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Denys Maryanov

REDUCED ENERGY LOSSES DURING TRANSPORTATION OF DRILLING FLUID BY PLATFORM SUPPLY VESSELS

The object of research is the process of drilling fluid transportation by Platform Supply Vessels. The subject of research is the energy losses when pumping drilling fluid from a platform supply vessel to an oil platform. The research was carried out on a vessel with deadweight of 3840 tons. It has been experimentally established that for a drilling fluid with an initial density of 1272 kg/m³ for transportation within 6–48 hours, the following changes in rheological characteristics occur:

– *a layer with a density of 1235–962 kg/m³ is formed on the surface of the cargo tank;*
– *a layer with a density of 1283–1422 kg/m³ is formed in the bottom part of the tank;*
– *sedimentation resistance decreases by 3.89–47.82 %.*

A variant of modernization of the drilling fluid transportation system by installing additional circulation pumps providing forced circulation of the drilling fluid between cargo tanks is proposed. Additional circulation of the drilling fluid with an initial density of 1272 kg/m³ for transportation within 6–48 hours ensures that the rheological characteristics are maintained in the following range:

– *density on the surface of the cargo tank 1270–1232 kg/m³;*
– *density in the bottom of the tank 1288–1338 kg/m³;*
– *decrease in sedimentation resistance 1.42–7.92 %.*

Similar results were established for drilling fluid with an initial density of 1323 kg/m³ and 1188 kg/m³.

To reduce energy losses, the process of unloading the fluid onto the oil platform is proposed to be performed at the completion of the technological process of unloading the vessel. At the same time, due to a decrease in draft and an increase in the height of the freeboard of the vessel, the static component of the pressure and hydraulic losses of the cargo pump decrease.

A set of studies for drilling fluids with different initial density (1272 kg/m³, 1188 kg/m³, 1323 kg/m³) confirmed that when using additional X-shaped drilling fluid circulation:

– *relative performance of cargo pumps increases from 37–57 % to 88–96 %;*
– *the time of pumping the drilling fluid from the vessel to the oil platform is reduced from 7.1–8.5 to 3.3–3.8 hours.*

The presented results confirm the expediency of using additional X-shaped circulation of the drilling fluid to reduce energy losses during transportation by Platform Supply Vessels.

Keywords: *Platform Supply Vessel, transportation system, drilling fluid density, sedimentation stability, energy losses.*

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1. Introduction

The main functional purpose of the vessels of sea and inland water transport is to provide freight and passenger traffic. At the same time, there is a large class of specialized vessels that perform work on:

– supply of offshore oil platforms (Platform Supply Vessel – PSV);
– laying pipes and cables, as well as installing anchors (Anchor Handling Tug Supply Vessel – AHTS);
– towing and emergency rescue of vessels and their crews.

The world fleet of such vessels (the so-called offshore fleet vessels) currently numbers more than 7,000 units [1, 2]. These high-tech vessels are largely owned by specialized firms in the USA, Norway, and Singapore [3].

Offshore vessels include the PSV class of specialized vessels. These vessels are distinguished by the forward location of the residential superstructure and the pilot house, an extensive open cargo deck, and cargo holds located in pairs on each side of the vessel [4].

PSV vessels deliver consumable drilling and process materials (including drilling fluids), spare parts, tools, production equipment, food, fresh, drinking and process water, fuel, maintenance personnel from the shore base and back [5, 6].

In studies [7, 8], it was found that when drilling fluids are transported by PSV class vessels to offshore oil platforms, a latent stratification of drilling fluids occurs along the depth of the cargo tank. The consequence of this is a decrease in the sedimentation stability of the drilling fluid and the formation in the bottom of the cargo tank of sediment from heavy components with which it is alloyed. This leads to increased resistance to cargo pumps (which pump the drilling fluid when it is unloaded from the PSV to the oil platform) and proportionally increases the energy loss to ensure the process of transporting the drilling fluid [9, 10].

Thus, maintaining the sedimentation stability of the drilling fluid during its transportation to oil platforms and reducing energy losses during its unloading is an urgent scientific and applied task.

2. The object of research and its technological audit

The object of research is the process of drilling fluid transportation by Platform Supply Vessels.

The subject of research is the energy losses when pumping drilling fluid from a platform supply vessel to an oil platform.

Drilling operations are carried out by destruction of the drilling zone. At the same time, cuttings accumulate in the well, which must be constantly removed from the drilling zone (to carry out flushing) [11]. To remove the destruction products during the drilling of oil-producing offshore wells, a hydraulic method is used, in which the cuttings are removed from the drilling zone and transported to the surface by the drilling fluid flow (Fig. 1).

