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INNOVATIVE TECHNOLOGY FOR PREPARING WASHING LIQUID IN THE COURSE OF DRILLING

A technique for washing liquid preparation has been designed. The advantages of the hydrodynamic super-cavitation technique to be used for preparation of washing liquids in the course of drilling have been described. The theoretical research has enabled setting parameters and designing a cavitation disperser. The results of theoretical research have been confirmed in practice and laid foundation for creating a technique for preparing washing liquid. The cavitation disperser has been tested in production environment.

Keywords: well drilling, well, washing liquid, hydrodynamic super-cavitation, and cavitation disperser.

Washing fluid is an integral part of any technology of drilling wells for various purposes, with technical and economic parameters of the drilling process depending on its quality and suitability for geological and technical conditions. The evolution of well drilling techniques is inextricably linked with the improvement of drilling/washing fluids that are complex heterogeneous poly-disperse systems. They not only wash over the destroyed rock from the bottom of the well to the surface, but also perform other important functions.. The share of cost of washing fluids ranges from 5 to 14% in the cost of well boring. The washing liquid should meet the requirements with respect to geological, technological, and organizational factors. In its turn, this entails specific requirements for the machines used for preparing washing liquids, their operational principles and performance, which should be modernized and improved.

The variety and, sometimes, contradictory character of requirements for washing fluid, as well as rapidly changing geological and technical conditions of well drilling cause the need for applying "customized" drilling fluids having certain properties that determine their functionality. The technological properties of drilling fluids are substantially determined by their stability, i.e. constant main parameters of disperse sys-tem: fineness (specific surface) and uniform distribution of the dispersed phase in the dispersion medium.

The major part (80%) of drilling fluids used for well drilling contains solid dispersed phase, with 60% of them having clay as main component of the dispersed phase. This is due to the fact that these drilling fluids meet most of the functional requirements.

There are the kinetic stability and the aggregate stability of disperse systems. The latter refers to the ability of the dispersed phase to resist to conglomeration and to keep the dispersed state. The main factors effect-ing the aggregate stability have been studied; they are interrelated and include the electric barrier and the adsorption-solvation barrier. The aggregate stability is controlled by adding special chemical reagents to washing liquid. These reagents generate an adsorption-hydration shell on the surface of solid particles, which prevents adhesion of the particles during the collision. The selection of chemical adsorption and the character of hydration

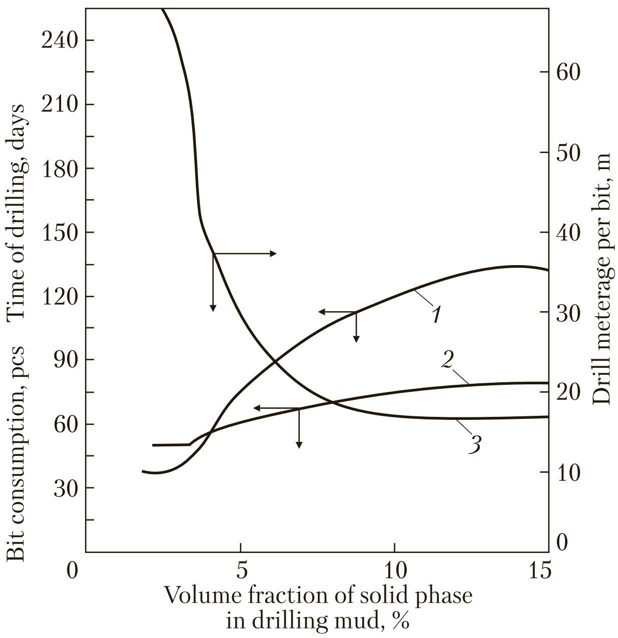

Fig. 1. Effect of solid particles in the drilling mud on the technical and economic parameters of drilling: *1* — consumption of drill bits; *2* — time of drilling; *3* — headway per drill bit

shell formation depend on the chemical and mineral composition of both the disper-sion medium and the dispersed phase. Such control of aggregate stability of drilling fluids is quite effec-tive, but, at the same time, it has several disadvantages: high cost of chemicals, environmentally hazardous reagents, etc.

The kinetic stability refers to the ability of dispersed particles to keep suspended under the influence of Brownian motion, i.e., stability with respect to mass gravitational forces. In addition to the Brownian mo-tion, the kinetic stability factors are variance (the most important factor, the higher the variance, the more stability), viscosity, density difference between the dispersion medium and the dispersed phase.

