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ON THE ISSUE CONCERNING IMPROVEMENT OF A MUD PREPARATION TECHNOLOGY AT THE EXPENSE OF HYDRODYNAMIC CAVITATION

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ДО ПИТАННЯ УДОСКОНАЛЕННЯ ТЕХНОЛОГІЇ ПРИГОТУВАННЯ БУРОВИХ РОЗЧИНІВ ЗА РАХУНОК ГІДРОДИНАМІЧНОЇ КАВІТАЦІЇ

Purpose is to improve the technology of drilling mud by applying hydrodynamic cavitation.

Research methodology is represented by the theoretical and experimental studies of hydrodynamic cavitation, performed with the help of modern methods of analytical analysis and experimental studies, i.e. by using general principles of mathematical and physical modeling, methods of processing research results in EXCEL, SolidWorks for further analysis.

Research results. Frequency of cavitation oscillations according to the parameters of a device for creating hydrodynamic cavitation has been calculated. The formula for determining the dispersion time of the washing liquid material by the frequency of cavitation oscillations has been theoretically substantiated and obtained. A process of moving drilling fluid in the device using the appropriate software in the SolidWorks package has been studied. The results of theoretical research have been confirmed by practical research and chosen as a basis for substantiation and development of the methods for preparing drilling fluids.

Originality is represented by modeling and research of the process of hydrodynamic cavitation in a cavitation device using flow visualization using SolidWorks software. This approach helped substantiate and predict the pressure and flow velocity at each point of transition of the diameters of a cavitation dispersant. This, in turn, has made it possible to reduce hydraulic resistance and improve the device design to implement a technology of preparation of drilling fluids due to hydrodynamic cavitation. This approach has allowed substantiating and performing virtual experiments on the technology of preparation of drilling fluids; that has helped select rational design parameters of the cavitation disperser and save a lot of money and time on the production of bench samples of the device, including various design features.

Practical implications. Basing on the results of both theoretical and experimental studies, the development of advanced technology for the preparation of stable drilling fluids be applying rational indicators of hydrodynamic cavitation has been substantiated and proposed.

Keywords: *well construction, well, dispersion method, cavitation, drilling mud, hydrodynamic supercavitation, cavitation dispersant.*

Introduction. In terms of rising energy prices, implementation of energy-saving technologies is a decisive economic activity of a mining enterprise. One of the trends in creating technical means to implement energy efficient technologies is associated with a new way for obtaining high-power discrete-pulse energy using hydrodynamics. Other energy properties of washing liquid include resistance, i.e. maintaining the main parameters of the disperse system: dispersion (specific surface) and uniform distribution of the dispersed phase in a dispersed medium (the same density by volume). Knowledge of the main factors of the stability of dissolving systems and the causes leading to its violation allows us to manage reasonably the resources of drilling fluids while drilling. [1]

One of the trends of such approaches is the use of modes of discontinuous cavitation in the flow of process fluid with the subsequent transformation of pressure pulsations into mechanical vibration loading of a rock-breaking tool while drilling, or a tool for expanding the casing pipe diameters.

The next trend is represented by the fact that hydrodynamic impact on rocks forms a longitudinal and transverse wave. They excite elastic (intrinsic) vibrations of the porous environment, which, in turn, lead to disruption of continuity, going with the formation of a network of microcracks.

Implementation of these trends is connected with obtaining discrete pulse energy of high power in a liquid flow with the help of special hydraulic channel of the Venturi high-amplitude oscillations in the range of sound frequencies. It is achieved only due to the corresponding channel geometry, without any moving parts and additional sources of energy.

Cavitation is used in various technological processes [2].

High-frequency cavitation self-oscillations, being of impact nature in a hydraulic system with local hydraulic resistance of the Venturi type, was studied in a wide range of geometric dimensions of a flowing part of the generator.

At the constriction, the kinetic energy of the liquid increases at the expense of pressure; and with effective throttling, pressure reduces below the vapor pressure of the liquid at the vena contracta, causing flashing of the liquid and generating numerous vapor cavities. Subsequently, as the liquid jet expands, the velocity decreases and the pressure recoveries in the downstream section of the cavitating device resulting in the collapse of cavities (Fig. 1) [3].

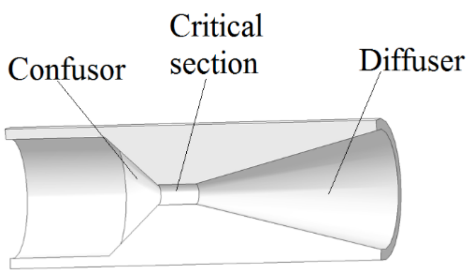

Fig. 1. Scheme of a Venturi tube

A Venturi tube with special geometric parameters was called a cavitation generator (CG), which scheme is shown in Fig. 1. Pressure drop below some critical pressures due to large local velocities in the flow of a moving droplet liquid in a narrow section conducts to rupture of continuity and the formation of a cavity. This cavitation is called hydrodynamic one.

