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DETERMINING FOAMING REGULARITIES ENABLED BY A FIVE-NOZZLE FOAM GENERATOR FOR DRILLING TECHNOLOGIES UNDER CONDITIONS OF ABNORMALLY LOW PRESSURES

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When studying the construction of oil and gas wells, it was found that the volume of drilling wells with abnormally low reservoir pressures increases over the years. This is due to significant difficulties such as a large absorption of drilling mud, possible clogging of a productive reservoir with drilling mud, and a failure to obtain the expected effect. These complications can be prevented by using gas-liquid mixtures as drilling mud, which have a number of advantages compared to washing liquids and make it possible to eliminate the above-mentioned negative phenomena. When opening productive horizons at low anomaly coefficients, foams must be used to flush wells. It has been established that at present in the practice of drilling oil and gas wells with foam there is no equipment that makes it possible to form foam with certain specified structure and dispersion. The use of a modernized foam generator for the preparation of foam has been proposed. To study the foaming process, computer modeling was carried out, with the help of which the processes that take place during the movement of flows of liquid, gas, and gas-liquid mixture along the foam generator were investigated, namely the distribution of pressure and speed in the longitudinal cross-section of the foam generator under changing boundary conditions, that is, at a pressure in the supply pipe of 10 and 7.5 MPa.

Computer studies have confirmed the possibility of using an improved foam generator design to increase the efficiency of foaming. The results could be the basis for the development of foam generators and their experimental and industrial research and testing

Keywords: foam, modernized five-nozzle foam generator, foaming, gas pressure, mixture speed

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1. Introduction

Drilling oil and gas wells in porous and unstable rocks is associated with significant difficulties, namely:

– large absorption of drilling mud, even to catastrophic, and the associated significant costs for the supply of chemicals, the preparation of washing liquids, the descent of intermediate columns, tamponage work, etc.;

– the erosion of unstable rocks with drilling mud, which does not make it possible to obtain a high-quality core for geological research;

– occurrence in the process of drilling wells of complications associated with erosion of well walls, cavern formation, accumulation of sludge on the faces, grabbing and jamming of the drilling tool, etc.;

– when opening oil and gas horizons, it is possible to block the productive reservoir with drilling mud and not receive the expected effect.

These complications can be prevented by using gas-liquid mixtures as drilling mud, which have a number of advantages compared to washing liquids and make it possible to eliminate the above-mentioned negative phenomena.

When opening productive horizons with an anomaly coefficient lower than 1.0, it is necessary to use aerated liquids with impurities of surfactants (SAS) for washing, and at low anomaly coefficients – foams and gaseous agents [1–3].

The most common in the oil and gas industry are aerated liquids and foams. When drilling by washing the face with foams compared to drilling fluids, the mechanical drilling rate in solid rocks increases (approximately by 4 times), it is possible to prevent absorption in porous and cracked rocks and clogging of permeable layers. When opening and mastering productive horizons, the productivity of the well increases by 1.5–2 times with a simultaneous reduction in development time by 4–5 times.

The foaming process is complex since the formation of high-quality foam is influenced by physicochemical, physicaltechnical, and other factors. As a rule, foam generators of various designs and principles of operation are used to obtain foam. Currently, in the practice of drilling oil and gas wells with foam, there is no equipment that makes it possible to form foam with certain specified structure and dispersion.

All this confirms the relevance of the task and the need for further research work aimed at increasing the efficiency of the foam system during the drilling process with foamy solutions.

2. Literature review and problem statement

Analyzing the results of work on the construction of oil and gas wells, it is clear that the volume of drilling wells with abnormally low reservoir pressures increases over the years. To study the geological structure in promising areas of Western Ukraine, drilling of exploration wells was carried out in the Kolomyia, Hutsulovskaya, Debeslavetska, and Starobohorodchanska areas. Analyzing the complications in the process of drilling wells [1], it was found that they are associated with unstable sediments of the unproductive (upper) part of the section and abnormally low reservoir pressures in them, which leads to collapses of the well walls, the formation of cavities, water gaps, acquisitions and grabbing of the tool due to pressure drop. Drilling conditions indicate the need for their construction using a flushing fluid of reduced density. Such a liquid can be obtained using any aeration, which makes it possible to adjust the density of the washing fluid within wide limits and thereby reduce or increase the hydrostatic pressure on the face [2]. When opening productive horizons with an anomaly coefficient lower than 1.0, it is necessary to use aerated liquids with impurities of surfactants (SAS) for washing, and at low anomaly coefficients – foams and gaseous agents [3]. The initial opening of the layers using foam as a washing agent makes it possible to get a minimum clogging value, and the use of foams can reduce the absorption of the filtrate of the washing liquid. A common foam formation technique is dispersion, which is based on intensive mixing of the foam-generating solution and air, namely the ejection of air by a jet of liquid using foam-generating ejector devices. To study the process of foaming with a single-nozzle ejector, a three-dimensional model of the device using the SolidWorks program was developed [4]. However, when large volumes of foam are supplied to the well, single-nozzle foam generators are ineffective since the process of mixing liquid with air will be of poor quality due to the production of insufficiently dispersed foam. Using structural analysis [5], the block diagram of a five-nozzle foam generator was selected and multi-nozzle foam generating devices were developed [6], devices of optimal design and geometric parameters, which are selected taking into consideration the conducted computer research [7]. The disadvantage of this device is that it does not provide sufficient efficiency of saturation of the liquid with air due to the small area of their contact in the ejector insert, and therefore does not enable proper mixing of the viscous flushing fluid with air during the initial process of mixing the liquid with air. The development of recommendations for the use of foaming surfactants (SAS) in the general task for layers with abnormally low reservoir pressures is given in [8]. However, there are no recommendations on the use of the proposed surfactants when creating a foam mixture. The improved design of the foam generator to increase the efficiency of foaming using a liquid and air mixer [9] ensures high efficiency by increasing the range of properties of the foam mixture at the outlet, without changing the pressure and supply of liquid and air at the inlet to the foam generator. The design of the liquid and air mixer is made such that it allows the simultaneous supply of liquid and air to the pre-mixing chamber, where fields of developed turbulence are created in the mixing working area [10–14]. However, there are no technological solutions to confirm these advantages. Therefore, in our work, we set the task of conducting computer studies of the improved design of the foam generator [14] and comparing them with the analog design [7] to confirm the declared advantages, which will make it possible to improve the efficiency of foaming.