Thus, the most promising direction related to washing fluids is to obtain high-quality stable systems.

While preparing the washing fluids using existing methods, it is impossible to reach full dispersion of dis-persed phase. Therefore, further dispersion of the dispersed phase of washing fluids using different disper-sants is an important problem to be studied. Dispersing enables reducing the amount of solid phase in the washing liquid preserving specified structural and mechanical properties. The lower is the quality of the clay, the greater is the dispersion effect.

Fig. 1 shows the dependence of the main indicators of drilling on the content of solid phase in the mud. The existing dispersants have a lot of drawbacks: additional power to drive, significant hydraulic losses in the jet dispersers, etc. Advanced methods for treating stable drilling fluids use cavitation generators based on the phenomenon of cavitation.

The analysis has showed that super-cavitation is the most promising technique for treatment of washing fluids. Super-cavitation occurs when axisymmetric bodies are flowed around by liquid. The operating prin-ciple of SC-mechanisms is that flow slipping around the cavitator results in the formation of super-cavities that close directly in the flow, far away from the working surface of the machine. The unsteady tail section of the cavity generates fields of cavitation micro-bubbles that, when collapsing, intensify the dispersion process, with the apparatus working surfaces not being affected by cavitation erosion and the service life not depending on the modes of cavitation treatment. The decisive factors are the number and size of cavita-tion bubbles.

THEORETICAL RESEARCH

For calculating basic parameters of cavitation disperser, the Bernoulli equation and the continuity equation for sections 0—0 and 1—1 (see Fig. 2) have been solved.

$$H = P_0 + \frac{\rho V_0^2}{2} = P_1 + \frac{\rho V_1^2}{2} + \Delta h_{0-1}, \qquad (1)$$

where H is pump pressure, ρ is density of washing fluid, and Δh_{0-1} is losses in confusor;

$$Q_0 = Q_1 = Q_i, \; V_0 F_0 = V_1 F_1 = V_i F_i, \qquad (2)$$

where F_0, F_1, F_i are respective cross sections, $F_i = F_1 - F_ш$ ($F_ш$ — cross section of the guide rod);

$$\Delta h_{0-1} = \frac{\xi_к \rho V_1^2}{2}, \qquad (3)$$

where $\xi_к$ is coefficient of hydraulic losses in confusor.

When transiting from the wide section of confusor to the narrow one, pressure decreases. In order to reduce the pressure drop, the confusor shall have a sinusoidal shape and a length equal to the pipe diameter at cross section 0—0 (see Fig. 3).

The angle of diffusor slope is defined assuming that there is no cavitation on the walls of generator; in ac-cordance with recommendations, the diffusor slope angle is $\gamma \leq 25°$, the diffusor section length is $L_Д \geq 2d$.

The hydraulic losses on the cavitator are calculated according to the formula:

$$\Delta h_к = \xi_{кав} \frac{\rho V_{кав}^2}{2}, \quad (4)$$

where $V_{кав}$ is velocity at the place of cone flow by fluid in the diffusor.

The total losses on cavitation disperser are:

$$\Delta h_{КД} = (\xi_к + \xi_Д + \xi_ц)\frac{\rho V_ц^2}{2} + (\xi_{кав})\frac{\rho V_{кав}^2}{2}, \quad (5)$$

where $\xi_{кав}$ is coefficient of hydraulic losses on the cavitator.

Minimum hydraulic losses should correspond to a cone angle of 15—20° and are equal to $\xi_{кав}$ = = 0,15—0,16.

The intensity of cavitation treatment should depend on geometric characteristics of super-cavity, number and size of cavitation micro-bubbles behind super-cavity. Since super-cavity size (intensity of cavitation treatment) is controlled by axial shift of cone in the diffusor, in order to describe the intensity of hydrody-namic cavitation, flow chocking coefficient $k_з$ is introduced:

$$k_з = \frac{F_к}{F_д} = \frac{D_к^2}{D_д^2}, \quad (6)$$

where $F_к$, $F_д$ are cross sections of the cone and the diffusor, respectively; $D_к$, $D_д$ are base diameters of the cone and the diffusor, respectively.