The evolution of well drilling techniques is inextricably linked with the improvement of drilling/washing fluids that are the complex heterogeneous poly-disperse systems. The variety and, sometimes, contradictory character of the 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 dispersion: fineness (specific surface) and uniform distribution of the dispersed phase in the dispersion medium [4].

Orifice and Venturi-based HC devices are found to be the most efficient in creating an intense cavitation condition. The cavitation in an orifice is transient in nature, whereas the cavitation in a Venturi tube is mostly stable because of its geometrical configuration [4].

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 motion, the kinetic stability factors are variance (the most important factor, the higher the variance is, the higher stability is), 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.

Cavitation through hydrodynamic means can also be generated by rotation of an object in a fluid at sufficiently high speeds. High speed homogenizer (HSH) is one of such devices, which can create cavitation conditions. It consists of an impeller or rotor (driven by motor) and a stator. Droplet breakup is achieved by the tensions produced by the liquid flow induced by the rotor and its impact against the stator [5].

While preparing the washing fluids using existing methods, it is impossible to reach full dispersion of a dispersed phase. Therefore, further dispersion of the dispersed phase of washing fluids using different dispersants is an important problem to be studied. Dispersing enables reducing the amount of a solid phase in the washing liquid preserving specified structural and mechanical properties. The lower the quality of the clay is, the greater the dispersion effect is [6-8].

Statement of the problem. The rheological properties of the washing liquid play a determining role in the successful implementation of drilling operations, e.g. it is viscosity, which is the main technological property of washing liquids. These properties influence mainly the technical and economic indicators of drilling wells. Unsatisfactory rheological properties can lead to serious complications: formation of plugs in the wellbore, reduction of the mechanical drilling speed, erosion of the shaft walls, crossing of a drill string, absorption of the washing liquid etc. The rheological properties of the washing liquid can influence in three ways:

- change in the dispersed phase composition;
- use of chemical reagents;
- in terms of the dispersion degree of the dispersed phase already present in the solution.

In the process of drilling wells, the technological properties of washing liquids deteriorate due to the transition of drill cuttings to the solution: face cleaning is deteriorating, hydrodynamic resistance and pressure losses in the well circulation system increase.

A high degree of fragmentation of the dispersed phase in washing liquids causes the interface development. Therefore, control of the technological properties of washing liquids is associated, first of all, with a complex of phenomena on the surfaces of solid particles in the dispersion medium. In order to have a large area in the wash fluid, it is necessary to ensure a high fragmentation degree of the dispersed phase. This can be achieved in two ways: by crushing pieces of some substance into the desired dispersion or by combining molecules and ions into aggregates of the appropriate size [9-11].

Results and Discussion. The analysis has shown that supercavitation is the most promising technique for treatment of washing fluids [12-14]. Supercavitation occurs when axisymmetric bodies are flowed around by liquid [15-17]. The operating principle 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 [18, 19]. 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 cavitation bubbles (Fig. 2).

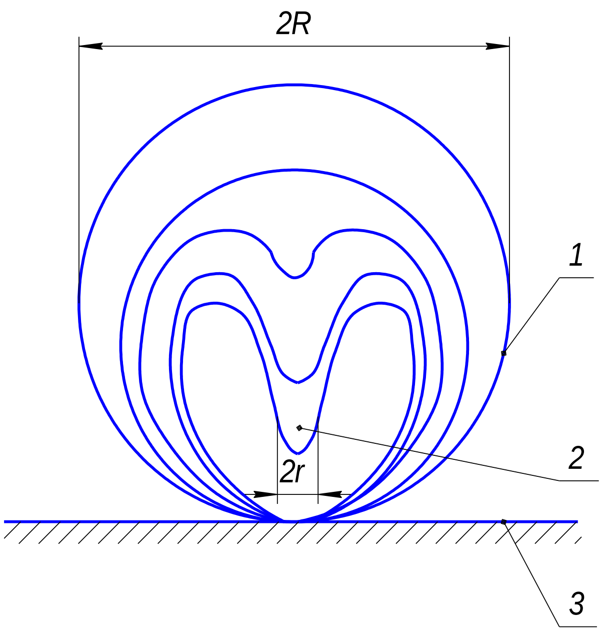

Fig. 2. Scheme of the formation of a cumulative trickle at the collapse of a cavitation bubble: 1 – cavitation bubble; 2 – drop cumulation; 3 – surface of the disperse phase particle

