pressure losses on local supports.

The value of β, which depends on the mass flow rate of compressed air, is determined by the formula

$$\beta = \frac{2{,}86}{G^{0.148}}, \tag{15}$$

where G - amount of compressed air flowing, kg/h; γ - air density, kg/m^3; V - air volume at gauge pressure $V = \frac{V_0}{\rho_m + 1}$, m/h; V_0 - air flow rate reduced to normal conditions, m^3 /h, (p_0=0,10393 MPa and T_o=273K).

As a rule, at the given values of G, p_m, l_n, taking the value Δp, the diameter of the air pipe is determined by known nomograms. For an approximate determination of the diameter of an air pipe, you can use the formula.

$$d_в = 20\sqrt{V}, mm, \tag{16}$$

3. The diameter of the slurry lift pipe can be determined by the formula of V.G.Geier

$$d_e = \sqrt[2,5]{\frac{Q}{k\cdot\alpha}}, sm, \tag{17}$$

where $\alpha = \frac{h}{H+h}$ - is the relative coefficient of nozzle immersion under the water level; k - is a coefficient that depends on the airlift parameters.

Within the range of changes in the capacity of the elevator Q=50-300 m^3/h, the height of the lift H=100 - 300 m and at the values of α=0,20 - 0,45 the value of k is 0,24.

Then, $d_e = 1,77\left(\frac{Q}{\alpha}\right)^{0,4}, sm,$

4. Working pressure of compressed air

$$P_{work}=0,01(h_{Д}+p_1), \text{ MPa}, \tag{18}$$

where p_1 - air pressure losses in the airlift air pipe and nozzle. Usually accepted p_1=0,03-0,05 MPa.

5. Starting compressed air pressure

$$P_{start}=0,01(h_{ст}+p_1), \text{ MPa}, \tag{19}$$

6. The compressor pressure is equal to the starting pressure plus losses in the airlift p_1 and along the route p_2

$$P_c=p_{start}+\Sigma p, \text{ MPa}, \tag{20}$$

where $\Sigma p=p_1+p_2$.

7. The compressor capacity is taken on the basis of the number of lifting units and a 20% margin is given for uneven operation

$V_c=1,2\cdot\Sigma\cdot V_0$, m^3/min. (21)

The choice of size and design of the mixer is essential. Mixer designs depend on the location of the air pipe. In addition, they are both chamber type and in the form of nozzles. However, with any type of mixer, the following rules must be observed:

- the air velocity in the mixer should be 3 times less than in the duct;
- the required number of holes in the mixer or nozzle is selected so that their total area is equal to two to three live sections of the duct

$$n_{hol} = (2 \div 3) \cdot \left(\frac{d_{в}}{d_{hol}} \right)^2, \tag{22}$$

where d_{hol} - diameter of the holes (d_{hol}=5-10 mm).

If the air pipe is located internally in the slurry pipe, the cross-section must be taken into account when determining the internal diameter of the slurry pipe.

2. Mathematical model of the control object

Selection of the control object. The object of control is the process of hydromonitoring scour in downhole hydraulic mining.

Rock fracturing is a key element of the downhole hydraulic production process. It involves breaking the integrity of the rock mass with a high-pressure hydraulic jet while moving the fluid mixture to the lifting device. Optimization of technological parameters and automation of the mudding process are important factors for achieving high technical and economic performance.

Due to the complexity of the processes and the variety of factors, a general theory of rock fracturing by hydraulic jet has not been developed. N.F. Tsyapko, A.M. Zhuravsky, V.S. Muchnik, M.A. Lavrentiev, V.F. Khnykin, and others made a significant contribution to the development of the theory of rock fracturing by hydraulic means.

Static and dynamic characteristics of hydromonitoring erosion. The program of experimental studies for the erosion of zeolite-smectite tuffs by a pressure water jet through nozzles with diameters of 15, 20, 25, 30 and 35 mm and a pressure of 1-3 MPa provides for the determination of productivity, maximum erosion radius, energy consumption and specific water consumption.

To conduct field studies in the basalt quarry, overlying rocks were removed from the test site to expose the mineral. The hydraulic monitor was installed at the top of the erosion sector. A trench was used as a compensatory workings to simulate the suction zone or the mouth of the outlet workings at a certain distance from the top of the sector. The research methodology was based on the time required to erode and remove a mineral with a thickness of h_n from the sector with an angle *of a*. The test was carried out in accordance with the current geological service guidelines.

The speed of movement of the hydraulic monitor's blasting nozzle along the face sector varied from 0,3 to 2,4 m/s. The rock was washed away in layers at a ledge height of 20-35 cm with the jet moving it to a boundary distance equal to the size of the scour radius. The rock removal and transportation were essentially a single process and were carried out by sequentially acting on the constantly moving face.

The transporting capacity of the jet during the erosion process significantly deteriorated with the distance of the face from the hydraulic monitor nozzle.

This was reflected in the fact that the distance over which the rocks were thrown during one cycle of the jet's impact on the face decreased, and much faster for larger fractions.

At a certain distance from the nozzle, the amount of movement of large rock fractions during one cycle of the hydraulic monitor jet impact on the face was practically zero. In the following, the scour radius will be understood as the maximum value of the distance over which the jet moves the largest rock fractions.

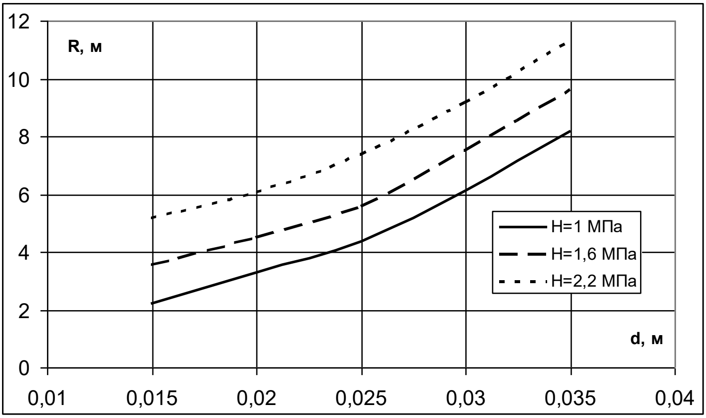
The study of the rock erosion process at different nozzle diameters and for different values of water pressure in the hydraulic monitor showed that the erosion of tuffs by jets of larger diameter leads to an increase in the radii of erosion, and with an increase in the pressure of the working agent before the nozzle, this increase becomes more significant.