3. The aim and objectives of the study

The purpose of this study is to devise conceptual solutions for foaming technology using a foam generator for pumping and circulation systems of drilling rigs under conditions of abnormally low reservoir pressures. This will increase the efficiency of such systems in the process of flushing wells with foams.

To achieve the set aim, the following tasks have been solved:

– computer studies at the pressure of the liquid at the inlet in the supply pipe of the foam generator of 10 MPa;

– computer studies at a fluid pressure at the inlet in the supply pipe of the foam generator of 7.5 MPa.

4. The study materials and methods

Analysis of existing practical solutions for the design of foaming devices used in the drilling and development of oil and gas wells makes it possible to optimize and more rationally simulate the structure of the foam generator, which in the future will enable maximum quality of foaming during drilling of wells, the depth of which reaches 5000 m.

The most rational foaming device is a multi-nozzle foam generating device such as PGP-100x25-5 [7].

Table 1

Technical characteristics of the foaming device PGP-100x25-5

No.	Indicator	Value
1	Maximum working pressure, MPa	25
2	Fluid pressure at the inlet, MPa	7.5, 10, 12
3	The maximum calculated pressure at the outlet, MPa	19–20.5
4	Coefficient of ejection, from	1.08
5	Overall dimensions, mm:	
	– length;	400
	– diameter	100

The upgraded foam generator [14] consists of a cylindrical housing 1, which houses a liquid and air mixer 2 with sealing rings 3, bushings 4 with pre-mixing chambers, an air supply channel 5, spacer rings 6 with individual parallel diffusers, clamping rings 7, a foam mixture twister 8 with guide blades, a common diffuser 9 with a turbulent mixing chamber. In the liquid and air mixer, there are vertical holes for supplying liquid 10 and horizontal ones 11 connected to vertical holes for air supply 12.

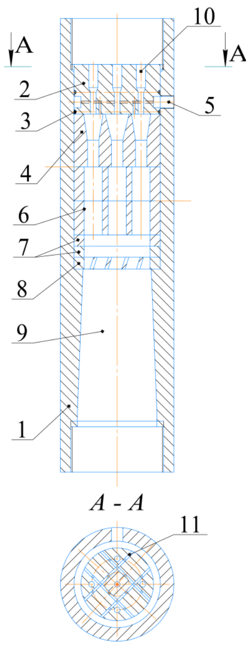

Fig. 1. Improved foam generator PGP-100x25-5:
1 – housing; 2 – liquid and air mixer; 3 – sealing rings;
4 – sleeve; 5 – channel for air supply; 6 – spacer rings;
7 – clamping rings; 8 – twister of the foam mixture;
9 – common diffuser; 10 – vertical holes for fluid supply;
11 – horizontal openings for air supply; 12 – vertical openings for air supply

Foam generator for saturation of liquid with air with subsequent foaming works as follows. The liquid enters housing 1 of the device and then, through holes 10 of the liquid mixer and air 2, the pre-mixing chamber 4. Compressed air is simultaneously supplied to the mixer through channel 5 in housing 1 and holes 11 and 12 of the liquid and air mixer 2.

After leaving the mixer, the air also enters the pre-mixing chambers 4, where fields of developed turbulence are created in the mixing working area. In the mixing chambers of spacer rings 6 and clamping rings 7 there is an intensive turbulization of jets, mixing of air with solution, and the formation of foam. Next, the mixture passes through the twister of foam mixture 8, which contributes to high-quality mixing and the formation of a foam mixture in the mixing chamber located in diffuser 9, where the liquid moves under a turbulent mode and the effect of liquid saturation with air and foaming is fixed.