Taking into consideration the continuity equation and the flow chocking coefficient, the cone flow rate is equal:

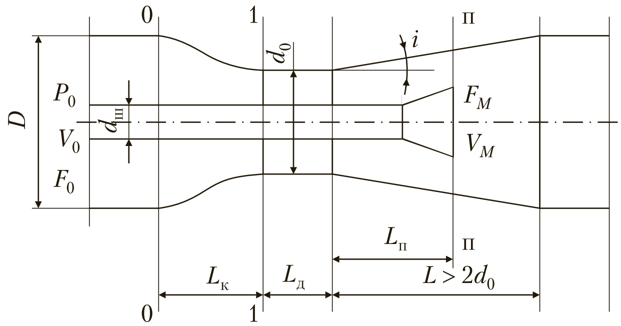

Fig. 2. Diagram of cavitation disperser

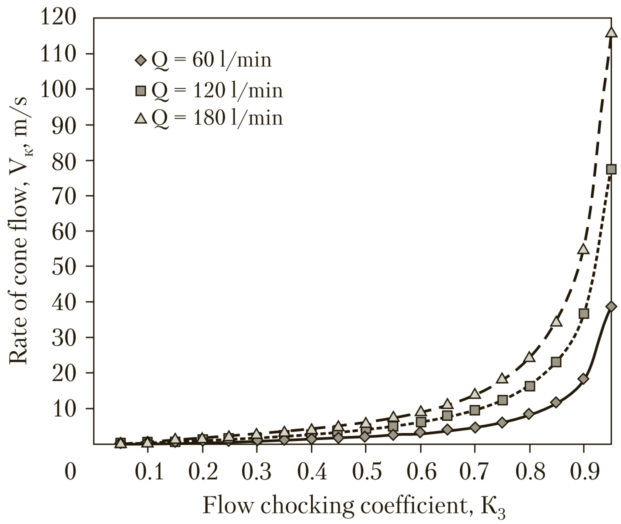

Fig. 3. Design rate of cone flow depending on flow chocking coefficient

$$V_k = \frac{Q}{0{,}785 d_k^2 (1/k_з - 1)}, \text{ м/с}, \quad (7)$$

where d_k is the cone's diameter; Q is consumption rate of washing fluid.

The graphical presentation of formula (7) is given in Fig. 3.

Fig. 3 shows that the flow chocking coefficient varies within the range $К_з$ = 0,6—0,8, insofar as therein the intensity of rate fluctuation is maximum, which enables controlling the intensity of cavitation effect within a wide range.

The nature of cavitation oscillations occurring during the cone flow is similar to that of phenomena known in hydrodynamics as *Strouhal fre-*

quencies. For these oscillations, a linear dependence of frequency on rate of approach flow and an inverse dependence on specific dimension (hydraulic diameter) are typical:

$$f = \frac{SrV}{d_г}, \qquad (8)$$

where *Sr* is Strouhal number (dimensionless quantity, one of non-steady flow similarity criteria).
The Strouhal number is a function of the Reynolds number; within the range 200 < *Re* < 200 000 the empirical law of Strouhal number constancy: $Sr \approx 0{,}2–0{,}3$. The final formula for calculating the frequency of cavitation oscillations is:

$$f = \frac{SrQ}{0{,}785 d_k^3 (1/k_з - 1)(1/\sqrt{k_з} - 1)}, \text{ Hz.} \qquad (9)$$

The results of calculations of frequency f at $d_к$ = 0,025 м, $Sr \approx 0{,}25$, $k_з$ = 0,6—0,8, Q = 0,001—0,003 м^3/с are given in Table 1.

Table 1 shows that in terms of flow chocking coefficient, the cavitation disperser operates efficiently within 0.6—0.8; as the cone diameter decreases the pressure losses on cavitation disperser increase, with the most intensive growth reported for the cone diameter less than 0.015 m.

When the jet colliding with solid particles of dispersed phase the pressure should exceed not only local strength of the particles, but also its inertial forces. Under the cumulative action, the solid particle material can behave like a liquid.

Table 1

Design Frequencies of Cavitation Oscillations

Diameter of the cone, $d_к$, m	Flow chocking coefficient		
	0.6	0.7	0.8
0.025	Q = 0.001 м^3/с		
	84	195	553
	Q = 0.002 м^3/с		
	168	390	1105
	Q = 0.003 м^3/с		
	252	585	1658

According to the experiment data, the dynamic yield limit is $P_д = 1{,}8\, s_т$; taking into consideration the inertial forces, it increases up to $P_д = 4{,}5 s_т$, where $s_т$ is yield limit of dispersed phase material.