Sudden pressure and velocity variation cause dynamic cavity oscillations, and as the cavity collapses, certain physical and chemical effects occur in its vicinity leading to the desired transformations. Also, the type of cavity collapse controls the desired transformation. Mahulkar and Pandit (2010) highlighted two conditions of cavity collapse: symmetric and asymmetric. The cavity may remain spherical till the point of collapse or nonspherical because of the presence of interface at the boundary wall or other particle/bubble surface near the oscillating cavity. The formation of reactive free radicals and the thermal pyrolysis of organic molecules are favorable under spherical collapse, i.e. symmetric collapse, which are essential for chemical transformations. By contrast, nonspherical collapse, i.e. asymmetric collapse, produces high-velocity liquid jets and intense local turbulence, which are beneficial for physical transformation.

For calculating basic parameters of cavitation disperser, the Bernoulli equation and the continuity equation for sections 0–0 and 1–1 (Fig. 3) were solved.

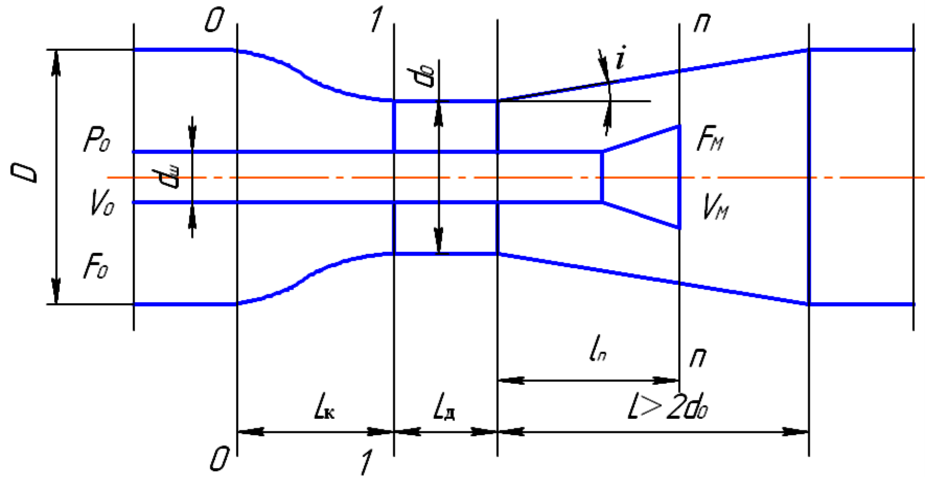

Fig. 3. Diagram of a cavitation disperser

Cavitation can be used efficiently for the formation of small size droplets. Cavitation is the phenomenon of formation, growth, and violent collapse of the cavities in a liquid, resulting in the release of energy instantaneously for very small durations and over very small locations. The shock waves of the collapse, along with the generated turbulence, leads to breakage of the droplets within a cavitation zone. Based on these effects, cavitation plays an important role in the process of emulsification. Cavitation can be generated numerous ways, among which cavitation generated by the pressure/flow variation (hydrodynamic cavitation) and ultrasound (US) (acoustic cavitation) are of great interest. Ultrasonic emulsification devices use high-intensity sound waves to generate pressure variations within the liquid that helps in droplet disruption.

Ultrasound-assisted emulsification has emerged as an advantageous method in terms of the required characteristics for the mean droplet size, particle size distribution, stability, ability to process different types of emulsion, and energy consumption. Ultrasonic reactors which are considered feasible for large scale operation include ultrasonic bath (a reactor using multiple transducers) and ultrasonic flow cell (a reactor operating in a continuous mode with the transducers attached to the wall). Cavitation through hydrodynamic means is generated by flow variations in a fluid introduced by the passage through a constriction (such as orifice plate, valve or Venturi tube) in a pipe. The cavity collapse near a liquid-liquid interface creates a microjet that is focused at the interface leading to droplet disruption.

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

where H is pump pressure, p is density of washing fluid, and Δh_{0-1} is losses in a confusor; $Q_0 = Q_1 = Q_i$, $V_0F_0 = V_1F_1 = V_iF_i$, where F_0, F_1, F are respective cross sections;

$$\Delta h_{0-1} = \frac{\xi_c \cdot \rho \cdot V_1^2}{2}, \tag{2}$$

where ξ_c is coefficient of hydraulic losses in a confusor.

When transiting from the wide section of a 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 (Fig. 3).

The angle of a diffuser slope is defined assuming that there is no cavitation on the walls of a generator; according to the recommendations, the diffuser slope angle is $y < 25°$, the diffuser section length is $L > 2d$.