To study the foaming process, computer studies have been carried out, since with their use it is possible to better investigate the processes that take place during the movement of flows of liquid, gas, and gas-liquid mixture along the foam generator compared to experimental studies. For research, the FlowSimulation software (USA) was applied, which is a SolidWorks application module, which makes it possible to change the input parameters of liquid and air in a wide range and provides objective information about the required parameter at any point of the foam generator. This program uses the method of finite volumes and non-stationary Navier-Stokes equations and heat transfer for numerical problem solving. The discretization of equations is carried out in a conservative form, partial derivatives are approximated with the second order of accuracy, time derivatives – according to Euler's implicit first-order scheme.

Table 2

Initial conditions

Thermodynamic parameters	Static pressure: 101325.00 Pa; Temperature: 293.20 K
Speed parameters	Velocity vector: – speed in the X direction: 0 m/s; – speed in the Y direction: –9.810 m/s; – speed in the Z direction: 0 m/s
Turbulence parameters	Intensity and scale of turbulence: – intensity: 2.00 %; – length: 0.001 m
Thermodynamic parameters	Full pressure 1.60e+07 Pa; Temperature type: temperature of the original components; Temperature: 293.20 K
Turbulence parameters	Intensity and scale of turbulence: – intensity: 2.00 %; – length: 0.001 m
Boundary layer parameters	Type of boundary layer: turbulent

Table 3

Ambient pressure

Type	Environmental pressure
Coordinate system	A coordinate system tied to a surface
Basic axis	X
Thermodynamic parameters	Ambient pressure: 101325.00 Pa; Temperature type: temperature of the original components; Temperature: 293.20 K
Turbulence parameters	Intensity and scale of turbulence: – intensity: 2.00 %; – length: 0.001 m
Boundary layer parameters	Type of final layer: turbulent

Table 4

Min/Max values

Indicator	Minimal	Maximal
Pressure [Pa]	22464.47	1.63e+07
Density (liquid medium) [kg/m^3]	0.31	192.21
Speed [m/s]	0	522.189
Speed (X) [m/s]	–219.739	211.135
Speed (Y) [m/s]	–157.952	159.655
Speed (Z) [m/s]	–522.027	130.490
Temperature [K]	154.54	318.00
Temperature (fluid medium) [K]	154.54	318.00
Vorticity [1/s]	1.23	135997.27
Speed in the rotating coordinate system [m/s]	0	522.189
Speed in the rotating coordinate system (*X*) [m/s]	–219.739	211.135
Speed in the rotating coordinate system (*Y*) [m/s]	–157.952	159.655
Speed in the rotating coordinate system (Z) [m/s]	–522.027	130.490
Mach number [ ]	0	2.10
Relative stress [Pa]	0	18231.65
Relative pressure [Pa]	–78860.53	1.62e+07
Heat flow non-collinearity indicator [ ]	1.5477947e–15	1.0000000
Thermal resistance indicator [ ]	5.1055861e–16	1.0000000
Heat transfer coefficient [W/m^2/K]	0	0
Heat convective flux density in the local coordinate system [W/m^2]	–1.522e+08	4.903e+08
Surface heat flux density [W/m^2]	0	0
Surface heat flux density (convection) [W/m^2]	0	0
Particle diameter [m]	9.996e–05	1.000e–04
Mass of particles [kg]	5.226e–10	5.226e–10
Relative velocity of particles [m/s]	0.095	601.240
Particle material density [kg/m^3]	998.15	999.22
Limit length of trajectories [m]	0	0.419
Limit time of trajectories [s]	0	0.023
Particle speed [m/s]	0.464	348.734
Particle velocity (*X*) [m/s]	–6.047	54.710
Particle velocity (*Y*) [m/s]	–105.922	25.113
Particle velocity (*Z*) [m/s]	–348.720	339.152
Particle temperature [K]	286.76	293.20
Trajectory *X* [m]	–0.029	0.029
Trajectory *Y* [m]	–0.040	0.026
Trajectory *Z* [m]	–0.176	0.228
Reynolds number for particles	51.1676728	66854.5438346
Acoustic power [W/m^3]	0	1549250.198
Sound power level [dB]	0	181.90

5. Results of the study of foam generators to increase the efficiency of pumping and circulation systems of drilling rigs in the process of flushing wells with foams

5. 1. Computer studies of modernized foam generators at a fluid pressure at the inlet in the supply pipe of 10 MPa

In the process of computer research of a modernized foam generator, an important factor is the achievement of the conditions for the formation of foam, set forth in [15]. At the end of the mixing chamber, a seal jump takes place, which is accompanied by the transformation of the airborne mixture into a liquid-bubble one. The compaction jump is characterized by a sharp increase in pressure. In order for it to occur, it is necessary that the speed of the airborne flow exceeds the speed of sound in it. The energy of working flow for the formation of a frothy solution will be the greater, the smaller the Mach number, that is, when the flow velocity approaches before the compaction jumps to the speed of sound in it. The speed of sound is recommended to be determined using a dependence plot of the speed of sound in the water-air mixture on the air content in it (Fig. 2) [15].