Fig. 4 shows the diagram of cavitation bubble collapse.

When the jet penetrated into the particle the pressure on interface in the case of rigid collision is

$$P = \frac{1}{2}\rho_к (V_{кс} - U)^2, \qquad (10)$$

where U is velocity of interface, $\rho_к$ is density of liquid in cumulative jet, and $V_{кс}$ is velocity of cumulative jet.
Taking into account the fact that having collided with the jet, the particle material starts to yield, from the Bernoulli equation for the particle material one can obtain:

$$P = \frac{1}{2}\rho_c U^2 + P_\partial, \qquad (11)$$

where $\rho_с$ is density of suspension material and P_∂ is dynamic yield limit.

Hence,

$$\frac{1}{2}\rho_к (V_к - U)^2 = \frac{1}{2}\rho_c U^2 + P_\partial. \qquad (12)$$

Having transformed the equation (10), one can get

$$U = \frac{\sqrt{\rho_k P_\partial + \rho_c \rho_k V_{kc}^2 - \rho_c P_\partial} - V_{kc}\rho_k}{\rho_k - \rho_c}. \qquad (13)$$

For the stationary process, within a sufficiently small time interval $d\tau$, the interface covers a distance $dl_u = U d\tau$. The cumulative jet can be represented as fluid wedge. For the time interval $d\tau$ the jet size as a result of contact with the particle surface increases by $dl_c = V_к d\tau$. While passing through the bubble, the cumulative jet reshapes from $2R$ to $2r$ (the minimum radius). Thus, time $d\tau$ is calculated from the identity

$$d\tau = dl_u / U = dl_c / V_{кс}. \qquad (14)$$

The depth of jet penetration is defined as

$$l = \int_{2r}^{2R} \left(\frac{\sqrt{\rho_k P_\partial + \rho_c \rho_k V_{kc}^2 - \rho_c P_\partial} - V_{kc}\rho_k}{V_{kc}(\rho_k - \rho_c)} \right) dR. \qquad (15)$$

Velocities V_{kc} and U are functions of radius of the collapsed bubble. Having integrated the expression, one can obtain the depth of penetration $l_{2\varpi}$ of jet into the particle in the case of rigid collision, when the particle contacts the bubble, with collision spreading along the whole jet length that is equal to initial diameter of the bubble:

$$l_c = 2R. \quad (16)$$

For the full collapse of the bubble, the minimum radius r is the jet radius. The particle will collapse after one collision with the jet if the depth of penetration l is deeper or equal to the average size of suspension particle $l_ч$. Therefore, for realizing the condition of at-once collapse of the particle of known size $l_ч$, it is necessary to get cavitation bubbles of radius R at which the depth of penetration is larger than the particle size:

$$l_{2R} \geq l_ч. \quad (17)$$

Having calculated the integral (15), one can get a formula for the depth of penetration of cumulative jet in-to the particle:

$$l = \frac{\sqrt{\rho_k P_\partial + \rho_c \rho_k V_{kc}^2 - \rho_c P_\partial} - V_{kc}\rho_k}{V_{kc}(\rho_k - \rho_c)} \times$$

$$\times (2r - 2R). \quad (18)$$

Taking into account the condition for at-once collapse of the particle, one can obtain

$$l = 2R. \quad (19)$$

Having equated the expressions (18) and (19), the jet velocity required for collapse of dispersed phase par-ticle is defined as:

$$V_{kc} = \frac{\sqrt{(4\rho_k(R^2 - Rr) + \rho_k r^2 - \rho_c R^2)P_\partial}(R - r)}{4\rho_k(R^2 - Rr) + \rho_k r^2 - \rho_c R^2} \quad (20)$$

Having the velocity of cumulative jet penetration into the particle and size as known values, one can de-termine time required for one collapse of the particle with initial specific size l_0:

