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Denys Maryanov

CONTROL AND REGULATION OF THE DENSITY OF TECHNICAL FLUIDS DURING THEIR TRANSPORTATION BY SEA SPECIALIZED VESSELS

The object of research is the process of transporting drilling slurry through specialized marine vessels of the Platform Supply Vessels class. The subject of research is the sedimentation stability of the drilling slurry along the height of the cargo tank, which is proposed to be defined as a relative change in vertical density near the surface and bottom of the cargo tank. The studies were carried out on a specialized sea vessel with a displacement of 7320 tons. The design of the vessel provided for the reception and transportation of drilling slurry in four cargo tanks located on the port and starboard sides of the vessel.

It has been experimentally established that during the 48-hour transportation, the density of the drilling slurry in the bottom part increases to 19.7 %; decrease in density on the surface – up to 7.8 %; decrease in the sedimentation resistance of the drilling slurry along the depth of the cargo tank – up to 29.85 %. A variant of modernization of the drilling slurry transportation system by installing additional circulation pumps providing forced circulation of the drilling slurry between cargo tanks is proposed. By using programmable microcontrollers (performing turning on/off the circulation pumps), it is possible to provide the following conditions for transporting the drilling fluid: an increase in the density of the drilling fluid in the bottom part up to 0.3 %; decrease in density on the surface – up to 0.25 %; decrease in the sedimentation resistance of the drilling slurry along the depth of the cargo tank – up to 8.01 %. It has been experimentally established that the creation of additional circulation and automatic support of the sedimentation resistance of the drilling fluid in the range of 2–7 % contributes to:

– increasing the relative performance of cargo pumps from 38–55 % to 92–96 %;

– reducing the time of pumping drilling slurry from cargo tanks to the drilling platform from 7.1 to 3.2 hours;

– maintaining the technical condition of equipment, pipelines and elements of the drilling slurry transportation and pumping system.

Keywords: *specialized marine vessel, drilling slurry density, transportation system, sedimentation resistance.*

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1. Introduction

Transportation, which is carried out by sea transport vessels, is not limited to bulk, bulk and bulk cargo. Along with vessels of the Bulk Carrier, Oil Product/Crude Oil/Chemical Tanker, Container Ship with fuel and oil necessary for the operation of the power plant of the drilling platform, as well as special equipment and technical fluids that are necessary for the production process of oil production. The most common type of technical fluids that transport PSV to an oil platform is drilling slurries [1]. Their use allows solving a wide range of problems: filtration and cleaning of the drilling zone, reduction of contact stresses between the drill and the soil, lubrication and cooling of drilling equipment, prevention of gas phase ingress into the hydraulic line, prevention of corrosion of pipes and equipment. At the same time, drilling slurries should contribute to the safety of work and maintain the environmental safety of the marine area. To ensure maximum drilling productivity, as well as to maintain the functional properties of drilling slurries for a long time, special reagents are introduced into the composition of suspensions (which are based on hydrocarbons) (for example, solutions of $NaCl$, KCl, $CaCl_2$, $MgCl_2$ salts, as well as organic silicon compounds). The result of such alloying is the formation of a strong adsorption film on the rubbing surfaces and an increase in the anti-wear properties of the drilling slurry. The content of alloyed components in the total mass of the drilling slurry can be 10–15 %, and their specific gravity exceeds the specific gravity of the hydrocarbon base into which they are introduced [2, 3]. The presence of the drilling slurry in a static state during its transportation from the shore to the oil platform leads to the gradual deposition of heavier reagents on the

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bottom of the cargo tank. This leads to a stratification of the density of the drilling slurry along the depth of the cargo tank and a decrease in its sedimentation stability. In addition, the settling of the heavy components of the drilling slurry causes an increase in hydraulic resistance when it is pumped from the vessel's cargo tank to the drilling platform, and in some cases can lead to damage to the cargo pumps. Further removal of sediment from cargo tanks is carried out mechanically and requires additional energy and time, and the first and second increase financial costs and reduces the economic performance of PSV [4, 5].