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

$$\Delta h_c = \xi_{cav} \frac{\rho \cdot V_{cav}^2}{2}, \tag{3}$$

where V_{cav} is velocity at the place of cone flow fluid in the diffuser.

The total losses on a cavitation disperser are:

$$\Delta h_{kd} = (\xi_c + \xi_d + \xi_z)\frac{\rho \cdot V_z^2}{2} + (\xi_{cav})\frac{\rho \cdot V_{cav}^2}{2}, \tag{4}$$

where ξ_{cav} is coefficient of hydraulic losses on the cavitator.

The intensity of cavitation treatment should depend on geometric characteristics of supercavity, 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 diffuser, in order to describe the intensity of hydrodynamic cavitation, flow suppression coefficient kc is introduced: where n-n are cross sections of the cone and the diffuser, respectively; D_c, D_d are base diameters of the cone and the diffuser, respectively.

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

$$k_c = \frac{F_c}{F_\mathrm{d}} = \frac{D_c^2}{D_d^2}. \tag{5}$$

The flow suppression coefficient varies within the range of $k_c = 0.6\text{-}0.8$, since in this context the intensity of rate fluctuation is maximum, which enables controlling the intensity of cavitation effect within a wide range.

$$V_c = \frac{Q}{0{,}785 \cdot d_c^2 \cdot (1/k_c - 1)}, \text{ м/с} \quad (6)$$

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

The nature of cavitation oscillations occurring during the cone flow is similar to that of phenomena known in hydrodynamics as Strouhal frequencies. For these oscillations, a linear dependence of frequency on the rate of approach flow and an inverse dependence on specific dimension (hydraulic diameter) are typical:

$$f = \frac{Sr \cdot V}{d_g}, \quad (7)$$

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 of $200 < Re < 200{,}000$ the empirical law of Strouhal number constancy is $Sr = 0.2\text{-}0.3$. The final formula for calculating the frequency of cavitation oscillations is:

$$f = \frac{Sr \cdot Q}{0{,}785 \cdot d_c^3 (1/k_c - 1)(1/\sqrt{k_c} - 1)}, \text{ Hz.} \quad (8)$$

In view of the research, an experimental model of a cavitation disperser was developed with the confirmed Ukrainian patent novelty (Fig. 4.).

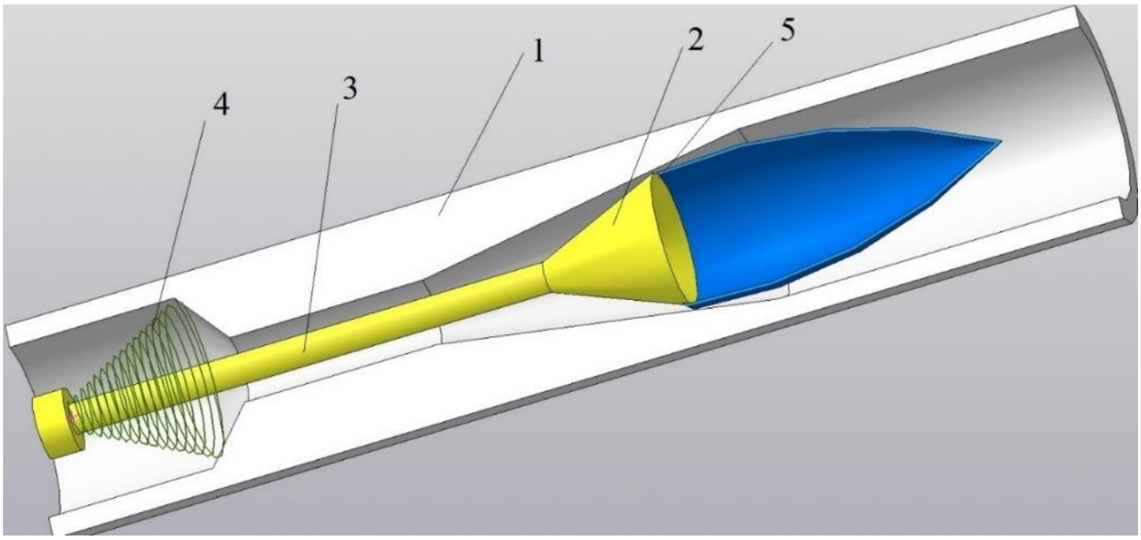

Fig. 4. Cavitation disperser

Formation of a cavity in a cavitation generator (SolidWorks) is shown in Fig. 5. The cavitation cavity itself (SolidWorks) is represented in Fig. 6.