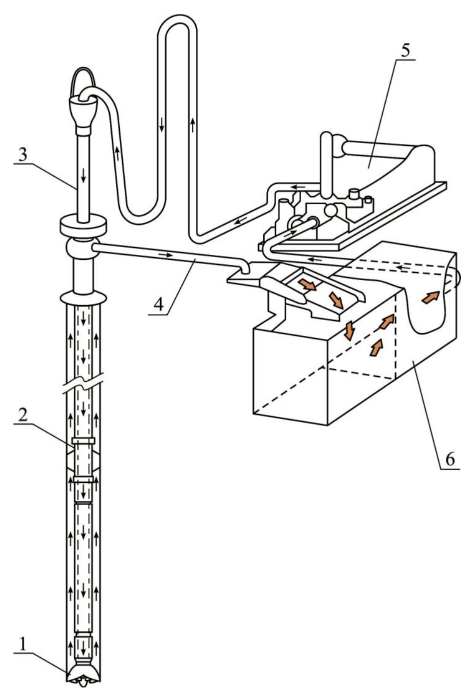

Fig. 1. Technological scheme for the use of drilling fluid: 1 – drill; 2 – drill pipe; 3 – rotary pipe; 4 – drilling fluid line; 5 – drilling fluid supply pump; 6 – drilling fluid tank

Thus, flushing wells with currently existing drilling methods is technologically necessary. This determines the purpose of the drilling fluid not only as a lubricant for the drill (position 1 in Fig. 1), but also as a means of cleaning the drilling zone from cuttings and bringing it to the surface [11, 12]. A necessary condition for the effective removal of cuttings from the drilling zone is the presence of drilling fluid circulation, which is carried out by pump 7, along the contour: drilling fluid tank 6 – rotary pipe 3 – drill pipe 2 – drilling fluid line 4 (Fig. 1).

In addition to the main purpose, the drilling fluid performs a number of target functions due to the specifics of drilling technology, their active interaction with deep and surface equipment of circulating systems, with ground rocks of different composition and properties [13, 14].

All functions of the drilling fluid can be divided into three groups:

– hydrostatic functions:

1) creation of counter pressure on the walls of the drill pipe;

2) providing counter pressure on sea water and underwater soil;

3) retention of the dispersed phase and sludge in fluid in the absence of circulation [15];

– hydrodynamic functions:

1) cleaning of the drilling zone;

2) drilling pipe cleaning and cuttings removal to the surface;

3) cooling of drilling equipment and rubbing surfaces [16];

– physical and chemical functions:

1) lubrication of friction surfaces;

2) protection of drilling equipment and tools from corrosion;

3) improving the drillability of underwater soil [17].

The listed functions of the drilling fluid are not equivalent, the necessity and completeness of the implementation of most of them is associated with the specific goals and conditions of drilling wells, as well as with the technology of their transportation.

General requirements are environmental and industrial safety, manufacturability and efficiency of the drilling fluid. The requirements of labor protection and environmental safety of the drilling fluid are fundamental. For drilling fluid used on offshore oil platforms, the efficiency of drilling fluid means not only the availability and low cost of its production, but, mainly, its transportation with the maintenance of all functional properties. Transportation of drilling fluid is one of the tasks assigned to PSV class vessels [18, 19].

3. The aim and objectives of research

The aim of research is to improve the technology for transporting drilling fluid by PSV class vessels. This will provide:

– reduction of latent stratification of the drilling fluid;
– minimization of the formation of sediment of heavy components that are part of the drilling fluid;
– reduction of energy losses when pumping drilling fluid from a PSV vessel to an oil production platform;
– maintenance of the technical condition of the vessel's drilling fluid transportation system.

This aim can be achieved by solving the following objectives:

1. Continuous monitoring of the rheological characteristics of the drilling fluid along the depth of the cargo tank.

2. Providing additional circulation of drilling fluid in cargo tanks.

3. Reducing hydraulic losses when unloading the drilling fluid from the vessel to the oil platform.

4. Research of existing solutions to the problem

The drilling fluid used on offshore oil platforms is a multi-component system. It consists of a liquid phase (usually hydraulic oil) and solid impurities, which are introduced into its composition in a crushed form. Maintaining the required dispersion of drilling fluid is possible due to external influence on its structural components. At the same time, solid impurities that are part of the drilling fluid are subjected to hydrodynamic, ultrasonic action or chemical treatment, which prevents the process of their coagulation and further precipitation [20, 21].

During hydrodynamic processing, a local increase in the speed of movement of the drilling fluid is provided with a simultaneous change in the direction of its movement [22, 23].

During ultrasonic treatment, the solid components of the drilling fluid are subjected to pulsed action of force loads [24, 25].

During chemical treatment, additional reagents are introduced into the composition of the drilling fluid, which prevent intermolecular associations of solid components [26, 27].

The above methods reduce hydraulic losses when pumping the drilling fluid inside the vessel's transportation system, but they have not received wide distribution on sea vessels. This is due to a wide range of heavy components with which drilling fluids are alloyed. Their physical and chemical features, as well as molecular structure, can significantly reduce the effectiveness of these processing methods. In addition, their use requires additional equipment, and in some cases independent installations, which affects the economic efficiency of the vessel [28, 29].

Thus, the optimal solution to the important problem of transporting drilling fluid in the cargo tanks of a PSV vessel and its further pumping to the oil platform with minimal energy losses has not been found to date.

5. Methods of research

Reducing energy losses in the drilling fluid transportation system of PSV vessels is possible by providing its additional constant or periodic circulation between cargo tanks located next to each other [30]. At the same time, the drilling fluid transportation system is additionally equipped with mobile circulation pumps according to the scheme shown in Fig. 2.