Studies of the input part of the modernized five-nozzle foam generator PGP-100x25-5 (Fig. 3) for comparison before and after the improvement of the mixing chamber were carried out under the following identical specified boundary conditions: fluid supply at the inlet, 0.01 m/s; liquid pressure at the inlet in the supply pipe, 10 MPa; pressure at the outlet of the device, 10 MPa.

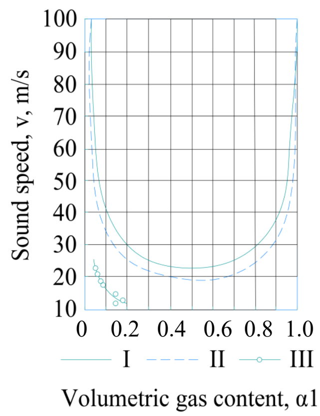

Fig. 2. Speed of sound in water-air mixture:
I – calculated values during the adiabatic process;
II – calculated values in the isothermal process;
III – experimental values on fine mixtures

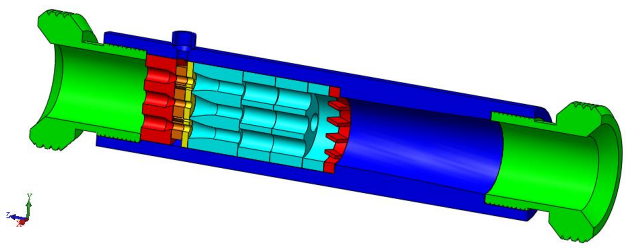

Fig. 3. Three-dimensional model of a five-nozzle foam generator of optimal design

Analysis of the graphical dependences of the distribution of pressure and speed in the longitudinal cross-section of the foam generator (Fig. 4, 5) shows that with the improvement of the mixing chamber, the maximum speed in the longitudinal cross-section of the device has significantly decreased (from 96 m/s to 80 m/s) and decreases to the speed of sound in the water-air mixture, which makes it possible to reduce the mixing chamber (from 0.2 to 0.13 m) where the compaction jump occurs (Fig. 4) and foam is formed.

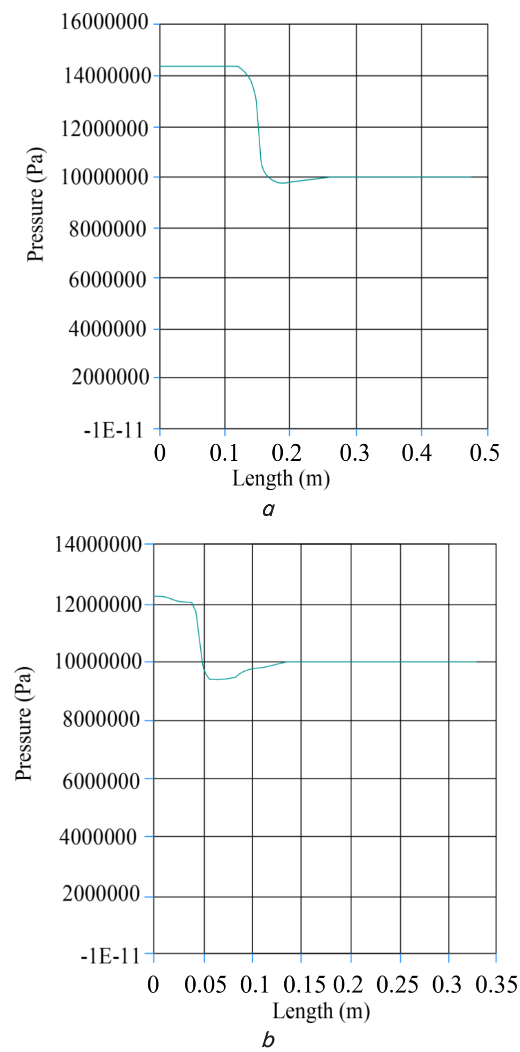

Fig. 4. Dependences of the pressure distribution in the longitudinal cross-section of the foam generator (air pressure at the inlet of 10 MPa): *a* – prior to improvement; *b* – after improving the design of the foam generator

