Temperature and blend composition influence on emulsion drilling mud effectiveness: a case study of the Yurubcheno-Tokhomskoye oil-gas condensate field

E V Averkina¹, E V Shakirova¹, N A Buglov¹, A K Sotnikov² and E V Nefedeva³

¹ Irkutsk National Research Technical University, Russia
² OJSC Udmurtneft, Russia
³ Irkutsk State Transport University, Russia

E-mail: viva160@mail.ru

Abstract. The use of the hydrocarbon-based emulsion mud (HEM) as a cleaning fluid makes it possible to eliminate many technological difficulties in well drilling. The article presents the results of the study of the temperature effect on the HEM rheological properties and suggests mud formulations for the geological conditions of the Yurubcheno-Tokhomskoye oil-gas condensate field. The study was conducted for six HEM blends with a hydrocarbon base (oil-to-diesel oil ratio being 100/0 and 60/40) as the dispersion medium, and a water solution of sodium salt (NaCl) as the dispersed phase. The HEM evaluation criteria were rheological properties, filtration, and electrical stability. The rheological characteristics were measured at the temperatures of 5, 10, 15, 20, 25, 30, 35, 40, and 45 °C, while the filtration and electrical stability, at room temperature (23±2 °C). The study has shown that for the mud with the oil-to-diesel oil ratio of 60/40, the increase of the content of the functional additives has almost no influence on the mud’s plastic viscosity and electrical stability, while the dynamic shear stress (DSS) increases by a factor of 1.8 - 2.1 and the static shear stress (SSS), by a factor of 1.87. The presented data implies that the HEM’s rheological properties depend on the percentage of diesel oil in the hydrocarbon base and on the mud temperature.

1. Introduction and Background
The commercial development of the Yurubcheno-Tokhomskoye oil-gas condensate field (YTF) is one of the current key projects of PJSC Rosneft Oil Company in Eastern Siberia. Since 2010, JSC East Siberian Oil and Gas Company (JSC Vostsibneftegaz) as the field developer, has been implementing the program of converting the 1C reserves to 2C by making horizontal branch holes from the prospecting wells that did not previously yield industrial oil inflows. The effectiveness of drilling the above wells has exceeded 70% since the program began.

By the geological oil-gas zoning system, the Yurubcheno-Tokhomskoye field is located within the Baikit petroleum bearing area as part of the Lena-Tunguska petroleum bearing province. In tectonic terms, the field is associated with the central part of the Kamovsky pool roof of the Baikit antecline, and its oil-and-gas bearing capacity is conditioned by the Vendian and Riphean carbonate and terrigenous deposits.
The YTF geological structure includes Ordovician, Cambrian, Vendian, and Riphean deposits. The discovered and estimated oil pool in the Riphean deposit presents a wide range of difficulties both in well construction and well completion [1,6].

The most common problems when drilling the above deposits are:
- fluid loss in the fractured rocks;
- fast transition of the well from the fluid loss regime to the regime of oil-gas and water showings (fluid loss with the mud circulating and well flow with no circulation);
- formation of wash-out zones in the salt-bearing deposits;
- flow slide and landslide in the terrigenous part of the oil basin column;
- accumulation of the cuttings and the drill bit seizure [6].

With the account of the abovementioned, the enhancement of the drilling quality requires special attention to the improvement of the drilling mud technological properties and its blend composition, as well as to the drilling mud flushing hydraulics for the wellbores with different zenith angles.

2. Materials and Methods

The use of emulsion muds is one of the effective ways to increase the quality of uncovering hydrocarbon deposits pay horizons under difficult natural, climatic, mining, and geological conditions [5].

The analysis of the YTF practices shows that the design of the drilling mud characteristics for controlled directional well construction should take into account the specifics of the drilling mud treatment by removing the cuttings, as well as the mechanism of the load transfer from the drill column to the drill bit.

As the laboratory and field research experience shows, the Boycott effect immensely intensifies the rock-shattering products sedimentation and complicates the cuttings lifting in the wells with the zenith angle 45°–60° [7]. To neutralize the above effect or to minimize its impact on the drilling process, it is necessary either to provide a turbulent regime of the mud’s flow or to improve the cleaning fluid’s rheological properties.

Besides, a horizontal or slant hole, in comparison with a vertical one, increases the area of the drilling mud influence on the pay horizon. Thus, the drilling of controlled directional wells at the YTF needs special attention to keeping the horizon collecting properties, controlling the contents and composition of the solid phase in the cleaning agent, and controlling the horizon’s water loss.