Drilling fluid is transported in cargo tanks 5 and 7, located in pairs on each side of the vessel. The loading of the drilling fluid into the tanks and its unloading onto the oil platform is carried out by cargo pumps 4. Additional *X*-shaped circulation of the drilling fluid in the cargo tanks is provided by pumps 6, while from the bottom of one of the tanks the drilling fluid is directed to the surface of the other. System modernization was carried out only for one group of tanks located on one side of the vessel (item 5 in Fig. 2). Mobile circulation pumps were used as pumps (discharge pressure 0.35–0.4 MPa, capacity 25 m^3/h, power consumption 5–7 kW). Circulation was provided through flexible pipelines, which were connected to the technological openings of the cargo tanks (designed to remove the residue – in the lower part of the tank and ventilation – in the upper part of the tank). The configuration of the system for another group of tanks (item 7 in Fig. 2) did not change.

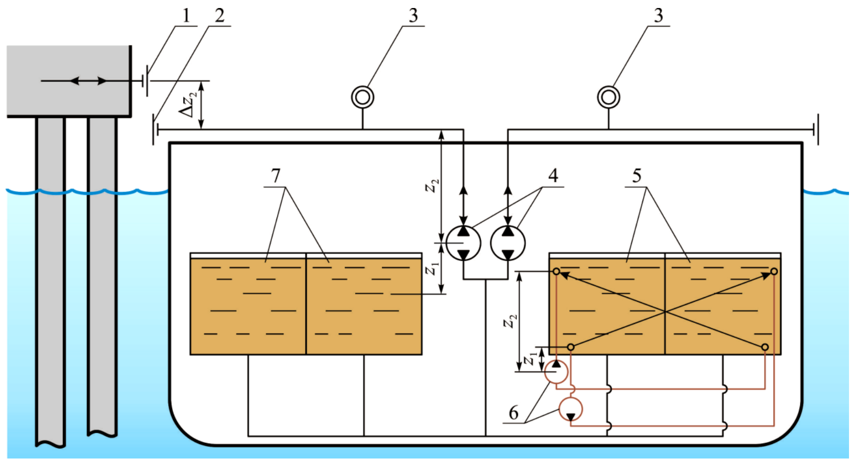

Fig. 2. Schematic diagram of the arrangement of cargo tanks of a PSV class vessel intended for transportation of drilling fluid (fragment): 1, 2 – drilling fluid inlet/outlet flange on the oil platform and the PSV; 3 – flow meter; 4 – cargo pumps; 5, 7 – cargo tanks; 6 – pumps for forced circulation of drilling fluid

An analysis of the configuration and functioning of the vesselboard system for storing and circulating drilling fluid showed its complexity and saturation with various equipment. At the same time, the main components of this system are a cargo pump that transfers energy to the drilling fluid flow, and a main pipeline through which the drilling fluid is pumped from the cargo tank to the oil platform. Transportation of drilling fluid (like any real fluid with viscosity) is accompanied by the appearance of friction, to overcome which part of the energy transferred to the drilling fluid is lost [31]. These losses are compensated by the pressure generated by the cargo pump. In accordance with the scheme shown in Fig. 2, a pressure H_{fr} for supplying the drilling fluid consists of:

– static component, independent of the flow rate and flow rate:

$$H_{st} = g(z_1 + z_2) + \frac{P}{\rho};$$

– dynamic component, which takes into account the hydraulic resistance of the entire main pipeline and consists of the sums of local resistances and resistances along the length of the suction and discharge pipelines:

$$H_{din} = \sum_{in} \xi \frac{\upsilon_{in}^2}{2} + \lambda \frac{l_{in}}{d_{in}} \frac{\upsilon_{in}^2}{2} + \sum_{out} \xi \frac{\upsilon_{out}^2}{2} + \lambda \frac{l_{out}}{d_{out}} \frac{\upsilon_{out}^2}{2};$$

$$H_{fr} = H_{st} + H_{din}.$$

In the formulas of the pressure components: z_1, z_2 – height of liquid rise during suction and discharge, m; P – pressure created by the cargo pump, Pa; ρ – density of the drilling fluid, kg/m^3; υ_{in}, υ_{out} – speed of movement of the drilling fluid in the suction and discharge main pipeline, m/s; d_{in}, d_{out} – the internal diameters of the suction and discharge pipelines, m; l_{in}, l_{out} – lengths of the suction and discharge pipelines, m; $\sum_{in}\xi$, $\sum_{out}\xi$ –sum of the coefficients of local resistance of the suction and discharge pipelines; λ – coefficient of friction in pipes.

An analysis of the equation for H_{fr} allows drawing the following conclusion. It is possible to control hydraulic losses in the drilling fluid circulation pipeline by changing:

- system design (diameter and length of pipelines);
- power and pressure of the cargo pump;
- vessel's draft.

A feature of the drilling fluid transportation process by PSV vessels is the «misalignment» of the drilling fluid delivery/receiving flanges located on the oil platform and on board the vessel. This is due to the different heights of the drilling fluid delivery/reception lines. The difference in this height (denoted as Δz_2 in Fig. 2) increases the static pressure loss component. Drilling fluid is unloaded from the vessel to the oil platform (in case of its supply height increase by Δz_2) by connecting additional flexible hoses. With their help, the flanges for receiving/discharging the drilling fluid on the oil platform and the PSV are connected (positions 1 and 2 in Fig. 2). Thus, it is expedient to unload the drilling fluid onto the oil-producing platform at the end of the technological process of unloading the PSV vessel (in conditions when, due to a decrease in the deadweight of the vessel, the draft of the vessel decreases proportionally and the freeboard increases). This contributes to a decrease in the liquid lift height during injection (z_2 in Fig. 2).