Drilling fluid on the discharge line enters a cavitation disperser. When flow around the cone section is formed, in which liquid drip completely absent, supercavities are generated. To be able to regulate operational parameters of a cavitation flow, a dispersant cone is configured to axial movement. The supercavity size depends on the flow rate.

In the new design, the stem of the cone-wrapping is not fixed rigidly but put on a special spring 4, with certain stiffness, which ensures free movement of the cone-flow in the diffuser of a cavitation disperser. The edge of the cone of flow is provided with toothed notches 5, which increase its contact area with the flowing disperse system and also provide for additional grinding of the large dispersed phase by dissection.

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

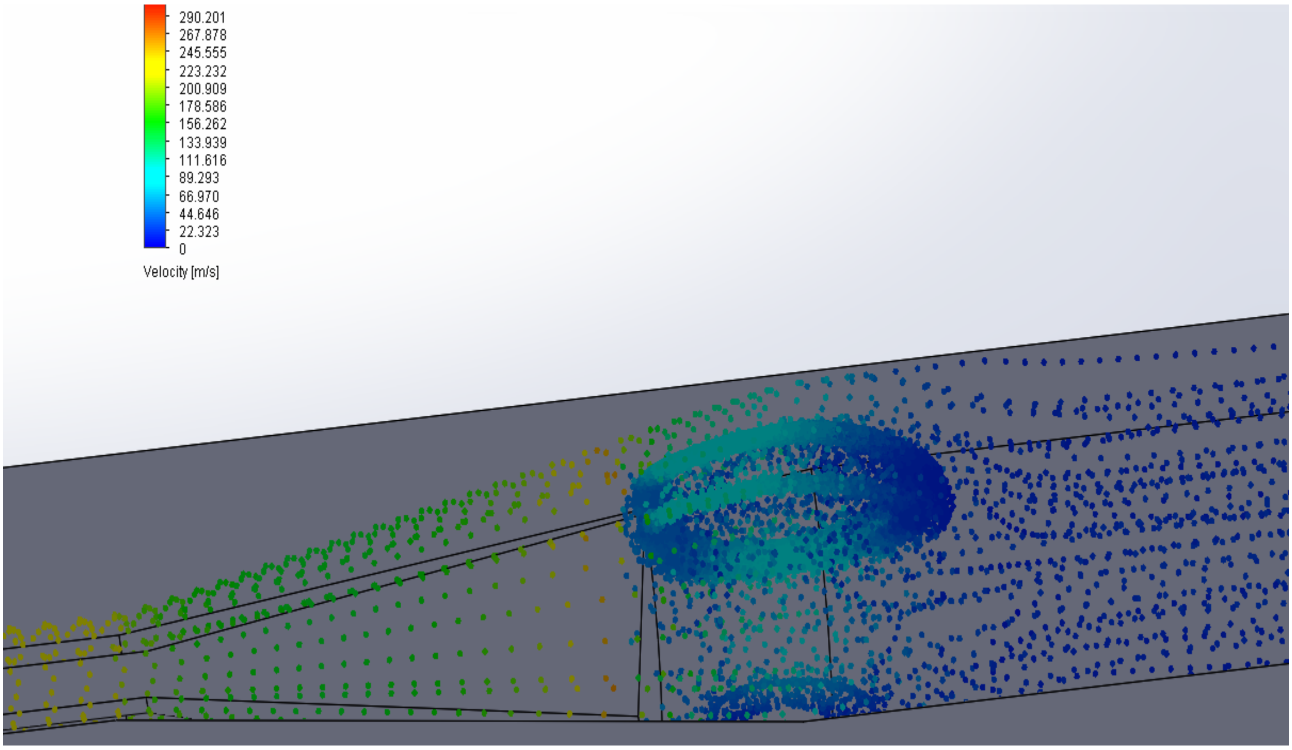

Fig. 5. Formation of a cavity in a cavitation generator (SolidWorks)