Therefore, maintaining the performance characteristics of drilling slurries during their transportation by PSV-class sea vessels is an urgent applied scientific and technical problem, the optimal solution of which has not yet been found.

2. The object of research and its technological audit

The object of research is the process of transporting drilling slurry by specialized marine vessels of the Platform Supply Vessels class.

The subject of research is the sedimentation stability of the drilling slurry along the height of the cargo tank in which it is transported.

From the standpoint of colloid chemistry, drilling slurries are a complex multicomponent mixture that, depending on external conditions, exhibits the properties of a molecular solution or a dispersed system [6, 7]. The dispersed medium of the drilling slurry is hydraulic oil, which consists of low and high molecular weight compounds. Low molecular weight compounds are mainly paraffinic, naphthenic and aromatic hydrocarbons. The high molecular weight part of the hydraulic oil consists of high molecular weight paraffinic hydrocarbons; mono- and condensed naphthenic, paraffinic, mono- and bicyclic aromatic hydrocarbons; resins and asphaltenes. As a dispersed phase, organometallic (alkaline, alkaline earth, transitional), organosilicon and organofluorine compounds are introduced into the drilling slurry. Compared to hydraulic oil, these compounds are characterized by several times higher molecular weight, the presence of a phase interface between them and the dispersion medium, high density, low volatility, and impart specific properties to the dispersed system. In this case, the system acquires:

1) structural and mechanical strength;
2) instability and the ability to separate into phases.

The structural and mechanical strength of the system increases the lubricity of the drilling slurry. The acquisition of this property is especially relevant when the drilling tool contacts the ground and when pumping the drilling slurry inside the vessel's system. In the first case, thermal and mechanical stresses in the contact zone decrease, in the second case, hydraulic resistances in pumps, pipelines and fittings [8].

The instability of the drilling slurry and the ability to separate into phases, as a rule, is characteristic of its high operating time, long-term stay in a static state, as well as in case of violation of operating conditions [9].

Maintaining the functional characteristics of drilling fluids ensures the reliable operation of the equipment and the continuity of the oil production process. In most cases, these issues are studied for continental fields, for conditions that do not take into account the specifics of transportation and transfer of drilling slurries to offshore or ocean drilling platforms [10]. The issues of ensuring the functional properties and performance characteristics of technical fluids, such as drilling slurries, have not been practically studied in relation to the marine industry. The latent deterioration of their density and sedimentation stability cannot always be determined, evaluated and eliminated by the vessel's crew. The rules for their transportation, as well as the regulation of the density of the drilling slurry and maintaining the density value with an acceptable mismatch range, do not have confirmed practical recommendations.

3. The aim and objectives of research

The aim of research is to develop a method for automatic control of the sedimentation stability of the drilling slurry during its transportation in the cargo tanks of PSVs. This will provide:

- maintaining the functional properties of the drilling slurry;
- minimizing the formation of sediment of heavy components with which the drilling slurry is alloyed;
- reduction of additional energy consumption associated with the constant operation of circulation pumps, and reduction of the time for pumping the drilling slurry from the cargo tanks of the vessel to the oil platform.

This aim can be achieved by solving the following objectives:

1. Monitoring the density of the drilling slurry along the height of the cargo tank.
2. Modernization of the board storage and transportation system for drilling slurry and determination of adjustable parameters.
3. Determination of the values of density and sedimentation resistance of the drilling slurry, at which its forced circulation is ensured.

4. Research of existing solutions to the problem

Maintaining the operational characteristics of working (fuel, oil) and technical (lubricating and cooling solutions, drilling slurries) fluids is ensured by their additional hydrodynamic, ultrasonic and chemical treatment.

During hydrodynamic treatment, the fluid flow is subjected to impact force loads of variable frequency with a simultaneous increase in speed and a change in the direction of its movement [11, 12]. This contributes to breaking the molecular bonds between the elements of the dispersed phase and maintaining the dispersity and homogeneity of the entire liquid volume [13, 14].