Table 2

Values of the radius of erosion of zeolite-smectite tuffs by a hydraulic monitor jet

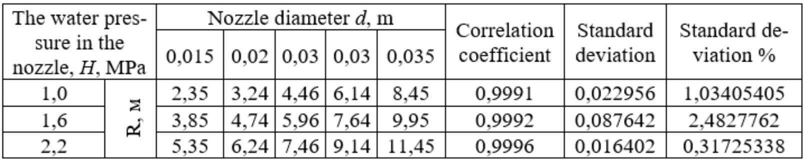
Water pressure in the nozzle	No. of experiment		Nozzle diameter *d*, m				
			0,015	0,02	0,025	0,03	0,035
H=1,0 MPa	1	The value of the scour radius R, m	2,2	3,3	4,25	6	8,1
	2		2,25	3,2	4,3	6,1	8,1
	3		2,2	3,4	4,5	6,2	8,3
	Average		2,22	3,3	4,35	6,1	8,17
H=1,6 MPa	1		3,5	4,4	5,5	7,4	9,5
	2		3,6	4,55	5,6	7,65	9,7
	3		3,5	4,5	5,6	7,5	9,7
	Average		3,53	4,48	5,57	7,52	9,63
H=2,2 MPa	1		5,1	6	7,3	9,1	11,5

	2		5,3	6,15	7,45	9,2	11,6
	3		5,1	6,05	7,4	9,15	10,9
	Average		5,17	6,07	7,38	9,15	11,33



$$R(d,H) = 0{,}9e^{0{,}064d} + 2{,}5 \cdot H - 2{,}5$$

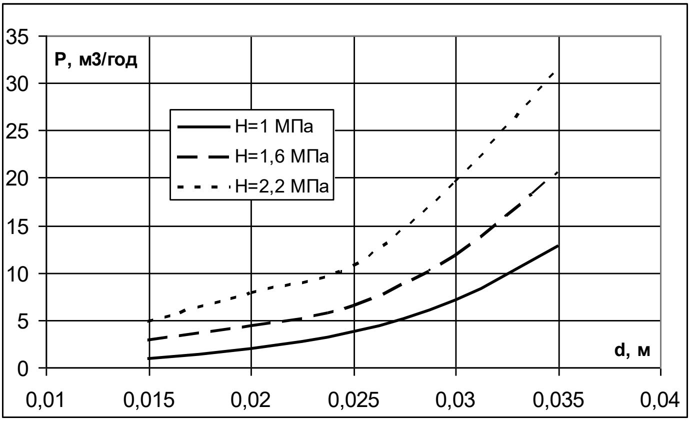
Calculation data:



The water pressure in the nozzle, H, MPa		Nozzle diameter d, m					Correlation coefficient	Standard deviation	Standard deviation %
		0,015	0,02	0,03	0,03	0,035			
1,0	R, м	2,35	3,24	4,46	6,14	8,45	0,9991	0,022956	1,03405405
1,6		3,85	4,74	5,96	7,64	9,95	0,9992	0,087642	2,4827762
2,2		5,35	6,24	7,46	9,14	11,45	0,9996	0,016402	0,31725338

Table 3

Erosion performance of zeolite-smectite tuffs P, m^3/h			
Nozzle diameter do , mm	H, MPa		
	1	1,6	2,2
0,015	0,9	2,8	4,9
0,02	1,9	4,3	7,8
0,025	3,8	6,5	10,7
0,03	7,1	11,8	19,5
0,035	12,8	20,5	31,5



$$P(d,H)=0{,}07e^{148d}+3{,}3\cdot H-2{,}8$$

Calculation data:

Erosion productivity of zeolite-smectite tuffs P, m /h^3

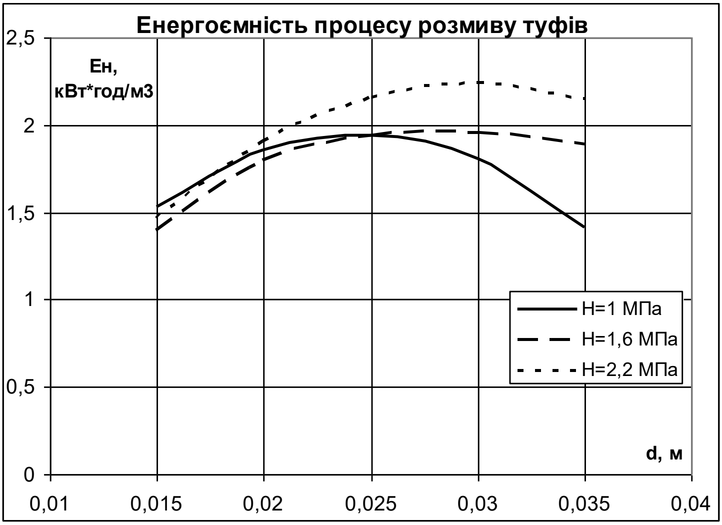
Nozzle diameter do , mm		H, MPa		
		1	1,6	2,2
Experimental data	0,015	0,9	2,8	4,9
	0,02	1,9	4,3	7,8
	0,025	3,8	6,5	10,7
	0,03	7,1	11,8	19,5
	0,035	12,8	20,5	31,5
Estimated data	0,015	1,14	3,51	5,88
	0,02	1,85	4,64	7,43
	0,025	3,33	7,01	10,69
	0,03	6,43	11,97	17,52
	0,035	12,94	22,38	31,82
Correlation coefficient		0,9967	0,9982	0,9948
Standard deviation		0,1488	0,8898	1,0270

Table 4

Nozzle diameter d, m	№ experiment	Energy intensity of the tuff erosion process En, kWh/m^3		
		H=1,0 MPa	H=1,6 MPa	H=2,2 MPa
0,015	1	1,45	1,41	1,46
	2	1,55	1,36	1,41
	3	1,6	1,42	1,52

	average	1,53	1,4	1,46
0,02	1	1,9	1,75	1,91
	2	1,85	1,84	1,92
	3	1,82	1,81	1,9
	average	1,86	1,8	1,91
0,025	1	2	1,91	2,2
	2	1,95	1,95	2,15
	3	1,88	1,97	2,13
	average	1,94	1,94	2,16
0,03	1	1,79	2,01	2,22
	2	1,8	1,95	2,25
	3	1,83	1,93	2,25
	average	1,81	1,96	2,24
0,035	1	1,4	1,94	2,12
	2	1,45	1,92	2,15
	3	1,38	1,82	2,17
	average	1,41	1,89	2,15