$$t_1 = \frac{l_0}{V_{kc}}. \quad (21)$$

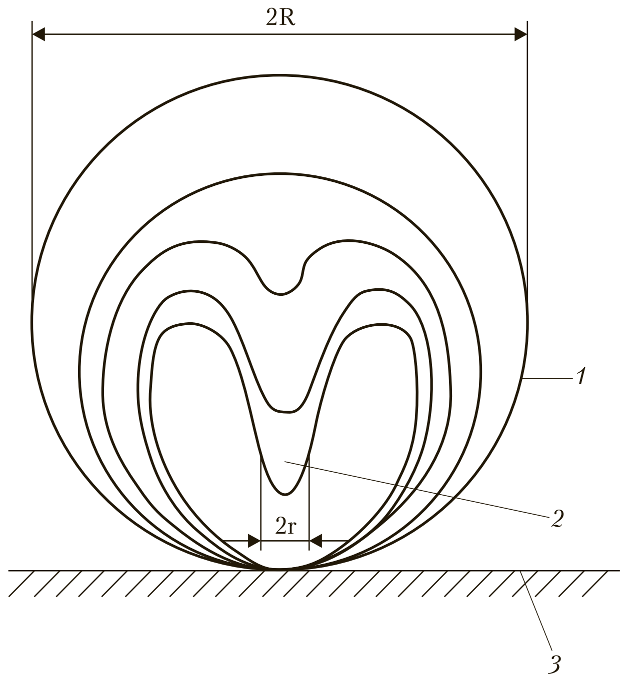

Fig. 4. Diagram of cavitation bubble collapse: *1* — cavitation bubble; *2* — cumulative jet; *3* — surface of dispersed phase particle

The initial number of particles within given volume of dispersed phase V is:

$$n = \frac{V}{V_0}, \quad (22)$$

where V is volume of dispersed phase, V_0 is initial volume of one particle of dispersed phase.

Time required for dispersing all particles of dispersed phase is defined as

$$T = t_1 n = \frac{l_0 V}{V_{kc} V_0}, \text{ c.} \quad (23)$$

However, for calculating time of dispersing the whole volume of dispersed phase it is necessary to take into account the number of particles dispersed at the same time, which is equal to frequency of cavitation oscil-lations. Therefore, time required for dispersing all particles of dispersed phase is equal to

$$T = \frac{l_0 V}{V_{kc} V_0 f}, \quad (24)$$

where f is frequency of cavitation oscillations.

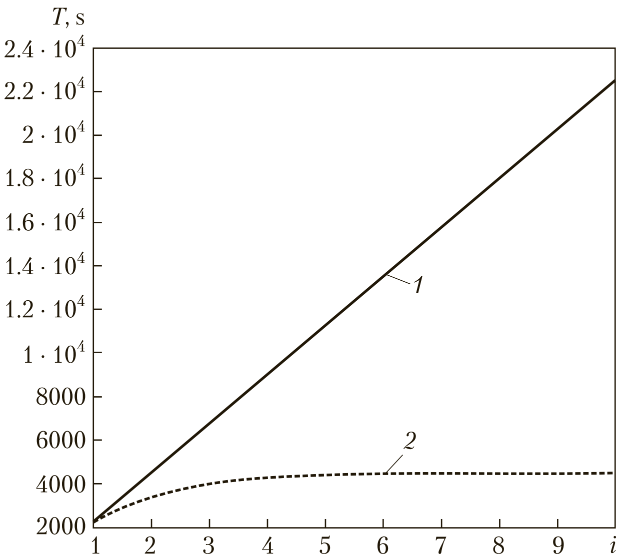

Fig. 5. Dependence of dispersing time Ton the number of treatment cycles *i*: *1* — at *f = const; 2* — at varying frequency of cavitation oscillations

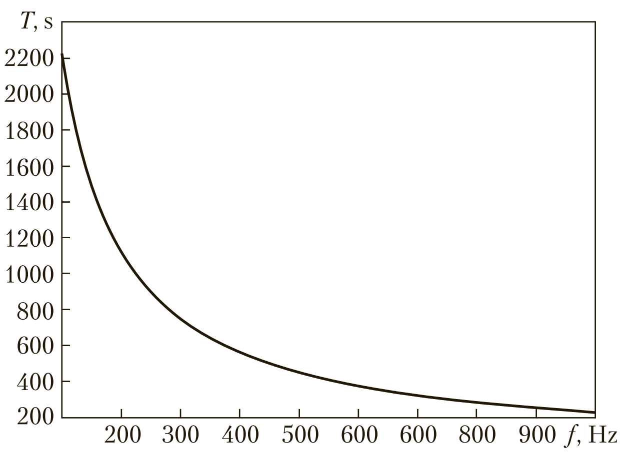

Fig. 6. Dependence of dispersing time on frequency of cavitation oscillations for single treatment cycle