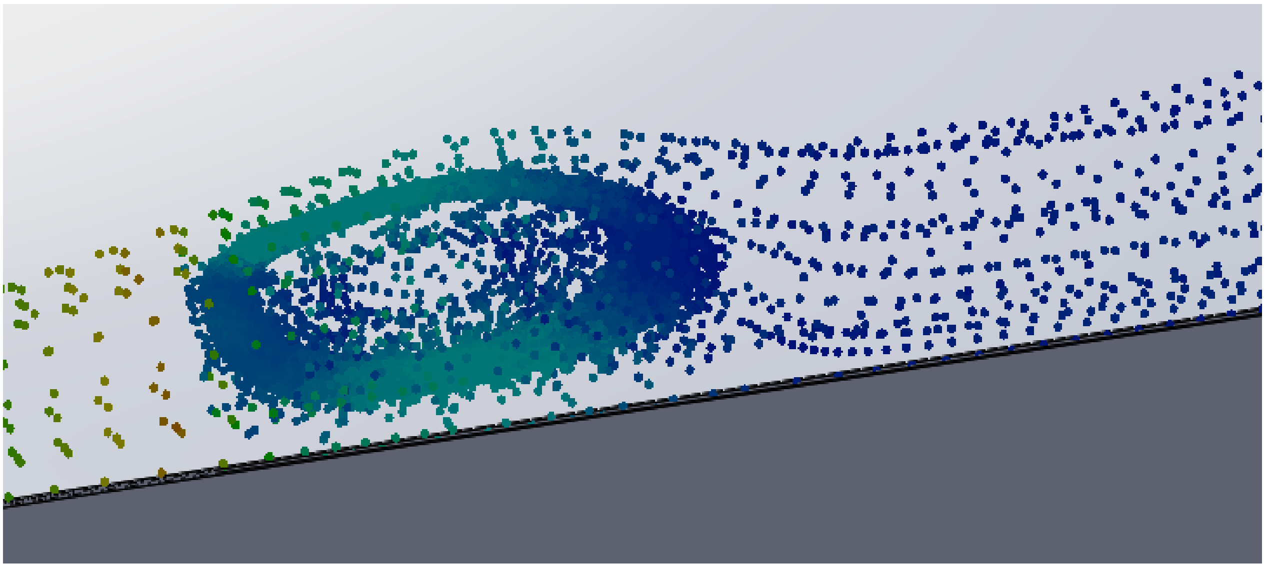

Fig. 6. Cavitation cavity (SolidWorks)

Fig. 7 shows the results of tests of frequency dependence of a cavitation disperser at a pumping rate of $Q = 0.001$ m^3/s. The difference between the experimental and theoretical data ranges in terms of 10%.

The time required for the dispersion of all particles of the dispersed phase is determined by the formula:

$$T_i = \frac{1}{l_0^2 \cdot f \cdot \left(\frac{\sqrt{(4 \cdot \rho_k \cdot (R^2 - R \cdot r) + \rho_k \cdot r^2 - \rho_c \cdot R^2) \cdot P_\partial} \cdot (R - r)}{4 \cdot \rho_k \cdot (R^2 - R \cdot r) + \rho_k \cdot r^2 - \rho_c \cdot R^2} \right)} \times \frac{\left[1 - \left(\frac{1}{n} \right)^{i-1} \cdot \frac{1}{n} \right]}{\left(1 - \frac{1}{n} \right)} \quad (9)$$

Dependence of the dispersion time on the frequency of the cavitation oscillations per one processing cycle is shown in Fig. 8.