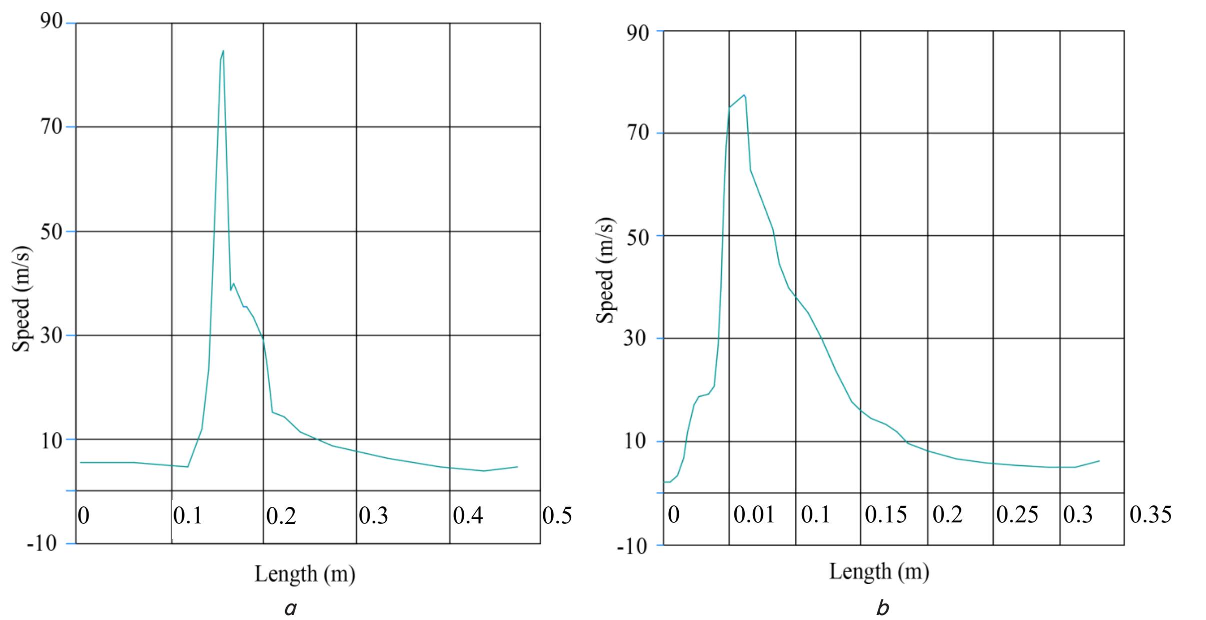

Fig. 5. Dependences of the speed distribution in the longitudinal cross-section of the foam generator (when fluid is supplied at an inlet of 0.01 m/s): *a* – prior to improvement; *b* – after improving the design of the foam generator

The compaction jump occurs, as in the analog at a mixture speed of 30 m/s, this speed according to Fig. 2 makes it possible to create foam with a volumetric gas content from 0.2 to 0.8.

Another significant advantage of the modernized foam generator according to the research is the possibility of obtaining a pressure at the outlet of 10 MPa with a significant decrease in air pressure at the inlet (from 14 to 12 MPa) (Fig. 4).

5. 2. Computer studies of modernized foam generators at a fluid pressure at the inlet in the supply pipe of 7.5 MPa

Further research of the five-nozzle foam generator was carried out under the following boundary conditions: liquid supply at the inlet, 0.02 m/s; liquid pressure at the inlet in the inlet nozzle, 7.5 MPa; pressure at the outlet of the device, 10 MPa (Fig. 6, 7). Fig. 7, 9 show the simulation results of the modernized foam generator in the Flow Simulation module of the SolidWorks software environment.

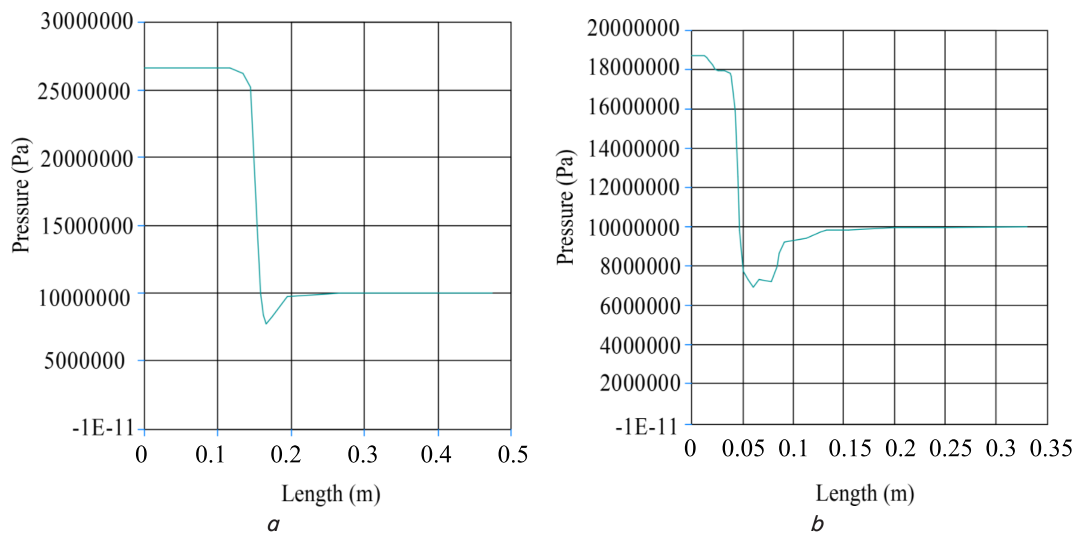

Fig. 6. Dependence of the pressure distribution in the longitudinal cross-section of the foam generator (pressure at the input of the device is 7.5 MPa): *a* – prior to improvement; *b* – after improving the design of the foam generator