Assuming that after each collapse, the initial volume of dispersed phase particles V_0 decreases, at least, twice, the dependence of time of dispersing T on the number of treatment cycle at $f = const$:

$$\sum T_i = i\frac{l_0 V}{V_{kc} V_0 f}, \text{ c.} \qquad (25)$$

The total time of dispersing given volume of dispersed phase with initial size l_0 and volume V_0 of particles up to size of l_i and volume V_i, when the frequency of cavitation oscillations of fluid pressure in the flux increases n times each cycle is equal to:

$$\sum T_i = \frac{l_0 V}{V_{kc} V_0 f} \frac{\left[1 - \left(\frac{1}{n}\right)^{i-1} \frac{1}{n}\right]}{\left(1 - \frac{1}{n}\right)}, \text{ c.} \qquad (26)$$

The dependences (25) and (26) are showed in Figs. 5 and 6.

The calculations have been made for the following initial conditions: radius of collapsing micro-bubble de-creases 10 times; initial size of dispersed phase particle is l_0 = 0,0001 м; dynamic strength of dispersed phase particles is P_∂ = 100 МПа; the number of full treatment cycles is i = 10.

Analysis of dependences given in Figs. 5 and 6 shows that:

- Time of dispersing is inversely proportional to the number of cavitation bubbles in the flux (fre-quency of cavitation oscillations) formed per unit of time;
- The number of dispersed phase particles in the flux increases with each collapse; consequently, to keep the intensity of dispersing at a fixed level it is necessary to vary the number of cavitation bubbles in the flux (frequency of cavitation oscillations).

EXPERIMENTAL RESEARCH

During the experiment, performance of cavitation disperser has been tested and geometrical parameters of cavity depending on flow chocking factor has been defined using the photographic method.

The test installation consisted of a cavitation disperser (technical parameters are given in Table 2); turbu-lence pump 2V-1.6; depositing tank; pipelines. In Fig. 7, there are pictures of cone flow by flux in different operation modes.

Technical Parameters of the Disperser

Casing diameter, mm	50
Cone diameter, mm	25
Diffusor angle, degree	15
Length (max), mm	300
Weight, kg	maximum 2.0

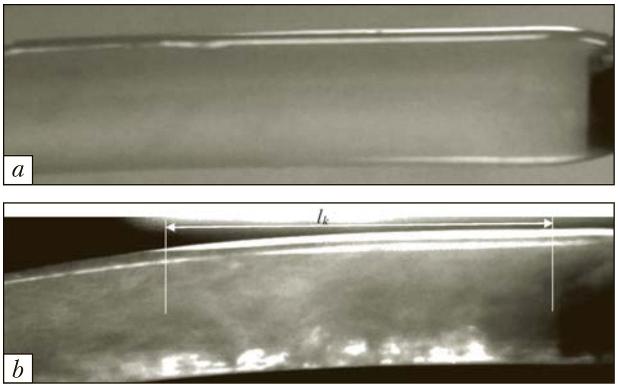

Fig. 7. Cone flow: *a* — without cavitation $Q = 1,2$ l/s, $k_з = 0,95$, $l_k = 0$ mm; *b* — with cavitation at $Q = 1,6$ l/s, $k_з = 0,7$, $l_k = 150$ mm

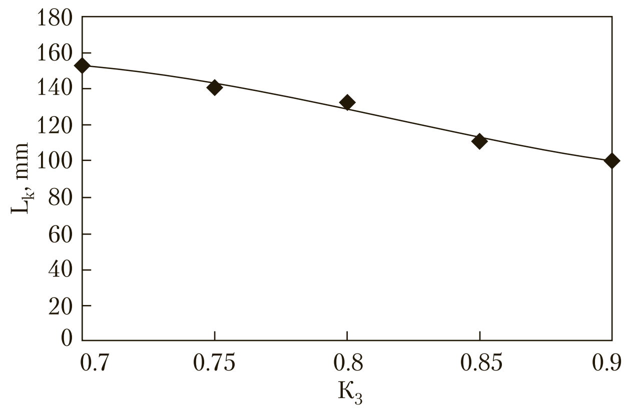

Fig. 8. Typical dependence of cavity length on flow chocking coefficient at a pumping rate of 0,0016 m³/s