When choosing the drilling mud for horizontal wells, it is advisable to take into account the previous successful experience for the areas with similar geological features. However, to achieve the best engineering-and-economic performance in the YTF conditions, it is necessary to modify the mud by controlling the following characteristics: lubricity, rheological properties, filter cake thickness, and solid-phase contents.

As all the above factors are interconnected, the basic requirements for the effective drilling of horizontal wells are quality cleaning fluid, proper hydraulic program, effective method of removing the cuttings from the drilling mud, and thorough engineering of the mud characteristics.

In recent years, the emulsion hydrocarbon-based drilling mud is widely used when constructing wells at oil-and-gas fields of the Eastern Siberian region. In comparison with the water-based cleaning fluids, it ensures:
- inertness in the interaction with the drilled rock, resistance to all kinds of salt attack, prevention of the boring tool seizure, increased bit penetration;
- borehole stability when drilling the swelling and sloughing rock, low filtration, and prevention of the high-viscosity mud filtrate penetrating the drilled rock mass;
- elimination or a significant decrease of the fluid loss in the fractured rocks with an abnormally low rock bed pressure;
- minimal effect on the pay horizon and keeping the natural permeability of the wellbore zone.
3. Experimental Section
The Laboratory of Drilling Fluids and Well Cementing together with the colleagues have conducted a study of the temperature effect on the rheological properties of the emulsion hydrocarbon-based drilling mud, and have developed the mud formulations for the geological-and-engineering conditions of the Yurubcheno-Tokhomskoye oil-gas condensate field.

The study was conducted for inverted (water-in-oil) emulsions made by the formulations presented in Table 1. The hydrocarbon base with the oil-to-diesel oil ratio of 100/0 and 60/40 was the dispersion medium and the water solution of sodium salt (NaCl) with the density of 1.17 g/cm³, the dispersed phase. The emulsion was obtained by infusing a reagent consisting of a mixture of fluid emulsifiers. The reagent reacted with lime (as a neutralizer of CO₂, CO₃), calcium soap being the product. As stabilizers, organophilic clay and a wetting agent were used. The drilling mud was being mixed for 40-60 min in a Hamilton Beach high-speed agitator, following which certain chemical reactants were infused in succession to control the rheological and filtration properties of the drilling mud.

Table 1. Drilling mud blend composition, kg (l) / m³.

| №  | Reagent            | HEM 100/0 | HEM 60/40 | HEM 100/0 | HEM 60/40 | HEM 100/0 | HEM 60/40 |
|----|--------------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 1  | Oil                | 601.0     | 360.5     | 620.0     | 372.0     | 611.0     | 366.6     |
| 2  | Diesel oil         | -         | 240.4     | -         | 248.0     | -         | 244.4     |
| 3  | Organophilic clay  | 15.0      | 15.0      | 25.0      | 25.0      | 25.0      | 25.0      |
| 4  | Rheology modifier  | 3.0       | 3.0       | 3.0       | 3.0       | 6.0       | 6.0       |
| 5  | Lime               | 35.0      | 35.0      | 25.0      | 25.0      | 25.0      | 25.0      |
| 6  | Fluid emulsifier mix | 14.0   | 14.0      | 15.0      | 15.0      | 15.0      | 15.0      |
| 7  | Wetting agent      | 1.0       | 1.0       | 1.0       | 1.0       | 3.0       | 3.0       |
| 8  | NaCl               | 90.0      | 90.0      | 40.0      | 40.0      | 25.0      | 25.0      |
| 9  | Water              | 141.0     | 141.0     | 175.0     | 175.0     | 180.0     | 180.0     |
| 10 | Heaver             | 195.0     | 195.0     | 96.0      | 96.0      | 110.0     | 110.0     |
| 11 | Fluid-loss reducer | 5.0      | 5.0       | -         | -         | -         | -         |

Table 2. Physical-mechanical properties of emulsion drilling mud.

| Density, g/cm³ | RV 700/500, S | PV, centipoise | DSS, lb/100 feet² (Pa) | SSS (10 min), lb/100 feet² (Pa) | pH | Electrical stability, V | Filtration, cm²/30 min | Cake, mm |
|----------------|--------------|---------------|------------------------|---------------------------------|----|------------------------|------------------------|---------|
| 1.08           | 75           | 58.6          | 16.3                   | 8.5/8.3                         | 9  | 727                    | 3.0                    | 3.0     |
| 1.08           | 28           | 28.5          | 6.0                    | 3.12/3.54                       | 9  | 450                    | 3.5                    | 1.5     |
| 1.00           | 33.18        | 65.5          | 36.8                   | 10.21/10.83                      | 10 | 602                    | 2.5                    | 2.0     |
| 1.00           | 37.88        | 24.1          | 12.9                   | 6.04/6.66                       | 10 | 500                    | 4.0                    | 2.0     |
| 1.00           | TIK          | 67.7          | 54.4                   | 26.6/26.8                       | 9  | 1419                   | 2.0                    | 3.0     |
| 0.94           | 40.8         | 25.8          | 10.8                   | 5.83/6.23                       | 9  | 440                    | 3.5                    | 2.0     |
The main criteria in evaluating the studied HEM effectiveness were the drilling mud’s rheological characteristics, filtration, and electrical stability that were measured following API standards.