Study of the energy intensity of the process of tuff erosion



$$\begin{cases} E_{н} = -ad^2 + bd - c \\ a = 3174 \cdot H^2 - 11158 \cdot H + 12755 \\ b = 134{,}8 \cdot H^2 - 448{,}1 \cdot H + 546{,}1 \\ c = 1{,}09 \cdot H^2 - 3{,}465 \cdot H + 3{,}26 \end{cases}$$

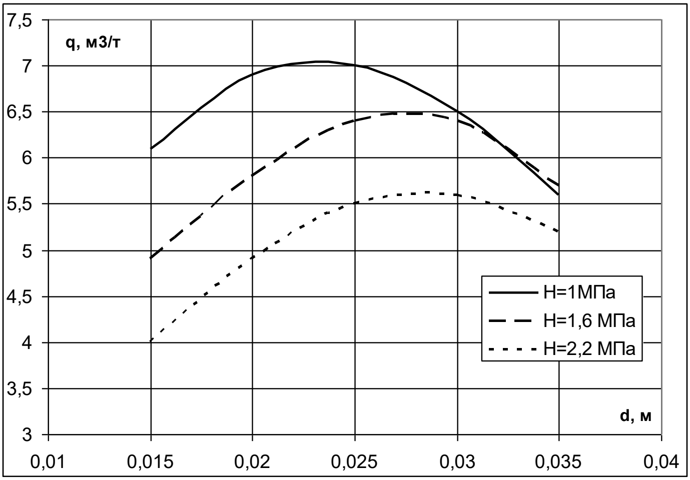
Calculation data:

Nozzle diameter d, m	Energy intensity of the erosion process En, kWh/m^3		
	Pressure H, MPa		
	1,0	1,6	2,2
0,015	1,53	1,43	1,47
0,02	1,86	1,77	1,91
0,025	1,95	1,96	2,17
0,03	1,81	2	2,26
0,035	1,42	1,88	2,16
Correlation coefficient	0,9997	0,992	0,9998
Standard deviation	0,00004	0,00078	0,00014
Standard deviation, %	0,003	0,056	0,01

Table 5

Value of specific consumption of the working reagent

Nozzle diameter d, m	Specific consumption q, m /t^3		
	H=1,0 MPa	H=1,6 MPa	H=2,2 MPa
0,015	6,1	4,9	4
0,02	6,9	5,8	4,9
0,025	7	6,4	5,5
0,03	6,5	6,4	5,6
0,035	5,6	5,7	5,2



$$\begin{cases} q = -ad^2 + bd - c \\ a = -1983 \cdot H^2 + 4203 \cdot H + 9209 \\ b = -174{,}2 \cdot H^2 + 525{,}3 \cdot H + 192{,}3 \\ c = -2{,}71 \cdot H^2 + 10{,}5 \cdot H - 8{,}3 \end{cases}$$

Calculation data:

Nozzle diameter d, m	Energy intensity of the erosion process En, kWh/m^3		
	Pressure H, MPa		
	1,0		1,0
0,015	6,09	4,8	3,9
0,02	6,81	5,83	4,87
0,025	6,95	6,32	5,4
0,03	6,53	6,27	5,49
0,035	5,53	5,68	5,13
Correlation coefficient	0,9966	0,9946	0,9987
Standard eviation	0,0033	0,0069	0,0076
Standard deviation, %	0,0589	0,1412	0,1895

Table 6

Dynamics of tuff destruction. Laboratory experiment on a scale model

Slaughte ring distance *l/d*	Water pressure at the nozzle inlet P_o , MPa					
	0,2		0,7	0,2		0,7
	Nozzle diameter *dн*, mm					
	4,2	6,0	4,2	4,2	6,0	4,2
	Erosion rate *V*, m/min			Blurring time *t*, min		
2	3,25	2,9	2,4	-	0	-
4	3,15	2,7	2,2	-	0,16	0
6	2,95	2,4	1,8	0	0,45	0,15
8	2,4	1,6	0,8	0,3	1	0,6
10	1,3	0,9	0,3	0,9	3,5	1,2
12	0,5	0,4	0,1	2	9,5	2,8
14	0,37	0,25	-	3,8	-	5,5
16	0,25	0,15	-	6,5	-	10
18	-	-	-	13,6	-	-

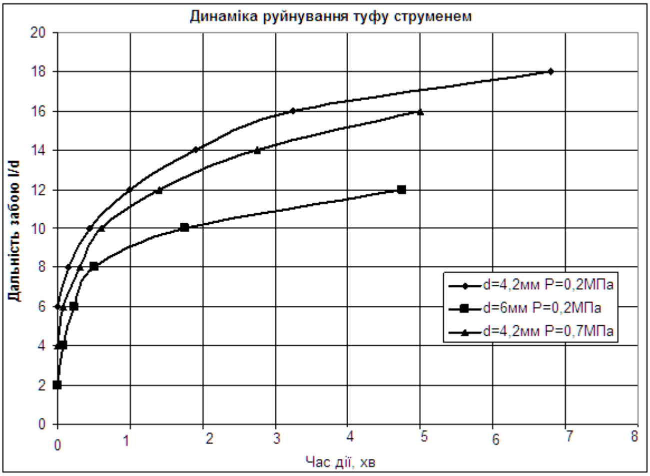


Fig. 5. Dynamics of tuff rock destruction

The approximation and statistical processing of the experimental data was carried out in MatLab and Microsoft Exel software packages. Most of the experimental data were approximated by second-order polynomials.

The polynomial approximation of the measurement data, formed as a certain vector *Y* at certain argument values that form a vector *X* of the same length as the vector *Y*, was performed using the built-in MatLab procedure polifit(*X*,*Y*,*Z*), where *Z* is the order of the approximating polynomial. The result of this procedure is a vector of length (*Z*+1) of the coefficients of the approximating polynomial [6].

The exponential approximation was performed in Microsoft Exel using the trend line addition function, which results in the construction of an approximating curve and the display of its equation on the graph of the experimental data.