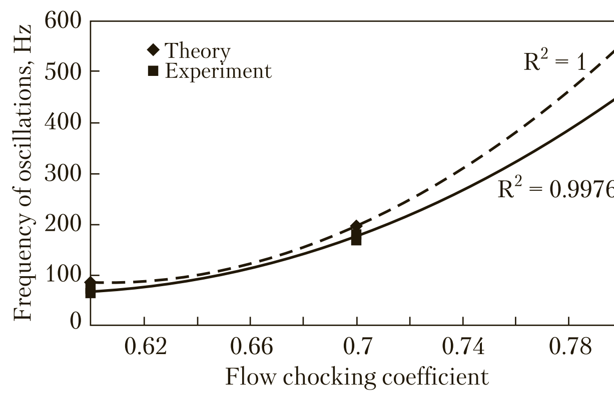

Fig. 9. Dependence of frequency of cavitation oscillations on flow chocking coefficient at $Q = 0,001$ m³/s

The tests have showed that as flow chocking coefficient increases the length of super-cavity l_k decreases with the same pace for different pumping rate (Fig. 8). The maximum pressure difference on cavitation disperser does not exceed 0.2 MPa.

The actual operational parameters of cavitation disperser (magnitude and frequency of cavitation pressure oscillations) have been measured by recording the process in different operation modes (varying pumping rate and flow chocking coefficient inn cavitation disperser). The installation included a cavitation disperser, a pump, a depositing tank, a suction pipeline, a pressure pipeline, and gauges.

Fig. 9 shows the results of tests of frequency dependence of cavitation disperser at a pumping rate of $Q = 0,001$ m³/s. The difference between the experimental and the theoretical data ranges between 15—20 %. Similar results have been obtained for pumping rates of $Q = 0,002$ m³/s and $Q = 0,003$ m³/s.

The results of bench tests of effect of cavitation disperser on the properties of washing fluids have showed that its use enables improving the properties as compared with the use of Venturi tube (Fig. 10).

PERFORMANCE TESTS

The purpose of performance tests is to determine technical and economic parameters of cavitation disperser. As a result, the following has been found:

- Effect of cavitation treatment of washing fluid on the consumption of primary components when preparing the washing fluid and in in the course of drilling;
- Effect of cavitation disperser on the parameters of washing fluids.

The tests were performed in expedition no.46 by *Kirovgeologia* enterprise. The average data by geological structure are given in Table 3.

The technological parameters of washing fluid used for drilling wells under geological conditions typi-cal for this expedition were adopted as basis for comparison. The cavitation disperser was included into additional pressure line and used for further dispersing of primary compo-

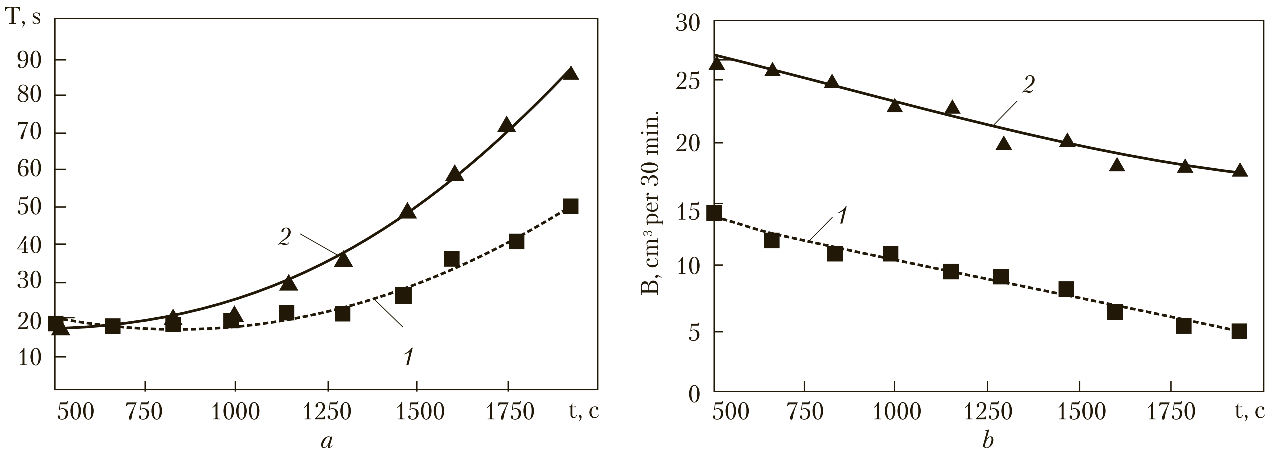

Fig. 10. Effect of treatment time on: *a* — funnel viscosity of drilling mug; *b* — filtration of drilling mug; *1* — treatment with the use of Venturi tube; *2* — treatment by cavitation disperser

nents of washing fluid both at the stage of preparation stage and in the course of drilling.