During ultrasonic treatment in a liquid flow, an impulse increase and decrease in pressure occurs in local volumes of the liquid. In this case, due to the occurrence of cavitation processes, additional turbulent flows arise, which increase the uniformity and prevent liquid separation [15, 16].

In the case of chemical treatment, additional reagents are introduced into the volume of the liquid, which, due to intermolecular interactions, ensure the maintenance of the homogeneity of the liquid at the desired level during periods of storage and transportation [17, 18].

The above methods for solving the problem of maintaining the density and sedimentation stability of technical fluids are used for fuels and oils that are used in vessel power plants of sea and inland water transport [19, 20]. Violation of the technology of hydrodynamic or ultrasonic processing of technical fluids (in particular, drilling slurries) can lead to excessive grinding of the dispersed phase and a further decrease in their tribotechnical characteristics [21]. This will subsequently negatively affect the drilling process [22, 23]. After chemical treatment, the suspensions contain reagents that have a negative effect on the metal or synthetic elements of the drilling system and the circulation of the drilling slurry. In addition, light fractions of these reagents can evaporate from an open surface and adversely affect the environment [24, 25]. Heavy ones increase the level of mechanical losses during their circulation [26, 27].

Thus, the optimal solution to the important problem of maintaining the density and sedimentation resistance of drilling slurries during their transportation by PSV class vessels with the simultaneous minimization of energy to ensure this process has not been found to date.

5. Methods of research

PSV class vessels belong to the medium speed class (their maximum speed, as a rule, does not exceed 12–13 knots). Therefore, the duration of their transition (and, accordingly, the time of transportation of the drilling slurry) from the port to the oil platform is 2–3 days. In addition, there may be cases when some operational and technological reasons, as well as adverse weather conditions, entail the need to drift or stop at drilling platforms. The value of this period of time can vary from several hours to 5–7 days. It was in such conditions that a specialized marine vessel of the PSV class with a displacement of 7320 tons (Hyundai Samho Heavy Industries, Japan) operated, on which the research was carried out. A fragment of the schematic diagram of the location of the cargo tanks of the vessel on which the research was carried out is shown in Fig. 1. The design of the vessel provided for the reception and transportation of drilling slurry in four cargo tanks 1, 2, 5, 6, located in pairs on the port and starboard sides of the vessel. Drilling slurry intake/pumping was carried out by pumps 3, 4 along lines 7, 8. The difference in overall dimensions of cargo tanks (length, width and depth) from each other did not exceed 0.1 %. Also, the volumetric amount of the drilling slurry, which was transported in them, was almost the same.

A set of previous studies on the study of the rheological characteristics of drilling slurries established the occurrence of stratification of its density along the depth of the tank. In this case, due to the stratification of the drilling slurry, the difference in its density on the surface and bottom of the tank can reach 40 % [1, 10]. As a way to reduce the density stratification of the drilling slurry, it is possible to use additional circulation of the slurry between the tanks (Fig. 2). At the same time, additional circulation pumps 5 and 6 pump the drilling slurry from the lower part of tanks 3 and 4 to the upper part of tanks 4 and 3. The system was modernized only for one group of tanks located on one side of the vessel (Fig. 1). The configuration of the system for another group of tanks did not change. The technology of work on the re-equipment of the system and the control of their implementation were agreed with the technical department of the company that provided the management of the vessel [28].

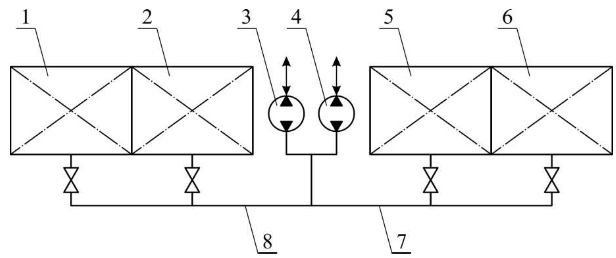

Fig. 1. Schematic diagram of the arrangement of cargo tanks of a PSV class vessel intended for transportation of drilling slurry (fragment): 1, 2, 5, 6 – cargo tanks; 3, 4 – cargo pumps; 7, 8 – lines for receiving/pumping out drilling slurry

In contrast to previous studies, the board drilling slurry transportation system was additionally equipped with an automatic control system for the drilling slurry density, which included laptop 1 and microcontroller 7 (Fig. 2).