To verify the reliability of the approximation and its quantitative assessment, the data were statistically processed, namely, the correlation coefficient and standard deviation between the experimental data and those calculated using the approximation dependencies were found.

The correlation coefficient was determined by the formula

$$r=\frac{\sum(x_i-x_{cp})(y_i-y_{cp})}{\sqrt{\sum(x_i-x_{cp})^2(y_i-y_{cp})}}, \qquad (23)$$

where x,y - experimental and calculated data, respectively.

The standard deviation was calculated using the formula

$$\delta=\frac{\sqrt{\sum(x_i-y_i)^2}}{n-1}\ , \qquad (24)$$

where n - number of measurement points.

To quantify the reliability of the established mathematical dependencies, the maximum relative error between the experimental results and the calculated values for each measurement point was determined

$$\gamma_i=\frac{x_i-y_i}{x_i}\cdot 100\% \cdot \qquad (25)$$

The dependence of the scour radius on the pressure of the working agent and the diameter of the nozzle for zeolite-smectite tuffs of the Polytsky open pit can be approximated by the following equation

$$R(d_0,H_0)=0{,}9e^{0{,}064\cdot d_0}+2{,}5\cdot H_0-2{,}5\,. \qquad (26)$$

The maximum relative error in calculating the rock scour radius was 9,07%.

The productivity of tuff erosion, depending on the pressure and diameter of the hydraulic monitor nozzle, is approximated by the following relationship

$$\Pi_p(d_0,H_0)=0{,}07H_0\cdot e^{148\cdot d_0}+3{,}3\cdot H_0-2{,}8\cdot \qquad (27)$$

The maximum error in the calculation of erosion performance is 12,3%.

When deriving analytical dependencies from experimental data that are complex functions of two variables, i.e., for families of curves, an approximation dependency of a certain type was built for each curve as a function of one variable. Then, based on the values of the coefficients in the equations of these curves, graphical and approximation dependencies were built as functions of the second variable. Replacing the coefficients of the first approximation dependence with the equations of the second variable gives a function of two variables.

The dependences of the energy intensity of the tuff erosion process and the specific consumption of the working agent on the pressure and diameter of the hydraulic monitor nozzle were approximated by the following equations, respectively

$$\begin{cases} E_{н} = -ad_0^2 + bd_0 - c \\ a = 3174 \cdot H_0^2 - 11158 \cdot H_0 + 12755 \\ b = 134{,}8 \cdot H_0^2 - 448{,}1 \cdot H_0 + 546{,}1 \\ c = 1{,}09 \cdot H_0^2 - 3{,}465 \cdot H_0 + 3{,}26 \end{cases}, \qquad (28)$$

$$\begin{cases} q = -ad_0^2 + bd_0 - c \\ a = -1983 \cdot H_0^2 + 4203 \cdot H_0 + 9209 \\ b = -174{,}2 \cdot H_0^2 + 525{,}3 \cdot H_0 + 192{,}3 \\ c = -2{,}71 \cdot H_0^2 + 10{,}5 \cdot H_0 - 8{,}3 \end{cases}. \qquad (29)$$

The maximum discrepancy between the calculated and experimental data with this method of approximation is much smaller and, accordingly, is 2,14% for determining the energy intensity of erosion and 2,5% for the specific flow rate.

Mathematical model of the object. The results of experimental studies of the dynamics of rock fracture under the influence of a water jet are shown in Fig. 5.

The figure shows that at small distances between the hydraulic monitor nozzle and the face wall, rapid rock destruction occurs. As the distance between them increases, the pressure on the face wall decreases and when it reaches a critical value, rock destruction stops.

The above dependencies are well described by a differential equation with an initial condition

$$\begin{cases} T(l_{P0}, P)\dfrac{dl_P(t)}{dt} + l_P(t) = K(P, l_{P0}) \cdot P(\mathrm{t}) \\ l_P(0) = l_{P0} \end{cases}, \qquad (30)$$

where l_P - the scouring distance; P - water pressure in the nozzle; $K(P, l_{po})$ - transmission coefficient; $T(l_{po}, P)$ - time constant; l_{P0} - initial distance from the nozzle to the face wall.

Thus, the process of hydraulic fracturing is a complex object in which the parameters K, T depend on the conditions of the process (pressure in the nozzle, physical and mechanical parameters of the rock, jet flow environment, distance from the nozzle to the face wall, shape and size of the nozzle, etc. From experimental studies, it was found that the time constant T under the existing technological conditions varies within 28-33 s. Therefore, to simplify the modeling, we take the time constant equal to T=30 s, which will not significantly affect the modeling results. The transmission coefficient K changes significantly and depends on two parameters and should be taken into account in the modeling.

Applying the Laplace transform to the equation, we obtain the transfer function of the object

$$W(s)=\frac{K(P,l_{po})}{T(l_{P0},P)\cdot s+1} \tag{31}$$

By modeling in MatLab/Simulink, the transient characteristics of the object in terms of range and scour rate were obtained (Fig. 6) at a pressure of P=1 MPa, l_{P0}= 0.55, K=1 m/MPa, T=32 s.

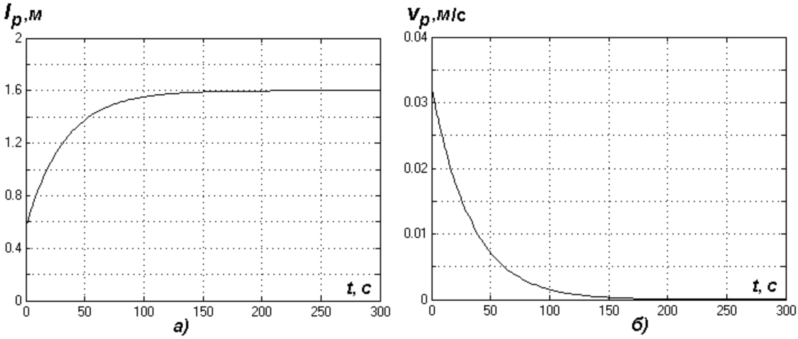


Fig. 6. *a* - Transient response of the object in terms of scour distance; *b* - transient characteristic of the object by scour rate

3. Development of an automatic control system

Selection and justification of control coordinates and control actions. A review of existing systems has shown an insufficient level of automation of the hydraulic scour process. Scour control is mainly carried out by the operator, which does not provide the required quality of control and productivity. The synthesis of modern control systems for hydraulic monitoring scour requires the establishment of structural links between the input and output parameters of the object, the correct choice of controlled parameters and control influences.