An analysis of the static component of the expression for H_{fr} and the operation features of PSV vessels allows drawing the following conclusion. The most rational place for installation of cargo pumps is the lower level of the cargo tank, since the liquid lift height during suction (z_1 in Fig. 2) cannot be changed by increasing/decreasing the deadweight.

Installation of additional pumps providing forced circulation of the drilling fluid should be carried out in accordance with positions 6 in Fig. 2.

A feature of the proposed method of installing pumps is the negative value of the liquid lift height during suction (z_1 in Fig. 2). In this case (in connection with the provision of the circulation process according to the scheme, the bottom part of one of the cargo tanks is the surface of the other cargo tank, as well as the equality of the level of the drilling fluid in these two cargo tanks), the following approximate equality $|-z_1| \approx |z_2|$ is fulfilled. This significantly reduces the value of the static component of the pressure H_{st} and the corresponding decrease total hydraulic losses H_{fr}. Additional lines connecting the circulation pumps may not have fittings installed before the suction of the pumps, and there is no need to install such fittings on the discharge of the pumps (due to the fact that the circulation of the drilling fluid is provided directly to the surface of the cargo tank).

The studies were carried out in the drilling fluid transportation system of a marine vessel PSV with deadweight of 3840 tons. 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. 3.

The design of the vessel provided for the reception and transportation of drilling fluid in four cargo tanks 1, 2, 5, 6, located in pairs on the port and starboard sides of the vessel. Drilling fluid intake/pumping out were 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 fluid, which was transported in them, was almost the same.

The power of cargo pumps (positions 3, 4 in Fig. 3) was determined by wattmeters installed at the control station. The amount of drilling fluid pumped from the cargo tanks (positions 1, 2, 5, 6 in Fig. 3) was determined by the flow meter, which was installed in the drilling fluid transportation system.

In cargo tanks 5 and 6 (Fig. 3), an additional *X*-shaped circulation of the drilling fluid was provided in accordance with the technology presented in Fig. 3. 2.

During the experiment, the technical condition, pressure and power consumption of the circulation pumps were monitored (position 6 in Fig. 2). This ensured the continuity of the flow of the drilling fluid in the flexible pipelines and the absence of its leakage in the joints.

The density of the drilling fluid was determined on the surface and at various points of the cargo tank, corresponding to 30, 60 and 90 % of its depth. At each level, six measurements were performed in accordance with the technology shown in Fig. 3.

Fig. 3 shows the density measurement only for cargo tank 6, similar measurements were carried out in cargo tanks 1, 2, 5. The density values obtained in this way were averaged. Density values were also averaged at the same level (at the same depth 0.1h, 0.5h, 0.9h) in tanks located in pairs on each side of the vessel. The density measurement cycle for all points and all tanks did not exceed 10 min.

Density was measured using a dm-230.1a electronic hydrometer from Bopp & Reuther Messtechnik (Germany). The hydrometer allows measurements in tanks up to 6 m deep. The hydrometer complies with the following standards:

- ASTM D 7777 (American Standard Test Method for Density, Relative Density);
- IP 559 (IP 559: Determination of density of middle distillate fuels);
- included in the State Register of Measuring Instruments of Ukraine.

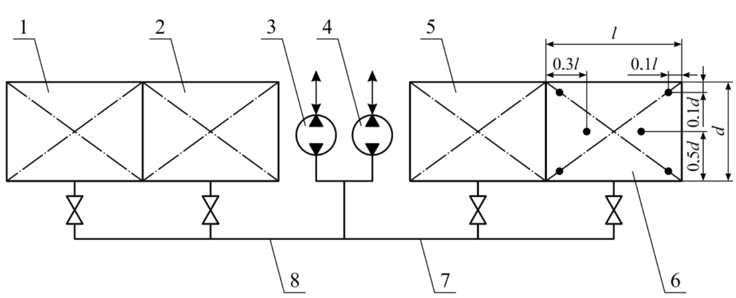

Fig. 3. Schematic diagram of the location of the vessel's cargo tanks and measurement technology: 1, 2, 5, 6 – cargo tanks; 3, 4 – cargo pumps; 7, 8 – lines for intake/pumping out of drilling fluid; l, d – length and width of the cargo tank

Density values at the surface and different depths of the cargo tank made it possible to calculate the sedimentation stability of the drilling fluid:

$$\Delta\rho = \frac{\rho_{max} - \rho_{min}}{\rho_{max}} \cdot 100\ \%,$$

where ρ_{max}, ρ_{min} – the maximum and minimum values of drilling fluid density at different depths of the cargo tank, kg/m^3 [12].