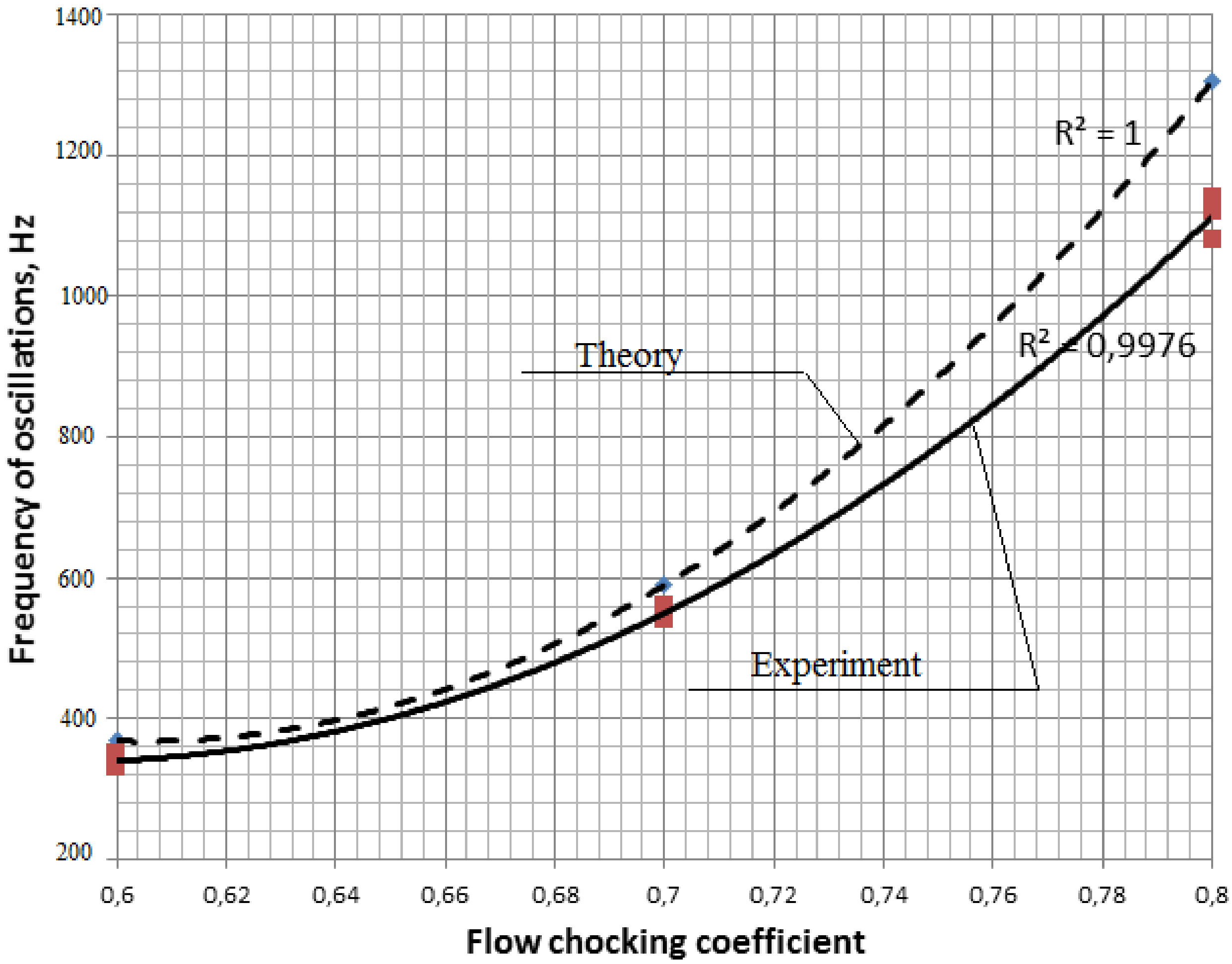

Fig. 7. Dependence of the frequency of cavitation oscillations on a flow suppression coefficient at $Q = 0.001$ m^3/s