The efficiency of erosion is determined by the performance of the hydraulic monitor and specific energy consumption, which depend on the parameters of the jet, physical and mechanical properties and structure of the mineral being mined, the magnitude of forces and pressures in contact with the face, and technological methods of rock erosion.

The controlling influences during hydraulic monitoring are the pressure and flow rate of the working agent (water), the speed of rotation and movement of the telescopic hydraulic monitor nozzle in the face.

The need for pressure management stems from a number of reasons:

- ressure control is essential to ensure the efficiency of the washing process and energy savings. Insufficient pressure results in a sharp decline in productivity. Excessive pressure creates a cut in the rock, resulting in a decrease in efficiency;
- excessive pressure scatters eroded rock around the chamber, making it difficult to transport;
- At the optimum pressure value, conditions are created to produce pulp with a certain rock fraction required for its efficient transportation and lifting;
- pressure control at short distances from the nozzle to the face wall prevents blockage of the transportation channel. The complexity and conditions of the underground hydraulic fracturing process make it difficult to monitor the process parameters.

Development of a control algorithm for hydraulic scouring. In order to control the HFD process technology in the optimal mode, it is necessary to rationally select methods and means of controlling its main parameters.

When analyzing downhole hydraulic production processes as an automation object, all process equipment can be divided into two groups. The first group includes compressor, pumping, etc. equipment for which standard schemes and levels of automation have been developed and are used.

The second group includes production equipment of the SGV (downhole hydraulic monitor, airlift, hydraulic elevator), for which there are practically no developed automation schemes.

When creating an automation project, it is necessary to establish structural relationships between input (control) and output (controlled) parameters, select methods and means of registering and transmitting information to control points, take static and dynamic characteristics of objects and determine their type as an automation object, develop and implement automation schemes, and set the required frequency of measurement and data transmission.

The controlling parameters of the hydraulic monitor are the pressure and flow rate of power water in the nozzle, as well as the speed of rotation and feeding of the nozzle into the face. The output (estimated) parameters are the density of the hydraulic mixture and its flow rate, which determine the productivity of the solid component.

The input parameters of the hydraulic elevator are the pressure and flow rate of working water, and the output parameters are the hydraulic elevator's hydraulic mixture capacity.

One of the existing variants of the fundamental structural scheme of automated control of hydraulic demolition equipment is an interconnected control system. The productivity of hydraulic destruction is regulated by changing the pressure of power water depending on the density of the hydraulic mixture measured after the dredge by a density meter. The comparative device of the pressure regulator (PR) receives signals from the pressure and density sensors of the hydraulic mixture (MH), as well as the water pressure setpoint. The PT regulator processes the received signals and generates a control signal to the actuator sleeve, which regulates the pressure of the power water.

According to the above-described existing scheme, the hydraulic monitor is controlled manually, depending on the density of the hydraulic mixture after airlift. As experience is gained and rock fracture patterns are established, it is necessary to switch to automatic control of the hydraulic monitor using programmable logic controllers.

We propose a strategy for the automatic control of the technological process of the LPG based on the mathematical apparatus of fuzzy sets. The advantage of the fuzzy logic approach over classical methods in describing control systems is that it is possible not to use analytical dependencies, but a professional description of how the process is controlled by an experienced operator is sufficient. At the same time, solving this problem by means of classical theory is quite a challenge, and creating an accurate mathematical model is too complicated.

Complex systems are successfully managed by experienced operators based on qualitative process analysis. Such operator control is based on intuitive rules such as "if...then", which are not fully quantified.

Fuzzy logic makes it possible to store and process inaccurate information. This approach emerged objectively because as control systems become more complex, the ability to make accurate and meaningful statements about the system's behavior decreases and the point is reached at which accuracy and meaningfulness become mutually exclusive characteristics.

The main procedure of fuzzy logic is the fuzzy inference procedure, which is used to obtain an approximate solution from fuzzy conditions. The fuzzy inference procedure is based on the operation of logical inference (implication). Implication allows you to formalize a knowledge base according to the rules "if X, then U where X - premise, U - conclusion. In the case of fuzzy control, X - base set of values of x of the controlled variable; U - base set of controls u.

Depending on the method of obtaining logical conclusions from fuzzy rules, there can be different types of controllers. For industrial use, we propose the Mamdani fuzzy controller algorithm, when the controller generates a clear unambiguous control based on the defuzzification procedure. The general structure of a fuzzy logicbased controller consists of a fuzzification unit, a knowledge base, a decision-making unit, and a defuzzification unit.

The phasing unit converts the current input clear values into fuzzy values expressed by linguistic variables. The phasing variables are flow rate F, power water pressure P, and pressure change ΔP.

Each linguistic variable is described by a membership function. In this case, each numerical value of the process variable is associated with the degree of membership in the fuzzy subset that symbolizes a particular linguistic variable. For example, the numerical range of pressure P is characterized by the linguistic values "Low", "Medium" and "High".

For the formation of fuzzy control influences in the block of logical decision formation, fuzzy conditional rules laid down in the knowledge base are used. The knowledge base has the form "F=...AND P=...,THEN ΔP=...". For example, "IF F="Large" AND P="High", THEN ΔP ='Reduce". In this case, the rules are formulated in such a way that the result is achieved when at least one of the rules is acceptable for any linguistic variable.

In the defuzzification block, the fuzzy data obtained in the decision block is transformed into a clear, specific value that is used to influence the control object. There are various methods of defuzzification. We use the center of gravity method to calculate the control influence.

$$\Delta P = \frac{\mu_{\text{decrease}} P_{\min} + \mu_{\text{increase}} P_{\max} + \mu_{\text{unchanged}} 0}{\mu_{\text{decrease}} + \mu_{\text{increase}} + \mu_{\text{unchanged}}}, \tag{32}$$

where

$\mu_{\text{decrease}}, \mu_{\text{increase}}, \mu_{\text{unchanged}}$ - membership functions for management.

According to the described algorithm, the fuzzy controller is realized by a program written into the permanent memory of the programmable logic controller.