The main characteristics of the drilling slurry transported to the drilling platform:

– name and brand – Rheliant barite OBM (manufacturer MiSWACO, Houston, USA);
– density at 15 °C – 1185 kg/m^3;
– base component – hydrocarbons, C_{11}–C_{14}, h-alkanes, iso-alkanes – 57–60 %; lubricating oils (petroleum) C_{20}–C_{50}, based on distillate oils – 22–25 %;
– doped additives – Mg (1.3–1.4 %), Ca (3.2–3.5 %), Cu (0.1–0.2 %), Si (6.2–6.4 %).

The change in the structural state of the drilling slurry was assessed by measuring its density at levels corresponding to 10, 50 and 90 % of the total depth of the tank. To measure the density, an immersion hydrometer was used (position 2 in Fig. 2), which makes it possible to perform measurements in the range of 650–1630 kg/m^3 with an accuracy of ±1 kg/m^3 [28, 29]. Six measurements were performed at each level, and the values thus obtained were averaged. The density values were also averaged at the same level (0.1*h*, 0.5*h*, 0.9*h* in Fig. 2) in tanks located in pairs on each side of the vessel (in two of which the drilling slurry was transported without forced circulation, in two – with circulation). The cycle of density measurements and further recording of the obtained values in the laptop program (position 1 in Fig. 2) did not exceed 10 min.

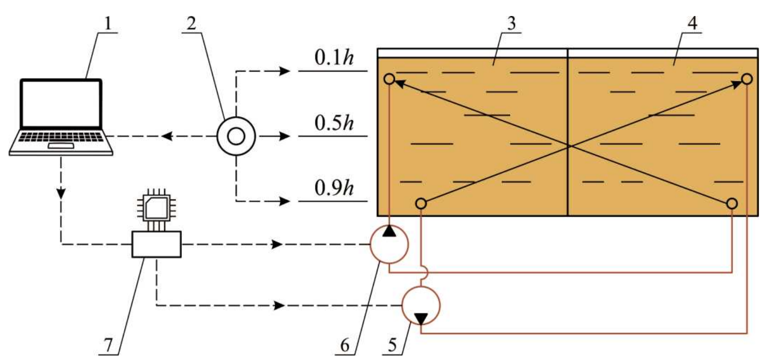

Fig. 2. Providing additional circulation of the drilling slurry in the cargo tanks of the vessel and the technology for carrying out experimental work: 1 – laptop; 2 – hydrometer; 3, 4 – cargo tanks for transportation of drilling slurry; 5, 6 – additional circulation pumps; 7 – microcontroller

The sedimentation stability of the drilling slurry was evaluated as a change in vertical density near the surface and bottom of the cargo tank:

$$\Delta\rho = \frac{\rho_{90} - \rho_{10}}{\rho_{90}} \cdot 100\ \%, \quad (1)$$

where ρ_{90}, ρ_{10} – drilling fluid density at levels $0.9h$ and $0.1h$, respectively (Fig. 2).

Large values of $\Delta\rho$ correspond to an increase in the amount of sediment of alloyed elements, a higher degree of stratification of the drilling slurry and a decrease in its sedimentation stability [30].

The value of sedimentation stability was an input parameter for controller 7, which provided switching on/off of forced circulation pumps 5 and 6 (Fig. 2).

6. Research results

The studies were carried out under constant external disturbances (in particular, when the sea was less than 3 points on a 12-point scale) while the vessel was moving and waiting for the approach to the drilling platform. The sea crossing of the PSV took place without a change in stability [31]; therefore, the height of the drilling slurry level in the cargo tank was assumed to be constant. The change in the temperature of the drilling slurry during its transportation did not exceed ±1 °C, which did not affect the coefficient of linear expansion and did not lead to an increase in its volume in the cargo tank.