Throughout the experiment, the maximum value of the density of the drilling fluid was recorded at a depth of 0.9*h*, the minimum – on the surface of the cargo tank. With this in mind, the sedimentation stability of the drilling fluid was determined as:

$$\Delta\rho = \frac{\rho_{0.9} - \rho_0}{\rho_{0.9}} \cdot 100\ \%,$$

where $\rho_{0.9}$, ρ_0 – drilling fluid density at a depth of 0.9*h* and on the cargo tank surface.

6. Research results

During experimental studies, drilling fluid was transported with the following main characteristics:

– name and brand – Rheliant barite OBM (manufacturer MiSWACO, Houston, USA);

– density at 15 °C – 1272–1275 kg/m^3;

– base component – hydrocarbons, C_{11}–C_{14} – 55–58 %; distillate oils C_{20}–C_{50} – 27–29 %;

– doped additives – Mg (1.9–2.3 %), Ca (3.6–3.9 %), Cu (0.3–0.4 %), Si (7.7–8.2 %).

The studies were carried out during the passage of the vessel from the port to the oil platform. The duration of the transition and waiting for unloading in the area of the oil platform was 52 hours. This made it possible to conduct research within 48 hours with a measurement interval of 6 hours. Roll, trim and stability of the vessel did not change during the experiment. Therefore, the height of the drilling fluid level in the cargo tank was assumed to be constant. Fluctuations in the temperature of the drilling fluid 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. Throughout the experiment, the energy and environmental performance of the vessel was monitored [32, 33].

The research results are given in Tables 1, 2.

Table 1

Changing the characteristics of the drilling fluid during transportation without changing the system configuration

Time, hours	Density, ρ, kg/m^3, at tank depth				Sedimentation stability, Δρ, %
	on the surface	0.3*h*	0.6*h*	0.9*h*	
0	1272	1274	1275	1278	0.47
6	1235	1272	1276	1283	3.89
12	1122	1261	1291	1303	10.89
18	1043	1205	1335	1341	19.52
24	1068	1172	1360	1383	29.49
30	1028	1112	1368	1402	36.38
36	1002	1089	1373	1414	41.12
42	988	1075	1373	1419	43.62
48	962	1065	1376	1422	47.82

Table 2

Changing the characteristics of the drilling fluid during transportation with additional *X*-shaped circulation

Time, hours	Density, ρ, kg/m^3, at tank depth				Sedimentation stability, Δρ, %
	on the surface	0.3*h*	0.6*h*	0.9*h*	
0	1272	1272	1274	1275	0.24
6	1270	1271	1279	1288	1.42
12	1264	1268	1282	1319	4.35
18	1259	1262	1288	1319	4.77
24	1256	1256	1290	1321	5.18
30	1242	1250	1290	1332	7.25
36	1242	1247	1293	1332	7.25
42	1238	1246	1297	1336	7.34
48	1232	1245	1303	1338	7.92

For all options, the results of which are given in Tables 1, 2, there is a decrease in the density of the drilling fluid in the upper part of the cargo tank (at the surface and a depth of 0.3*h*) and an increase in density in the lower part (at depths of 0.6*h* and 0.9*h*).

According to the values given in Tables 1, 2, there are the diagrams shown in Fig. 4.

A characteristic indicator of the latent stratification of the drilling fluid is its density on the surface and in the bottom of the cargo tank (at a depth of 0.9*h*).

From the point of view of colloidal chemistry, a drilling fluid is a dispersed system in which the dispersed phase is hydraulic oil, and the dispersed medium is the organometallic elements with which it is alloyed. The deterioration of the dispersed state of the drilling fluid during its transportation leads to a deterioration in its sedimentation stability (an increase in the value Δρ in Tables 1, 2).

The density values of the drilling fluid on the surface ρ_0, at the depth of 0.9*h* of the cargo tank $\rho_{0.9}$ and the sedimentation stability of the drilling fluid Δρ can be considered as the criteria for the efficiency of its transportation. Comparison of these values for different conditions of transportation of drilling fluid with a density of 1272 kg/m^3 is shown in Fig. 5, *a*.

The efficiency of using additional X-shaped circulation can be estimated by the area of sectors corresponding to the density at a depth of 0.9*h* – $\rho_{0.9}$, on the surface – ρ_0 and sedimentation stability – Δρ. A decrease in the area of these sectors indicates a decrease in the stratification of the drilling fluid along the depth of the cargo tank and an increase in its dispersion [34–36]. This helps to reduce energy losses for its unloading from the vessel to the oil platform.

The given research cycle was repeated during similar passages of the vessel (with the same duration and the same volume of drilling fluid in cargo tanks) when transporting drilling fluids with an initial density of 1323 and 1188 kg/m^3. The generalized results of these studies are given in Table 3. At the same time, the values of density and sedimentation stability at the initial and final moments of the studies (for the time of 0 and 48 hours) for different conditions of drilling fluid transportation (without changing the system configuration and with additional *X*-shaped circulation) are indicated.