The use of a fuzzy algorithm to control technical objects ensures:

- Reducing the fluctuation of the controlled value;
- maintaining the controlled parameters at the minimum tolerance level, which reduces energy consumption;
- the ability to use this algorithm for various objects without prior mathematical research.

The operating conditions for monitoring and control equipment in SAGM production are rather unfavorable. Process sensors and power cables are installed outdoors and are exposed to the weather. Frequent moves from one well to another (as they are developed) complicate their installation. Most sensors are subject to hydro-abrasive wear, which significantly increases their failure rate and, accordingly, operating costs, so it is necessary to provide for increased redundancy conditions when designing. For receiving and transmitting information from several similar GHG installations, it is economically feasible to have one set of telemechanics receiving and transmitting equipment in the central control room (CR).

Nowadays, with the rapid development of science and technology, many tasks of human activity are becoming complex and cumbersome and require an accurate mathematical description to solve them. Sometimes, when it is possible to solve such a problem using classical theory, the mathematical models created are too complex and require a lot of time and effort to create. The implementation of such models increases the requirements for technical support, and due to their complexity, the number of calculations is rapidly increasing, which in turn leads to a decrease in the performance of the system as a whole.

At the same time, complex systems are successfully managed by experienced operators based on qualitative process analysis. Such operator control is based on intuitive rules such as "...if...then", which are not fully quantified.

It is the experience and way of thinking of an expert operator that is intended to be used in a new direction of control systems and system approach called Fuzzy logic. Fuzzy logic is one of the most promising areas of modern control theory. Currently, this theory is experiencing a real upswing all over the world.

Expert systems are a likely area for the implementation of fuzzy logic algorithms, including expert systems:

- non-linear process control (production);
- self-learning systems;
- research of risks and critical situations;
- Pattern recognition;
- financial analysis (securities markets);
- data research (corporate repositories);
- improving management and coordination strategies. For example, complex industrial production.

Classical or Boolean logic has a significant drawback: it cannot be used to describe associative thinking. It operates with only two concepts: TRUE and FALSE, and excludes any intermediate values.

The basis of fuzzy logic is the theory of fuzzy sets, where the function of an element's membership in a set can take any value in the range 0-1. The whole range of logical operations is provided for such values: union, intersection, negation, etc. Fuzzy logic makes it possible to build knowledge bases and expert systems of a new generation that can store and process inaccurate information. This approach has emerged objectively because as control systems become more complex, the ability to make accurate and meaningful statements about the system's behavior decreases and the line is reached where accuracy and meaningfulness become mutually exclusive characteristics. The author of the theory of fuzzy sets, the American mathematician L. Zadeh, stated: "...as complexity increases, exact values lose significance, and significant statements lose precision".

The general structure of the fuzzy logic-based controller is shown in Fig. 7. and consists of:

- phasing unit;
- knowledge base;
- decision-making unit;
- defuzzification unit.

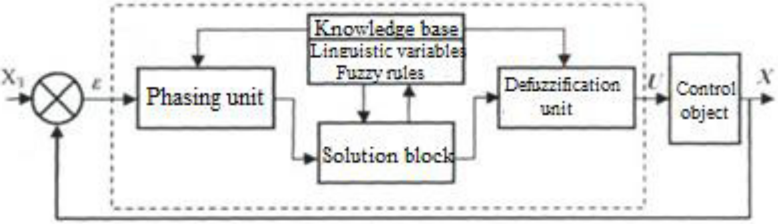


Fig. 7. General structure of the fuzzy controller

The fuzzification unit converts the current input crisp values into fuzzy values, which are expressed by linguistic variables. Each linguistic variable is described by a membership function. Each numerical value of a process variable is assigned a degree of membership in the fuzzy subset that symbolizes a particular linguistic variable.

To generate fuzzy control influences, the logical decision-making unit uses fuzzy conditional *"if"-"then"* rules laid down in the knowledge base. The "*if* part (precondition) can mean the conjugation of any complexity of logical operations. The *"then"* part (decision. conclusion) is the definition of a linguistic variable for the output value of the controller. In this case, the rules are formulated in such a way that a result is achieved in which at least one of the rules is acceptable for any linguistic variable.

In the defuzzification block, the fuzzy data obtained in the decision block is converted into a clear value that is used to influence the control object.

Controlling the process of hydraulic monitor washout by speed. In existing systems, the hydraulic monitor is controlled by operating time and pulp consistency. This choice of controlled parameters does not allow for effective process control for a number of reasons:

- since the pulp density measurement is carried out on the surface, there is a large transportation delay;
- he eroded rock is raised to the surface by airlifts or hydraulic el-

evators, the efficiency of which decreases when the consistency of the pulp changes;

- the change in pulp consistency is also affected by the settling of eroded rock during its transportation to the lifting mechanism.

We propose to control the process of hydraulic monitoring scouring on the basis of controlling the distance between the hydraulic monitor nozzle and the face wall and the rate of rock scouring. Monitoring the change in the size of the extraction chamber over time also provides information on the performance of the scouring process. Modern ultrasonic and laser rangefinders allow for non-contact distance measurement with high accuracy. Their hermetically sealed design and small size allow them to be used in downhole hydraulic applications.

Modeling of the scour rate control system. The block diagram of the modeling of the scour rate control system is as follows:

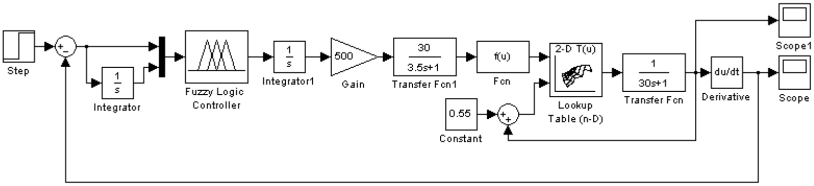


Fig. 8. Mathematical model of the scour rate control system in downhole hydraulic production

Step - input task of the speed control loop.

Integrator + Fuzzy logic controller is a fuzzy PI controller. It is customized by the operator based on previous experience.

Integrator 1 - integrating link to ensure the astatism of the system (ensuring zero error in the steady-state mode).

Gain is a frequency converter.

Transfer fcn 1- transfer function of the induction motor.

Fcn - piston pump, the output is pressure.

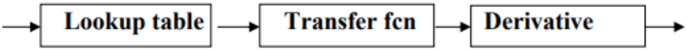
Constant - setting the initial distance from the nozzle to the face wall (0,55 m is the initial distance from the hydraulic monitor nozzle to the face wall).