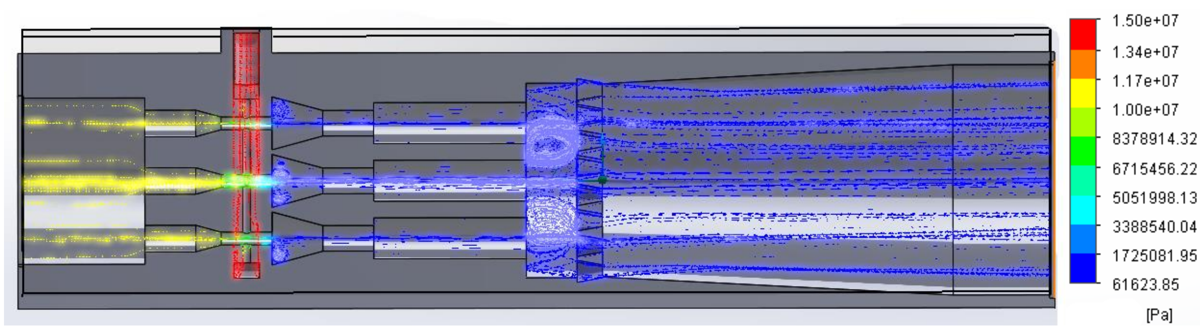

Fig. 7. Modeling the pressure field in the longitudinal cross-section of the foam generator

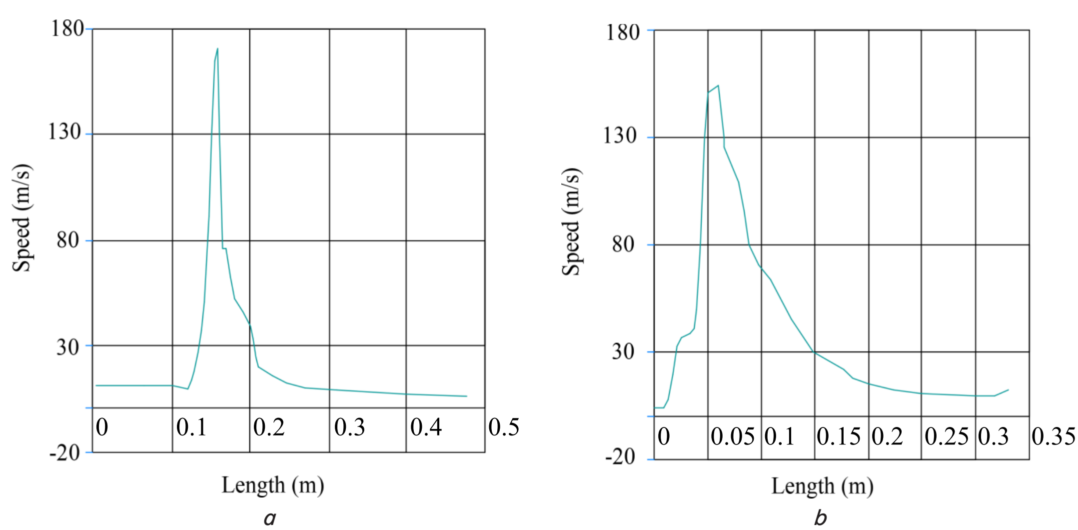

Fig. 8. Dependence of the speed distribution in the longitudinal cross-section of the foam generator (when fluid is supplied at the inlet of 0.02 m/s): *a* – prior to improvement; *b* – after improving the design of the foam generator

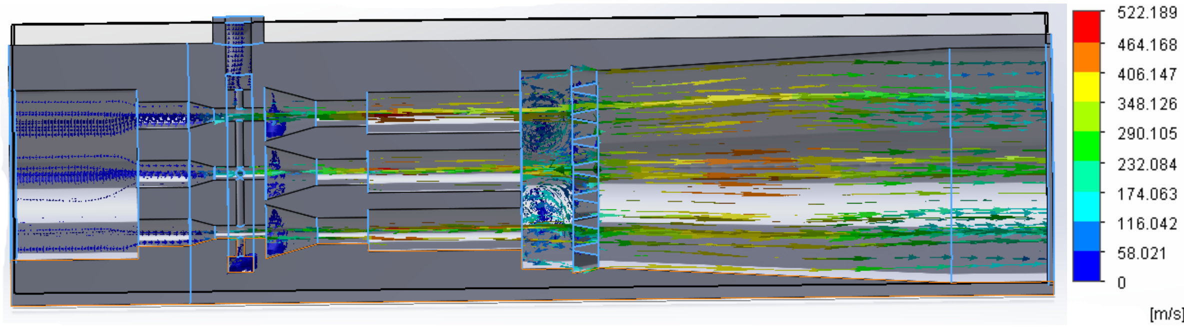

Fig. 9. Modeling the velocity field in the longitudinal cross-section of the foam generator