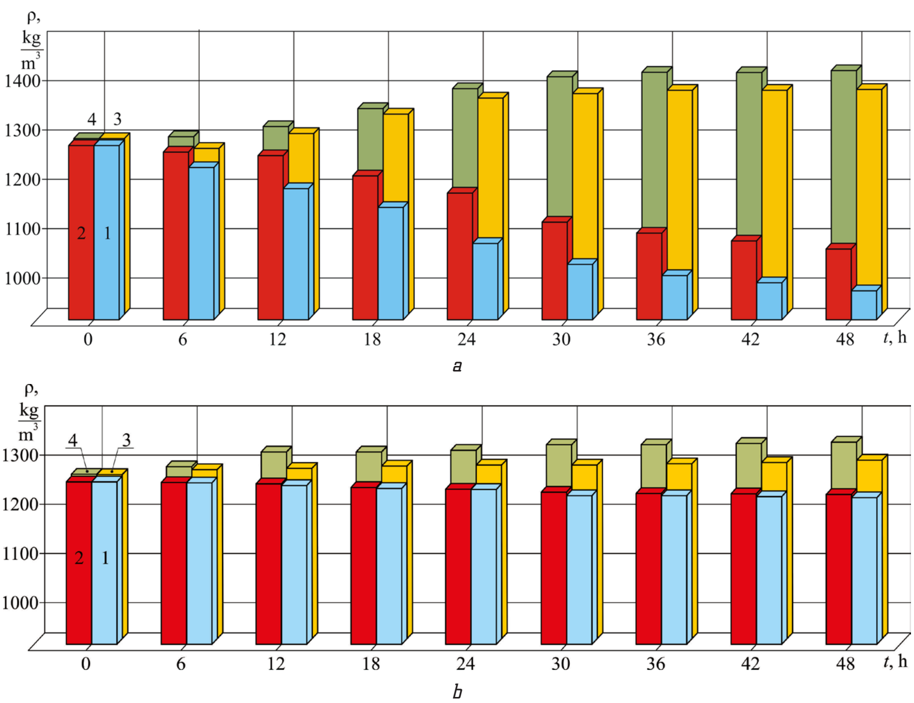

Fig. 4. Change in the density of the drilling fluid at various points in the cargo tank of a PSV vessel: *a* – transportation without changing the configuration of the system; *b* – transportation with additional *X*-shaped circulation; 1 – on the tank surface; 2 – at a depth of 30 % of the tank surface; 3 – at a depth of 60 %; 4 – at a depth of 90 %