Lookup table - block for approximating the nonlinear transmission coefficient *K* depending on the inlet pressure and the distance from the nozzle to the face wall.

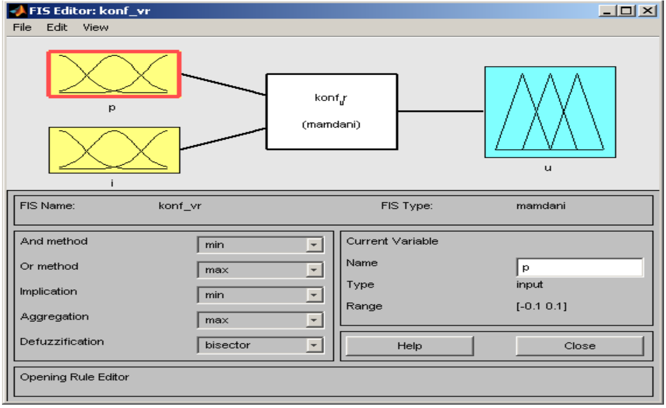
Scope – output by the scour velocity V_p, m/s.

Scope 1 – object output in terms of blurring distance L_p , m.

- object of regulation.



The method of defuzzification of the fuzzy controller is Centroid (calculation of the center of gravity of the figure).



FIS Name: konf_vr

FIS Type: mamdani

And method: min

Or method: max

Implication: min

Aggregation: max

Defuzzification: bisector

Current Variable

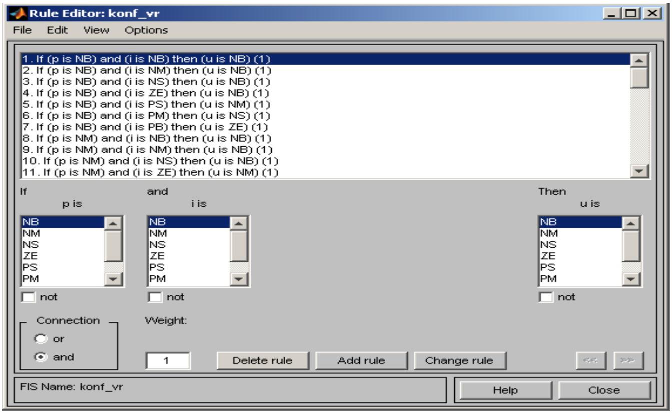
Name: p

Type: input

Range: [-0.1 0.1]

Opening Rule Editor

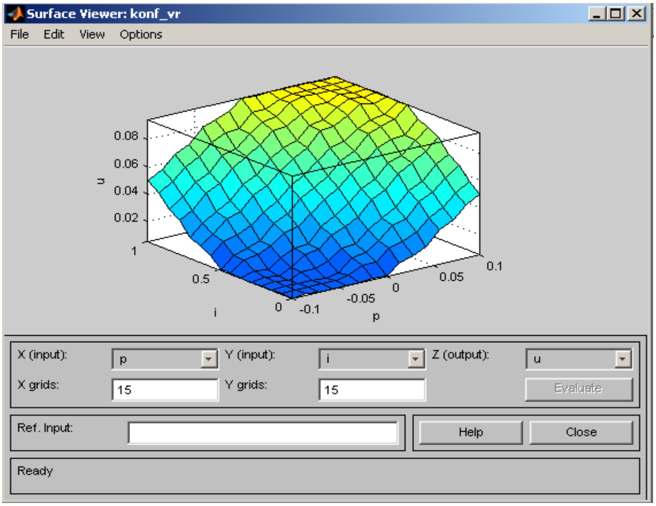
Fig. 9. Fuzzy controller of the scour rate control system



```
1. If (p is NB) and (i is NB) then (u is NB) (1)
2. If (p is NB) and (i is NM) then (u is NB) (1)
3. If (p is NB) and (i is NS) then (u is NB) (1)
4. If (p is NB) and (i is ZE) then (u is NB) (1)
5. If (p is NB) and (i is PS) then (u is NM) (1)
6. If (p is NB) and (i is PM) then (u is NS) (1)
7. If (p is NB) and (i is PB) then (u is ZE) (1)
8. If (p is NM) and (i is NB) then (u is NB) (1)
9. If (p is NM) and (i is NM) then (u is NB) (1)
10. If (p is NM) and (i is NS) then (u is NB) (1)
11. If (p is NM) and (i is ZE) then (u is NM) (1)
```

FIS Name: konf_vr

Fig. 10. The rule base of a fuzzy controller.



Surface Viewer: konf_vr

X (input): p

Y (input): i

Z (output): u

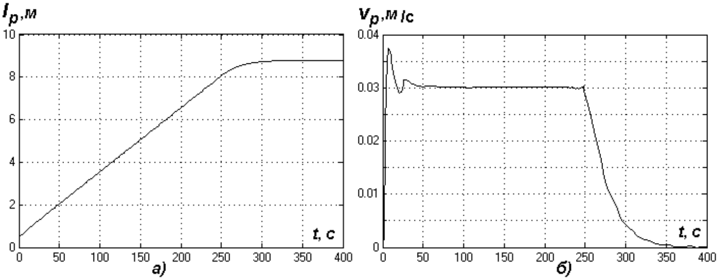
X grids: 15

Y grids: 15

Ref. Input:

Ready

Fig. 11. Erosion rate control surface



a)

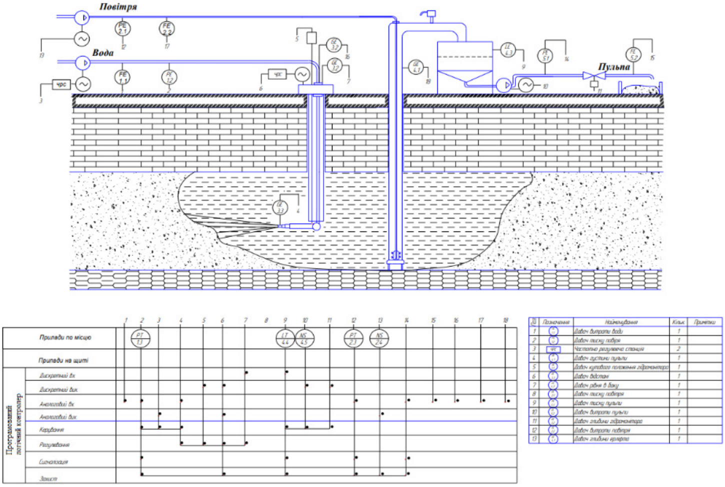
б)

Fig. 12. *a* - transient response of the ATS by scour range;
b -transient response of the ATS by scour rate

The organization of the control process by the speed and range of erosion will ensure reliable and efficient control over the process of hydraulic monitoring erosion.