Analysis of the graphical dependences of the distribution of pressure and speed in the longitudinal cross-section of the foam generator (Fig. 6–9) shows that with the improvement of the mixing chamber when the boundary conditions change, that is, the pressure in the supply pipe decreases to 7.5 MPa, the pressure at the outlet of the device is 10 MPa, and with an increase in the fluid supply at the inlet to 0.02 m/s, the maximum speed in the longitudinal cross-section of the device has significantly decreased (from 177.7 m/s to 159 m/s) and decreases to the speed of sound in the water-air mixture, which makes it possible to reduce the mixing chamber (from 0.2 to 0.15 m) where a compaction jump occurs (Fig. 6) and foam is formed. The compaction jump also occurs, as in the previous study, at a speed of 30 m/s. In this case, the air pressure at the inlet (from 27 to 18 MPa) is significantly reduced, which causes less pressure in the supply pipe.

6. Discussion of results of studying the improved foam generator for drilling wells with abnormally low reservoir pressures

In the process of conducting computer studies of a five-nozzle foam generator under different modes of its operation, graphical dependences of the required air pressures at the entrance to the device were obtained depending on the projected value of the foam pressure at the outlet, as well as the set pressure of the liquid at the inlet. Our results are represented in the form of dependences of pressure distribution in the longitudinal cross-section of the foam generator (Fig. 4, 6) and dependences of the speed distribution in the longitudinal cross-section of the foam generator (Fig. 5, 8).

The studies were carried out using a five-nozzle foam generator of optimal design [10], in which the mixing chamber with the conical receiving part, different lengths of the mixing chamber, and the length of the cylindrical part of the mixing chamber is 1...1.5 of its diameter. The foam generator has the possibility of replacing nozzles of different diameters within 4...8 mm, which shows high efficiency for the specified conditions of their use. The length of the cylindrical part of the nozzle was taken equal to 1...2 of its diameter.

The results confirm the advantages of the improved design of the foam generator [14] since when comparing them with the analog design [7], a significant decrease in air pressure at the inlet was obtained (Fig. 4, *a, b*) and (Fig. 6, *a, b*), which will allow the use of compressors of lower pressure. At the same time, there is a jump in compaction, which is accompanied by the transformation of an airborne mixture into a liquid-bubble mixture (Fig. 4, *b*, 6, *b*). This is confirmed by the dependence of the speed distribution in the longitudinal cross-section of the foam generator (Fig. 5, *b,* 8, *b*) because the speed of the airborne flow at the point of the compaction jump exceeds the speed of sound in it. Turbulence occurs along the movement of the liquid (Fig. 7, 9), indicating the effectiveness of the saturation of the liquid with air.

Such advantages of the modernized foam generator [14] are obtained by introducing a modified ejector insert into its structure, which enables proper mixing of the liquid with air during the initial process of mixing them. A foam mixture twister is also installed, which contributes to high-quality mixing and the formation of a foam mixture in the mixing chamber. Thus, studies have proven the effectiveness of the modernized design of the foam generator.

In the process of using a modernized foam generator, it is important to take into consideration the real limits and conditions of use, namely, taking into consideration its technical characteristics (Table 1). The maximum working pressure of the foam generator is 25 MPa, and in the studies of the analog (Fig. 6, *a*) at the pressure of the liquid at the inlet in the supply pipe of 7.5 MPa, and the air pressure at the inlet is 27 MPa. This indicates the impossibility of using an analog under such modes. The upgraded foam generator is operational under such operating modes (Fig. 6, *b*) since the air pressure at the inlet is 18 MPa. In further research, it is important to comply with the requirement that in order for a compaction jump to occur, and therefore the formation of foam, it is necessary that the speed of the airborne flow at the point of the seal jump exceeds the speed of sound in it.

Further research should be directed to the creation of graphical dependences of the required gas pressure at the inlet to the foaming device on the projected value of the foam pressure at the outlet at different inlet and liquid pressure. These graphic dependences will make it possible to select the necessary operating modes of the pumping unit and compressor to obtain foam of the specified parameters. The obtained results will be the basis for experimental and industrial research and testing of foam generators.

7. Conclusions

1. In the process of studying the modernized design of the foam generator at the liquid pressure at the inlet in the supply pipe of 10 MPa, its advantages over the analog for foaming technology for pumping and circulation systems of drilling rigs under conditions of abnormally low reservoir pressures were proved. The result is explained by the structural features of the modernized foam generator, in which the ejector insert is changed, which enables proper mixing of the liquid with air at the initial process of mixing them.

A foam mixture twister is also installed, which contributes to high-quality mixing and the formation of a foam mixture in the mixing chamber. A significant advantage of the modernized foam generator according to the research is the possibility of obtaining a pressure at the outlet of 10 MPa with a significant decrease in air pressure at the inlet (from 14 to 12 MPa) at a liquid pressure in the inlet pipe of 10 MPa.