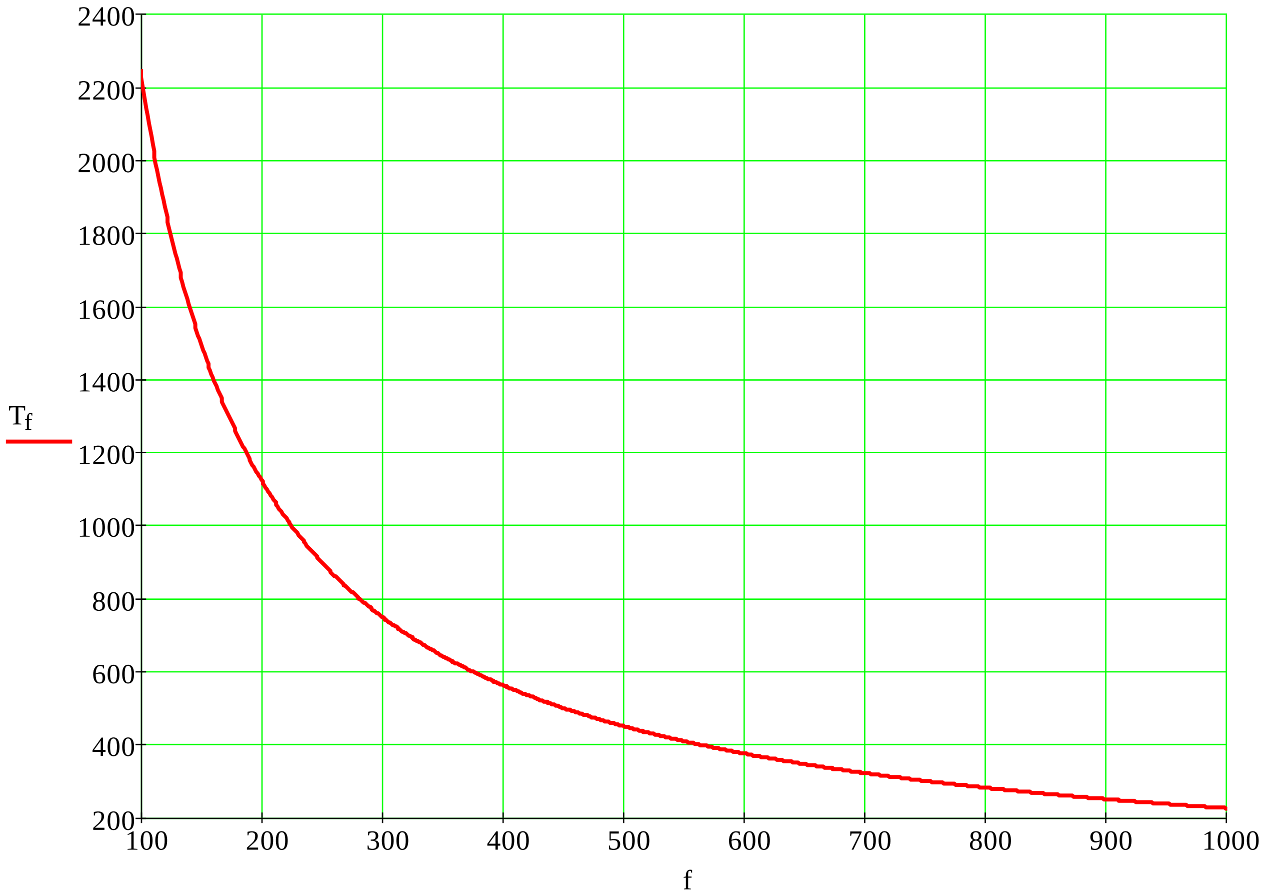

Fig. 8. Dependence of dispersion time T_f (s) on the frequency of cavitation oscillations f (Hz) per one treatment cycle

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 supercavitation.

The dispersion time is inversely proportional to the number of cavitation bubbles in the flow (frequency of cavitation oscillations) produced per time unit.

The hydrodynamic supercavitation, occurring when the fluid flows around axisymmetric bodies, has been substantiated to be the most promising technology in terms of energy efficiency for the preparation of washing fluids.

A new design of a cavitation disperser has been developed; its novelty has been certified by the patent of Ukraine.

The flow suppression coefficient kc is the key controllable parameter influencing the intensity of cavitation treatment.

The cavitation disperser enables the effective dispersion of washing liquid components and can be commercialized in the drilling practice.

The most rational value of the blocking factor (from the viewpoint of minimum hydraulic resistances) for the operation of the cavitation disperser is within the range of 0.6-0.8.

On the basis of theoretical studies, it has been established that the dispersion time of the disperse phase for a single treatment cycle is inversely proportional to the frequency of cavitation oscillations.

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АНОТАЦІЯ

Мета. Вдосконалення технології виготовлення бурових розчинів за рахунок застосування гідродинамічної кавітації.

Методика дослідження. Теоретичні та експериментальні дослідження гідродинамічної кавітації, виконано із застосуванням сучасних методів аналітичного аналізу і експериментальних досліджень, зокрема шляхом використання загальних принципів математичного та фізичного моделювання, методик обробки результатів досліджень у середовищах EXCEL, SolidWorks для подальшого їх аналізу.

Результати дослідження. Отримано розрахунок частоти кавітаційних коливань за параметрами пристрою для створення гідродинамічної кавітації. Теоретично обґрунтовано та отримано формулу для визначення часу диспергування матеріалу промивної рідини за частотою кавітаційних коливань. Досліджено процес переміщення бурової рідини у пристрої за допомогою відповідного програмного забезпечення у пакеті SolidWorks. Результати теоретичних досліджень були підтверджені практичними дослідженнями та були обрані основою для обґрунтування та розробки методики приготування бурових рідин.

Наукова новизна. Виконано моделювання та досліджено процес гідродинамічної кавітації в кавітаційному пристрої за допомогою візуалізації потоку із застосуванням програмного забезпечення SolidWorks. Такий підхід допоміг обґрунтувати та спрогнозувати тиск та швидкість потоку в кожній точці переходу діаметрів кавітаційного диспергатора. Це у свою чергу надало можливість за його допомогою зменшити гідравлічний опір та удосконалити конструкцію пристрою для реалізації технології приготування бурових розчинів за рахунок гідродинамічної кавітації. Такий підхід дозволив обґрунтувати та виконати віртуальні експерименти щодо технології приготування бурових розчинів, що дало змогу обрати раціональні конструктивні параметри кавітаційного диспергатора та у значній мірі заощадити кошти й час на виготовлення стендових зразків пристрою, зокрема різними конструктивними характеристиками.

Практичне значення. За результатами теоретичних та експериментальних досліджень обґрунтовано та запропоновано розробку удосконаленої технології приготування стабільних бурових розчинів за рахунок застосування раціональних показників гідродинамічної кавітації.

Ключові слова: *спорудження свердловин, свердловина, метод диспергування, кавітація, буровий розчин, гідродинамічна суперкавітація, кавітаційний диспергатор.*