Experimental studies were carried out for 48 hours, the interval for measuring the density of the drilling slurry was 6 hours. The results of the experiment are given in Table 1.

The obtained values of drilling fluid density at different levels of the cargo tank $0.1h$–$0.9h$ confirm the latent stratification of drilling fluid that occurs during its transportation on PSVs.

The sedimentation stability of the drilling slurry was calculated by expression (1), its values for different transportation methods are given in Table 2.

Graphic dependences showing the change in the density and sedimentation stability of the drilling slurry are shown in Fig. 3.

Table 1

Drilling slurry density, ρ, kg/m^3

Time, h	Transportation method					
	a			*b*		
	0.1*h*	0.5*h*	0.9*h*	0.1*h*	0.5*h*	0.9*h*
0	1185	1185	1187	1186	1186	1188
6	1182	1198	1212	1183	1196	1212
12	1172	1225	1258	1171	1224	1256
18	1160	1241	1298	1178	1192	1206
24	1151	1258	1335	1183	1209	1197
30	1136	1283	1358	1177	1218	1238
36	1118	1316	1381	1162	1224	1255
42	1101	1326	1402	1178	1191	1212
48	1092	1342	1418	1182	1188	1191

Note: *a* – transportation without changing the design of the system; *b* – transportation with additional X-shaped circulation

Table 2

Sedimentation stability of drilling slurry, Δρ, %

Time, h	Transportation method	
	a	*b*
0	0.17	0.17
6	2.54	2.45
12	7.34	7.26
18	11.89	2.38
24	15.99	1.18
30	19.54	5.18
36	23.52	8.01
42	27.34	2.89
48	29.85	0.76

Note: *a* – transportation without changing the design of the system; *b* – transportation with additional X-shaped circulation

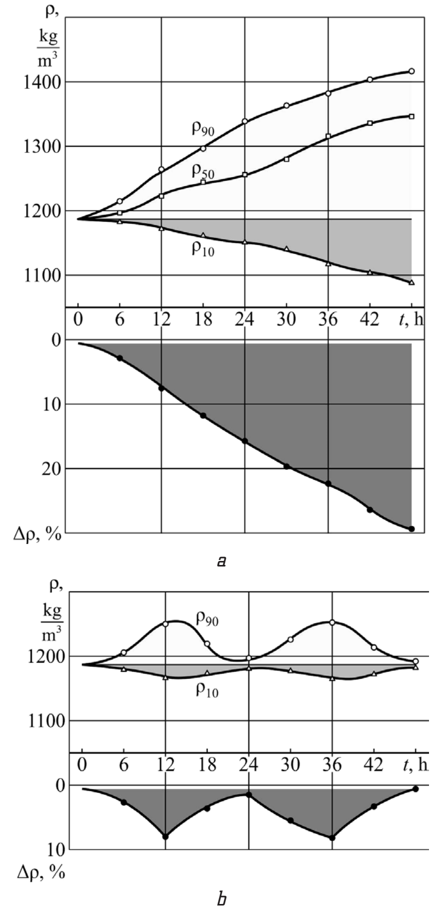

Fig. 3. Change in density, ρ, and sedimentation stability, Δρ, of the drilling slurry depending on time: *a* – transportation without upgrading the system design; *b* – transportation with additional X-shaped circulation

The area under the curves $\rho=f(t)$ and $\Delta\rho=f(t)$ characterizes the change in the density and sedimentation stability of the drilling slurry. An increase in the area under the curves $\rho_{90}=f(t)$ and $\rho_{50}=f(t)$ corresponds to an increase in density and sedimentation in the lower and middle parts of the cargo tank. An increase in the area under the curve $\rho_{10}=f(t)$ corresponds to a decrease in density and the formation of a liquid phase in the upper part of the tank. An increase in the area under the curve $\Delta\rho=f(t)$ corresponds to the stratification of the drilling slurry and a decrease in its sedimentation stability.