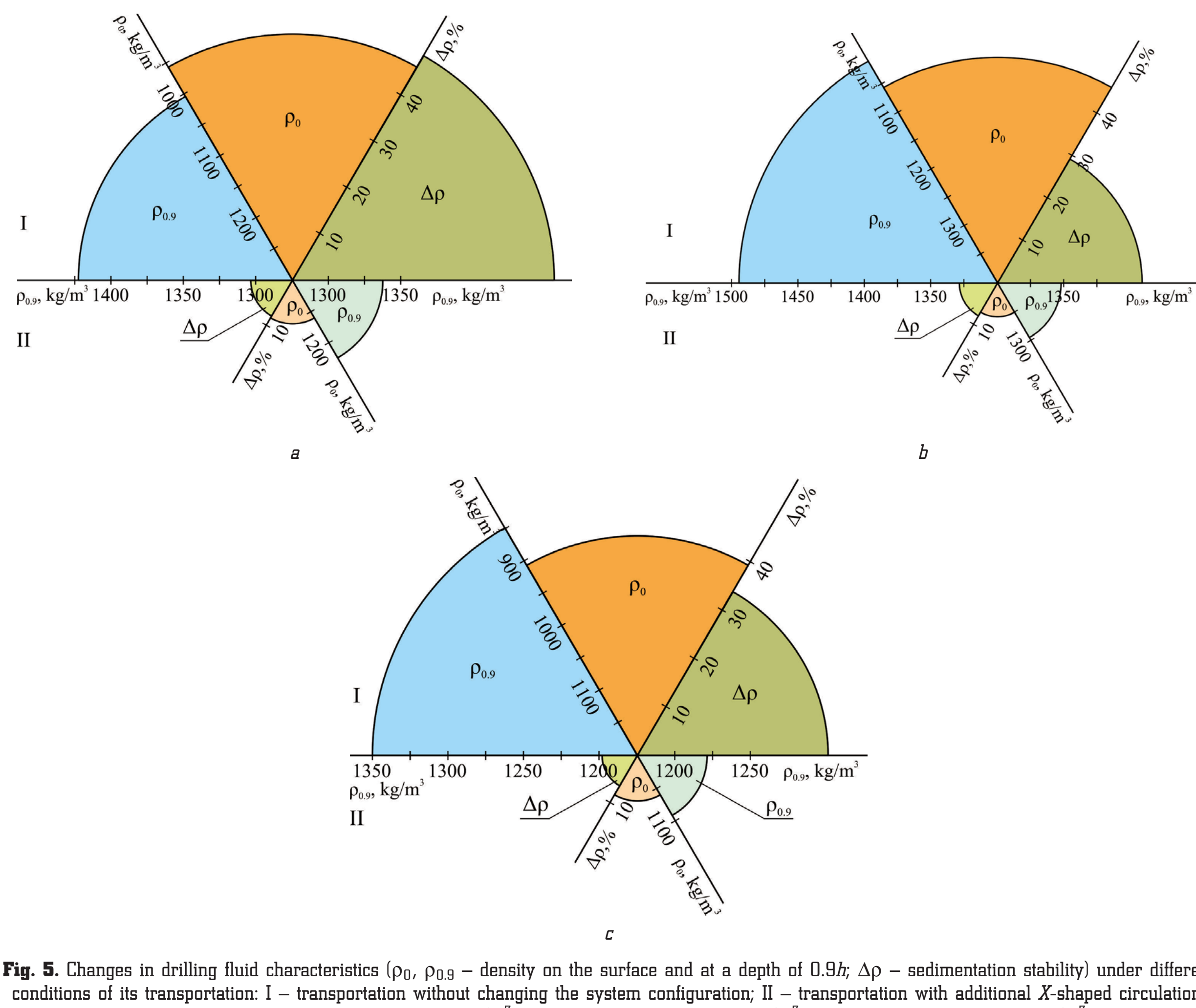

Fig. 5. Changes in drilling fluid characteristics (ρ_0, $\rho_{0.9}$ – density on the surface and at a depth of 0.9*h*; $\Delta\rho$ – sedimentation stability) under different conditions of its transportation: I – transportation without changing the system configuration; II – transportation with additional *X*-shaped circulation; *a* – drilling fluid with a density of 1272 kg/m^3; *b* – with a density of 1323 kg/m^3; *c* – with a density of 1188 kg/m^3

Table 3

Changing the characteristics of the drilling fluid with initial density 1323 and 1188 kg/m^3 under different conditions of its transportation

Time, hours	Density, ρ, kg/m^3, at tank depth		Sedimentation stability, Δρ, %
	on the surface	0.9h	
Transportation without changing the system configuration			
0	1323	1328	0.38
48	1056	1492	29.22
Transportation with additional X-shaped circulation			
0	1323	1327	0.31
48	1251	1348	7.19
Transportation without changing the system configuration			
0	1188	1192	0.34
48	904	1351	33.10
Transportation with additional X-shaped circulation			
0	1188	1190	0.17
48	1143	1222	6.46

Pie charts shown in Fig. 5, *b*, *c* are built according to Table 3. Analysis and comparison of the results performed for drilling fluids with different characteristics shows good convergence and identity of the results obtained, and also confirms the correctness of the experiments.

The general analysis and determination of pressure losses when pumping drilling fluid is difficult (due to the complex expression for H_{fr}). At the same time, it is possible to estimate the level of these losses by changing the flow rate of the drilling fluid pumped by the cargo pump under different operating conditions of the system. For this purpose, when conducting research, a flow meter was additionally installed in the vesselboard system for transporting drilling fluid (position 3 in Fig. 2). After determining the flow rate of the drilling fluid, the relative performance of cargo pumps (position 4 in Fig. 2) was calculated by the expression:

$$\Delta Q = \frac{Q_{real}}{Q_{\max}} \cdot 100~\%,$$

where ΔQ – the relative performance of the pump, %; Q_{real} and $Q_{\max}$ – the actual and maximum performance of cargo pumps, m^3/h.

In this case, both capacities are determined at the same value of the power consumed by the cargo pumps (position 4 in Fig. 2).

Higher values of ΔQ correspond to higher productivity of cargo pumps (higher hourly consumption of drilling fluid in the line) and indicate a decrease in energy losses in the process of pumping drilling fluid to the oil platform. A similar assessment can be made by measuring the pumping time of the drilling fluid from the cargo tanks to the oil platform under different operating conditions of the system. The value of these parameters was determined during the transportation of drilling fluids with different characteristics (density 1272, 1323 and 1188 kg/m^3). The research results are given in Table 4.

Let's note the range of changes in the values of the relative performance of cargo pumps. In the case of transportation of the drilling fluid without changing the design of the system, it is in the ranges of 42–57 %, 37–52 %, 45–58 %. This indicates flow heterogeneity and stratification of the drilling fluid in the main pipeline. When transporting drilling fluid with additional X-shaped circulation, the change in ΔQ values is within 91–94 %, 88–94 %, 92–96 %. This is a confirmation of the uniformity of the drilling fluid and the absence of its stratification.

To visualize the results given in Table 4, pie charts are built that display the effectiveness of various methods of drilling fluid transportation (Fig. 6).

A decrease in the area of sectors corresponding to the pumping time, as well as an increase in the area of sectors corresponding to the relative productivity of cargo pumps, indicates a decrease in energy costs for the process of transporting drilling fluid. The results in Table 4 and in Fig. 6 are characterized by identity, which confirms the correctness of the experiments.

Table 4

Research results

Parameter	A		B		C	
	I	II	I	II	I	II
Relative performance of cargo pumps, ΔQ, %	42–57	91–94	37–52	88–94	45–58	92–96
Drilling fluid pumping time from the vessel to the oil platform, t, hours	7.8	3.6	8.5	3.8	7.1	3.3

Notes: A – drilling fluid with a density of 1272 kg/m^3; B – with a density of 1323 kg/m^3; C – with a density of 1188 kg/m^3. I – transportation without changing the system configuration; II – transportation with additional X-shaped circulation