2. Further studies of the five-nozzle foam generator at a fluid pressure at the inlet of 7.5 MPa confirmed its advantages over the analog for foaming technology for pumping and circulation systems of drilling rigs under conditions of abnormally low reservoir pressures. According to the studies, it is possible to obtain a pressure at the outlet of 10 MPa with a significant decrease in air pressure at the inlet (from 27 to 18 MPa) with a liquid pressure in the inlet pipe of 7.5 MPa. Our result makes it possible, after additional research, to give a recommendation for the development of a modernized design of the foam generator for its experimental and industrial testing.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

References

1. Marukhniak, V. M. (2005). Heolohotekhnolohichni problemy rozkryttia horyzontiv z anomalno nyzkymy plastovymy tyskamy ta hranuliarnymy kolektoramy v Zakhidnomu rehioni Ukrainy. Mineralni resursy Ukrainy, 1, 35–37.
2. Tagirov, K. M., Gnoevykh, A. N., Nifontov, V. I. (1991). Burenie s promyvkoy penoy po germetizirovannoy sisteme tsirkulyatsii. Gazovaya promyshlennost', 8, 32–34.
3. Nesterenko, N. P., Savik, V. M., Lyakh, M. M. (2008). Vliyanie rabochikh parametrov penogeneriruyuschikh ustroystv na sokhranenie kollektorskikh svoystv produktivnykh plastov. PRACE Instytutu Nafty i Gazu: materialy konferentsii GEOPETROL 2008. Krakov, 693–698.
4. Savyk, V. M. (2012). Otsinka vplyvu heometrychnykh parametriv na efektyvnist roboty pinoheneruiuchoho prystroiu. Rozvidka ta rozrobka naftovykh i hazovykh rodovyshch, 2 (43), 173–188.
5. Savyk, V. M., Liakh, M. M., Vakaliuk, V. M., Solonychnyi, Ya. V. (2012). Analiz i ratsionalizatsiia konstruktsiyi pinoheneruiuchoho ustatkuvannia abo prystroiu. Rozvidka ta rozrobka naftovykh i hazovykh rodovyshch, 3 (44). Available at: http://nbuv.gov.ua/UJRN/rrngr_2012_3_9
6. Savyk, V. M., Liakh, M. M., Mykhailiuk, V. V. (2012). Pat. No. 77955 UA. Multi-nozzle foam-generating unit. No. u201205435; declareted: 03.05.2012; published: 11.03.2013, Bul. No. 5. Available at: https://uapatents.com/5-77955-pinogeneruyuchijj-pristrijj-bagatosoplovijj.html
7. Lyakh, M. M., Savyk, V. M., Molchanov, P. O. (2017). Experimental and industrial research on foamgenerating devices. Naukovyi visnyk natsionalnoho hirnychoho universytetu, 5 (161), 17–23.
8. Shendrik, O., Fyk, M., Biletskyi, V., Kryvulia, S., Donskyi, D., Alajmeen, A., Pokhylko, A. (2019). Energy-saving intensification of gas-condensate field production in the east of Ukraine using foaming reagents. Mining of Mineral Deposits, 13 (2), 82–90. doi: https://doi.org/10.33271/mining13.02.082
9. Isaev, Yu. M. (2008). Issledovanie techeniy v sisteme SOLIDWORKS. FLOWORKS. Uspekhi sovremennogo estestvoznaniya: nauchniy zhurnal, 4, 36–39.
10. Savyk, V. M. (2013). Pidvyshchennia efektyvnosti pinoheneruiuchykh prystroiv nasosno-tsyrkuliatsiynykh system burovykh ustanovok. Ivano-Frankivsk, 139.
11. Guo, B., Lyons, W. C., Ghalambor, A. (2007). Petroleum Production Engineering. Gulf Professional Publishing, 312. doi: https://doi.org/10.1016/B978-0-7506-8270-1.X5000-2
12. Amiyan, V. A., Amiyan, A. V. (1985). Povyshenie kachestva vskrytiya plasta. Obzornaya informatsiya. Ser. burenie. Moscow: VNIIOENG, 50.
13. Mysliuk, M. A. (2005). Do otsinky pervynnoho rozkryttia horyzontiv na rodovyshchakh Ukrainy. Naftova i hazova promyslovist, 6.
14. Savyk, V. M., Liakh, M. M., Mamyshov, N. K., Molchanov, P. O. (2016). Pat. No. 111893 UA. Pinohenerator. No. u201605132; declareted: 11.05.2016; published: 25.11.2016, Bul. No. 22. Available at: https://uapatents.com/4-111893-pinogenerator.html
15. Liakh, M. M., Savyk, V. M., Molchanov, P. O. (2016). Improving the efficiency of foamgenerating devices of pump-circulative systems of drilling sets. Naukovyi visnyk natsionalnoho hirnychoho universytetu, 3, 16–23.