The programmable microcontroller (position 7 in Fig. 2) was configured in such a way that when the sedimentation stability reached a value of 7 %, the circulation pumps were switched on (positions 5 and 6 in Fig. 2). Forced circulation helped to reduce the separation of the drilling slurry and restore its uniformity. In this case, the vertical density of the drilling slurry ρ (*b* in Fig. 3 and Table 1) was «levelled» and the value of Δρ decreased (*b* in Fig. 3 and Table 2). Upon reaching the sedimentation stability of 2 %, the programmable microcontroller (position 7 in Fig. 2) switched off the circulation pumps (positions 5 and 6 in Fig. 2) [29]. This provided a reduction in energy consumption for their operation and increased the design coefficient of the vessel's energy efficiency [3, 23].

The results, which are given in Table 1 and in Fig. 3 indicate that the change in the density and sedimentation stability of the drilling slurry during its transportation in the cargo tanks of PSV occurs according to an exponential law. The maximum increase in density (and the corresponding weighting of the drilling slurry) corresponds to the bottom of the cargo tank (90 % depth). The minimum decrease in density corresponds to the drilling slurry layer, which is located on the surface and in the upper part of the cargo tank (at a depth of 10 %).

Stratification of the density of the drilling slurry along the depth of the tank helps to reduce its sedimentation stability. In the case of transportation of the drilling slurry without changing the design of the system over a period of 6–48 hours, its sedimentation stability decreases by 2.54–29.85 %. Maintaining forced X-shaped circulation in cargo tanks with periodic switching on/off of circulation pumps reduces the density stratification along the depth of the cargo tank. With this method of transportation, the decrease in the sedimentation stability of the drilling slurry for the same period of time is 0.17–8.01 %.

To confirm the feasibility and efficiency of using additional X-shaped circulation of the drilling slurry after the completion of its transportation to the oil platform, the calculation of the relative performance of cargo pumps ΔQ, % was performed:

$$\Delta Q = \frac{Q_{real}}{Q_{max}} \cdot 100\ \%, \qquad (2)$$

where Q_{real} and Q_{max} – actual and maximum performance of cargo pumps, m^3/h. As well as measuring the time of pumping drilling slurry from cargo tanks to the drilling platform. The values of these parameters are given in Table 3, and also displayed in the diagrams of Fig. 4, 5.

Table 3

Experiment results

Parameter	Transportation method	
	a	*b*
Relative performance of cargo pumps, ΔQ, %	38–55	92–96
Time of drilling slurry pumping from cargo tanks to the drilling platform, *t*, h	7.1	3.2

Note: *a* – transportation without changing the design of the system; *b* – transportation with additional X-shaped circulation

The lower value of ΔQ in the case of transportation of the drilling fluid without changing the design of the system is explained by the lower (compared with the transportation of the drilling fluid with additional X-shaped circulation) value of the actual performance of the transfer pumps. The latter is associated with an increase in hydraulic resistance arising in the system due to stratification of the drilling slurry and the formation of sediment from alloyed components.

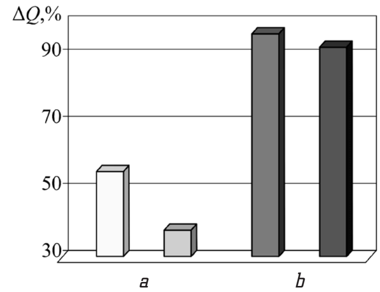

Fig. 4. Relative performance of cargo pumps, ΔQ, %: *a* – transportation without changing the design of the system; *b* – transportation with additional X-shaped circulation

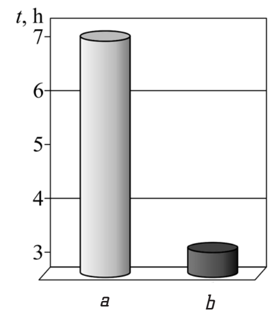

Fig. 5. Time of pumping the drilling slurry from the cargo tanks to the drilling platform, *t*, h: *a* – transportation without changing the system design; *b* – transportation with additional X-shaped circulation

This also explains the increased pumping time of the drilling slurry in the case of its transportation without changing the design of the system.