The developed mathematical model of the object can be the basis for the design of flexible control systems for the process of hydraulic monitoring scour using adaptive, extreme, self-tuning and fuzzy control methods, which will allow them to be used for the extraction of various minerals.

4. Implementation of the proposed automation system



№	Позначення	Найменування	Кільк.	Примітки
1	[illegible]	Давач витрати води	1	
2	[illegible]	Давач тиску повітря	1	
3	ЧРС	Частотно регулююча станція	2	
4	[illegible]	Давач густини пульпи	1	
5	[illegible]	Давач кутового положення гідромонітора	1	
6	[illegible]	Давач відстані	1	
7	[illegible]	Давач рівня в баку	1	
8	[illegible]	Давач тиску повітря	1	
9	[illegible]	Давач тиску пульпи	1	
10	[illegible]	Давач витрати пульпи	1	
11	[illegible]	Давач глибини гідромонітора	1	
12	[illegible]	Давач витрати повітря	1	
13	[illegible]	Давач глибини [illegible]	1	

Fig. 13. Functional diagram of hydraulic scour automation

The functional diagram of the automation (Fig. 13) shows the following control, management and measurement circuits:

1. The signal from the water flow sensor is input to the analog input and is used to account for the water used, which is necessary for the technical and economic analysis of the process.

2. The signal from the water pressure sensor is input to the analog input, which is also the main parameter for controlling the pump pressure. In the event of an emergency, an alarm is triggered and a signal is simultaneously sent to the protection, i.e. the entire system stops until the problem is corrected.

3. The pressure measurement at the outlet of the pump with the frequency control station is used to supply water to the hydraulic monitor. The signal is input to the analog input and is used to regulate the hydraulic scouring process. When a signal is received from the distance sensor and the water pressure sensor, the controller sets the necessary task for the frequency control station to create the required pressure by the pump.

4. Distance sensor, which is the main indicator of the performance of the hydraulic monitor and at the same time an indicator of the balance of all regulatory bodies (2,3,5,6,7,8).

5. The signal from it is fed to the analog input, and is used for regulation and control (2,3,5,6,7,8).

6. The hydromonitor's telescope position sensor, the signal from which is input to the discrete output and to the control, i.e., regulates the telescope extension length based on the distance sensor 4.

7. Frequency control station of the hydraulic monitor angle reducer. It is designed for sectoral rotation of the hydraulic monitor barrel. The signal is sent to the analog input and to the control. Also, when the protection is activated, this device stops.

8. The hydraulic monitor rotation angle sensor, the signal from which is fed to the gearbox to rotate the hydraulic monitor to a certain sector of the scour. It is connected to a digital input and directly to the control.

9. Distance sensor from the hydraulic monitor nozzle to the eroded rock. The signal from this sensor is input to the analog input and interconnected with (4,5,6,7).

10. The pulp level sensor in the hopper. It is used to regulate the level of pulp in the hopper and control the dredge pump 10 and valve

11. The signal from the sensor is sent to a discrete input and control. The sensor is also connected to the protection system of the entire system, which is triggered by an alarm, for example, when the hopper is overfilled.

12. A dredge used for pumping pulp from the hopper to the sump. The signal from which is driven to the discrete output and to the control. That is, the dredge is switched on only after the maximum signal of the level sensor 9, and off after the minimum signal.

13. A valve used to prevent the dredge from flooding. The signal from this valve is input to the digital output and connected to the control of devices 9 and 10.

14. Air pressure sensor, the purpose of which is mainly to prevent accidents in the air supply pipeline. The signal from which is sent to the analog input. When the alarm is triggered, the protection is activated and the entire system stops.

15. A compressor station designed to provide air of a certain pressure (1-6 atm) to the elevator. The signal is connected to an analog output and a protection system. Moreover, the station itself also contains a protection system, which is connected to the protection system of the entire scour system.

16. Slurry pressure sensor, the signal from which is connected to the analog input, alarm and protection system. The main task of this

device is to prevent pressure overload in the pipeline from the hopper to the settling tank.

17. The pulp flow sensor, the signal from which is fed to the analog input. The main task is to record the extracted pulp, which is necessary for the technical and economic analysis of the process.

18. Depth sensor of the hydraulic monitor - for controlling the height position.

19. Air flow sensor - required for technical and economic analysis of the process.

20. Airlift depth sensor - for controlling the height position.

Conclusion

The efficiency of erosion is determined by the performance of the hydraulic monitor and specific energy consumption, which depend on the parameters of the jet, physical and mechanical properties and structure of the mineral being mined, the magnitude of forces and pressures in contact with the face, and technological methods of rock erosion.

The controlling influences during hydraulic monitoring are the pressure and flow rate of the working agent (water), the speed of rotation and movement of the telescopic hydraulic monitor nozzle in the face.

The need for pressure management stems from a number of reasons:

- Pressure control is essential to ensure the efficiency of the washing process and energy savings. Insufficient pressure results in a sharp decline in productivity. Excessive pressure creates a cut in the rock, resulting in reduced efficiency;
- Overpressure scatters the eroded rock around the chamber, making it difficult to transport;
- At the optimum pressure value, conditions are created to produce pulp trol at small distances from the nozzle to the face wall prevents bwith a certain rock fraction required for its efficient transportation and lifting;
- Pressure conlockage of the conveying channel.

The complexity and conditions of the underground hydraulic leaching process make it difficult to monitor process parameters. In the existing systems, the hydraulic monitor is controlled by the operating time and pulp consistency. This choice of controlled parameters does not allow for effective process control for a number of reasons:

- Since the pulp density measurement is carried out on the surface, there is a large transportation delay;
- The eroded rock is raised to the surface by airlifts or hydraulic elevators, the efficiency of which decreases when the consistency of the pulp changes;
- The change in pulp consistency is also affected by the settling of eroded rock during its transportation to the lifting mechanism.

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