As a result, the performance tests have showed that:

- The application of cavitation disperser reduces by 20—30% the consumption of reagents and primary components used for preparing the washing fluid and maintaining its technological properties in the course of drilling;
- The cost of preparing 1 m3 washing liquid with the use of pilot sample of cavitation disperser decreases by 30%;

Table 2

Average Data by Geological Structure

Rock	Depth, m	Drilling category	Possible complications	Type of w.f.
Clay loam	5	III		Drilling mud
Limestone	20	IV		
Clays	10	IV		
Malmstone	10	IV		
Lime stones	40	IV	Karst, absorption of washing fluid	
Sandstone	5	VI		
Siltstone, argillite	45	VIII		
Sandstone with siltstone layers	50	IX		Thin clay drilling mud treated with emul-sol
Gravel stone	5	IX		
Gneiss, crystalline schist, migmatite	30	IX		
Granite, pegmatoid granite	30	IX	Fracture porosity	
Total	250	X		

- The cavitation disperser enables the effective dispersion of washing liquid components and can be recommended for the serial use in the drilling practice with various disperse systems used as washing fluid.

CONCLUSIONS

As a result of theoretical and experimental research, a technology for preparing stable finely dispersed washing fluids has been developed using hydrodynamic effect of super-cavitation.

- The hydrodynamic super-cavitation that occurs when the fluid flows around axisymmetric bodies has been justified to be the most promising technology in terms of energy efficiency for the preparation of washing fluids;
- The minimum pressure drop at cavitation disperser has been found to be ensured by small angle cones as bluff body;
- A new design of cavitation disperser has been developed; its novelty has been certified by patent of Ukraine;
- The flow chocking coefficient k3 is the key controllable parameter influencing the intensity of cavita-tion treatment;
- The theoretical studies have showed that the time of dispersing the dispersed phase for a single treat-ment cycle is inversely proportional to the frequency of cavitation oscillations;
- The theoretical and experimental studies have allowed the researchers to develop guidelines for the use of cavitation disperser for treating the washing fluids in the course of drilling;
- The recommendations have been put into practice and enabled reducing the cost of materials for the treatment of washing fluids in the course of drilling by 20—30% in average. The Guidelines have been adopted and approved by the State Geological Service of the Ministry of Environment and Natural Re-sources of Ukraine;
- The cavitation disperser enables the effective dispersion of washing liquid components and can be commercialized in the drilling practice.

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ІННОВАЦІЙНА ТЕХНОЛОГІЯ ПРИГОТУВАННЯ ПРОМИВАЛЬНИХ РІДИН ПРИ БУРІННІ СВЕРДЛОВИН

Розроблено технологію приготування промивальних рідин. Обґрунтована перспективність використання гідродинамічної суперкавітації для приготування промивальних рідин при бурінні свердловин. Теоретичні дослідження дозволили обґрунтувати параметри і розробити конструкцію кавітаційного диспергатора. Результати теоретичних досліджень знайшли підтвердження в ході практичних досліджень і стали базою для створення методики приготування промивальної рідини і конструкції кавітаційного диспергатора, випробуваних у виробничих умовах.

Ключові слова: буріння свердловин, свердловина, промивальна рідина, гідродинамічна суперкавітація, кавітаційний диспергатор.

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ИННОВАЦИОННАЯ ТЕХНОЛОГИЯ ПРИГОТОВЛЕНИЯ ПРОМЫВОЧНЫХ ЖИДКОСТЕЙ ПРИ БУРЕНИИ СКВАЖИН

Разработана технология приготовления промывочных жидкостей. Обоснована перспективность использования гидродинамической суперкавитации для приготовления промывочных жидкостей при бурении скважин. Теоретические исследования позволили обосновать параметры и разработать конструкцию кавитационного диспергатора. Результаты теоретических исследований нашли подтверждение в ходе практических исследований и стали базой для создания методики приготовления промывочной жидкости и конструкции кавитационного диспергатора, опробованных в производственных условиях.

Ключевые слова: бурение скважин, скважина, промывочная жидкость, гидродинамическая суперкавитация, кавитационный диспергатор.

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