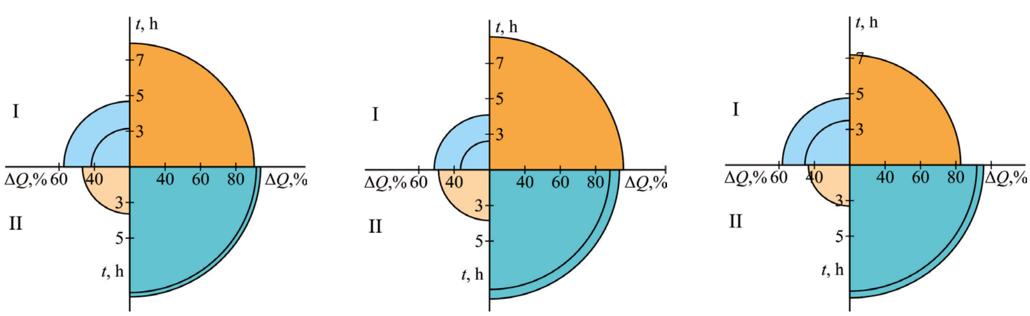

Fig. 6. Evaluation of the effectiveness of various methods of transporting the drilling fluid (ΔQ – relative pump performance, %; t – pumping time, hours): I – transportation without changing the system configuration; II – transportation with additional X-shaped circulation; *a* – drilling fluid with a density of 1272 kg/m^3; *b* – with a density of 1323 kg/m^3; *c* – with a density of 1188 kg/m^3

7. SWOT analysis of research results

Strengths. Strengths of this research:

– the proposed technology for unloading the drilling fluid onto the oil platform at the end of the technological process of unloading the PSV vessel helps to reduce hydraulic losses in the delivery line of the cargo pump;

– provision of an additional *X*-shaped circulation of the drilling fluid between the bottom of one cargo tank and the top of a nearby tank reduces the latent separation of the drilling fluid and prevents the formation of sediment of heavy components;

– maintaining an additional *X*-shaped circulation of drilling fluid minimizes the time of its pumping from the vessel to the drilling platform and reduces energy losses that occur in cargo pumps.

Weaknesses. The weaknesses of this research are related to the fact that in order to use additional *X*-shaped circulation of the drilling fluid, it is necessary to re-equip the system. To perform such work, a temporary decommissioning of the vessel is required.

Opportunities. The application of the proposed method for reducing energy losses in the process of transporting drilling fluid is possible on all PSV class vessels. Re-equipment of the vessel's drilling fluid transportation system, as well as its further operation and control of work, can be carried out independently by the vessel's crew, taking into account the proposed technological scheme.

Threats. The method proposed in this paper to reduce energy losses in the process of transporting drilling fluid is of an applied nature and is based on practical experience. The studies were carried out under constant external disturbing influences on the vessel. To implement the results for all modes and operating conditions of the vessel's propulsion complex, it is necessary to conduct additional studies taking into account the component composition of the drilling fluid, the hydraulic characteristics of the drilling fluid transportation system, as well as external disturbances to the vessel.

8. Conclusions

1. The process of drilling fluid transportation by PSV class vessels must be accompanied by continuous monitoring of its rheological characteristics – density and sedimentation stability. It is advisable to control these parameters at several points and at different depths of the cargo tank. It has been experimentally established that for a drilling fluid with an initial density of 1272 kg/m^3 for a transportation time of 6–48 hours, the following changes in rheological characteristics occur:

– a layer with a density of 1235–962 kg/m^3 is formed on the surface of the cargo tank;

– a layer with a density of 1283–1422 kg/m^3 is formed in the bottom part of the tank;

– sedimentation stability decreases by 3.89–47.82 kg/m^3.

Latent stratification of the drilling fluid leads to the formation of a deposit from heavy components with which it is alloyed. This can lead to breakdown or failure of cargo pumps, the impossibility of pumping the drilling fluid to the drilling platform and further disruption of the oil production process.

2. It is advisable to provide additional *X*-shaped circulation of the drilling fluid along the lines connecting the bottom and upper parts of adjacent cargo tanks.

Additional *X*-shaped circulation of the drilling fluid with an initial density of 1272 kg/m^3 at a transport time of 6–48 hours helps to maintain rheological characteristics in the following range:

– density on the surface of the cargo tank 1270–1232 kg/m^3;

– density in the bottom of the tank 1288–1338 kg/m^3;

– decrease in sedimentation stability 1.42–7.92 kg/m^3.

Similar results were established for drilling fluid with an initial density of 1323 kg/m^3 and 1188 kg/m^3.

3. Reduction of hydraulic losses during unloading of the drilling fluid is achieved by performing this operation at the end of the technological process of unloading the PSV vessel. At the same time, by reducing the draft and increasing the height of the freeboard of the vessel, the static component of the pressure and the hydraulic losses of the cargo pump are reduced.

The complex implementation of these tasks for drilling fluids with different initial density (1272 kg/m^3, 1188 kg/m^3, 1323 kg/m^3) provides:

– increase in the relative performance of cargo pumps from 37–57 % to 88–96 %;

– reduction of drilling fluid pumping time from the vessel to the oil platform from 7.1–8.5 hours to 3.3–3.8 hours;

– maintenance of the technical condition of cargo tanks, lines and cargo pumps of the vessel's drilling fluid transportation system.

The results presented confirm the feasibility of using an additional *X*-shaped circulation of the drilling fluid to reduce energy losses during its transportation by Platform Supply Vessels.

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