7. SWOT analysis of research results

Strengths. The strengths of this research are that the proposed method of additional X-shaped circulation helps to maintain the density and sedimentation stability of the drilling slurry along the depth of the tank in which it is transported. At the same time, due to the automatic control of the on/off of the circulation pumps, a reduction in additional energy consumption is ensured. Maintaining the required density and sedimentation stability of the drilling slurry minimizes the time of its pumping from the vessel to the drilling platform, reducing the dead time of PSV vessels.

Weaknesses. The weaknesses of this research are related to the fact that in order to use additional X-shaped circulation of the drilling slurry, it is necessary to re-equip the system. Performance of such work is possible only upon agreement with the vessel-owner, and in some cases with the Register or other classification society supervising the operation of the vessel and its power plant.

Opportunities. The application of the proposed method for maintaining and automatically controlling the density

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and sedimentation stability is possible for various technical fluids and various objects of the technological complex for ensuring oil production. These include drilling slurries and cutting fluids, which are produced and temporarily stored at shore bases, and transported from shore bases to PSVs by vehicles.

Threats. The option proposed in this paper to maintain and control the density and sedimentation stability of the drilling slurry is of an applied nature and is based on practical experience. For the analytical calculation of the optimal on/off time for additional circulation pumps, which ensures its minimum stratification and a decrease in sedimentation stability, it is necessary to develop a mathematical model and conduct mathematical modeling. In this case, it is necessary to take into account the component composition of the drilling slurry, the hydraulic characteristics of the drilling slurry transportation system, as well as external disturbances to the vessel.

8. Conclusions

1. The conducted studies allow to conclude that during the transportation of the drilling slurry, its stratification occurs, an increase in density in the bottom of the cargo tank and a decrease on the surface of the tank. It has been experimentally confirmed that during 48-hour transportation, the following occurs:

– increase in drilling fluid density in the bottom part up to 19.7 %;
– decrease in density on the surface – up to 7.8 %;
– decrease in the sedimentation stability of the drilling slurry along the depth of the cargo tank – up to 29.85 %.

2. It is shown that one of the methods to prevent the separation of the drilling slurry and the formation of sediment from the heavy components with which it is alloyed, as well as the automatic control of its sedimentation stability, is the creation of an additional X-shaped circulation of the drilling slurry between adjacent cargo tanks. Additional X-shaped circulation of the drilling slurry is provided by circulation pumps along the lines connecting the bottom and upper parts of adjacent cargo tanks. Using programmable microcontrollers (which turn on/off circulation pumps), it is possible to provide the following conditions for transporting drilling fluid:

– increase in drilling fluid density in the bottom part up to 0.3 %;
– decrease in density on the surface – up to 0.25 %;
– decrease in the sedimentation stability of the drilling slurry along the depth of the cargo tank – up to 8.01 %.

The decrease in density stratification and sedimentation stability with this transportation option is explained by cross-traffic and artificial creation of a laminar flow of drilling slurry (due to its forced circulation between adjacent cargo tanks). This leads to a force effect on organic and inorganic compounds in the volume of the drilling slurry, prevents their settling and keeps them in suspension.

3. It is revealed that automatic maintenance of the sedimentation stability of the drilling slurry in the range of 2–7 % contributes to:

– increasing the relative productivity of cargo pumps from 38–55 % (in the case of conventional transportation of the drilling fluid) to 92–96 % (with additional X-shaped circulation of the drilling fluid);
– reducing the time of pumping the drilling fluid from the cargo tanks to the drilling platform from 7.1 hours (in the case of conventional transportation of the drilling fluid) to 3.2 hours (with additional X-shaped circulation of the drilling fluid);
– maintenance of the technical condition of equipment, pipelines and elements of the drilling slurry transportation and pumping system.

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Denys Maryanov, *Postgraduate Student, Department of Ship Power Plants, National University «Odessa Maritime Academy», Odessa, Ukraine, e-mail: denismaryanovv@gmail.com, ORCID: https://orcid.org/0000-0002-1355-5844*