**Table 3.** Rheological parameters of HEM 1: test results for different temperatures.

| Spindle RPM | 600 | 5°C  | 10°C  | 15°C  | 20°C  | 25°C  | 30°C  | 35°C  | 40°C  | 45°C  |
|-------------|-----|------|-------|-------|-------|-------|-------|-------|-------|-------|
|             |     | 204.9| 185.7 | 141.1 | 131.9 | 126.0 | 103.2 | 94.1  | 86.0  | 78.9  |
| 300         | 116.1|      | 104.2 | 80.3  | 74.3  | 67.8  | 59.1  | 55.5  | 49.9  | 45.8  |
| 200         | 82.6 |      | 74.0  | 56.9  | 54.2  | 49.3  | 43.1  | 40.8  | 36.8  | 35.2  |
| 100         | 47.4 |      | 49.9  | 34.8  | 32.9  | 29.9  | 26.9  | 25.7  | 23.9  | 23.1  |
| 60          | 37.2 |      | 32.3  | 29.5  | 24.0  | 22.5  | 22.0  | 20.8  | 18.9  | 18.1  |
| 30          | 23.2 |      | 20.4  | 17.2  | 18.7  | 16.4  | 14.5  | 14.2  | 13.6  | 13.3  |
| 20          | 17.8 |      | 16.4  | 14.2  | 14.7  | 13.5  | 11.5  | 11.3  | 11.2  |       |
| 10          | 12.9 |      | 11.8  | 10.2  | 10.8  | 10.2  | 9.1   | 9.0   | 9.2   |       |
| 6           | 10.5 |      | 9.7   | 9.1   | 9.4   | 8.9   | 8.6   | 8.3   | 8.5   | 8.7   |
| 3           | 7.9  |      | 6.5   | 6.3   | 6.3   | 5.8   | 5.5   | 5.0   | 5.1   | 5.1   |
| PV. cp      |     | 89   | 81.5  | 60.8  | 58.6  | 58.2  | 44.1  | 38.6  | 36.7  | 33.1  |
| DSS. lb/100 feet$^2$ (Pa)| 27  | (13.0)| 22.7  | 19.5  | 16.7  | 9.6   | 15.0  | 16.9  | 13.2  | 12.7  |
|             |     | (10.8)| (9.4) | (7.8) | (4.6) | (7.2) | (8.1) | (6.3) | (6.1) |       |

The rheological indices were measured at the temperatures of 5, 10, 15, 20, 25, 30, 35, 40, and 45°C; the filtration and electrical stability parameters, at room temperature(23±2°C).

**Table 4.** Rheological parameters of HEM 2: test results for different temperatures.

| Spindle RPM | 600 | 5°C  | 10°C  | 15°C  | 20°C  | 25°C  | 30°C  | 35°C  | 40°C  | 45°C  |
|-------------|-----|------|-------|-------|-------|-------|-------|-------|-------|-------|
|             |     | 89.0 | 78.0  | 67.2  | 65.1  | 56.9  | 51.6  | 49.0  | 44.1  | 40.8  |
| 300         | 48.2 |      | 41.8  | 33.7  | 35.8  | 28.4  | 29.6  | 26.9  | 24.4  | 22.6  |
| 200         | 33.6 |      | 29.5  | 26.1  | 25.7  | 21.5  | 21.7  | 18.8  | 17.7  | 16.5  |
| 100         | 18.6 |      | 16.8  | 14.9  | 15.0  | 12.0  | 12.2  | 11.7  | 10.7  | 10.0  |
| 60          | 12.6 |      | 11.6  | 10.1  | 10.6  | 8.6   | 8.9   | 8.6   | 8.1   | 7.7   |
| 30          | 8.0  |      | 7.2   | 6.6   | 6.6   | 5.7   | 5.8   | 5.7   | 5.4   | 5.2   |
| 20          | 5.8  |      | 5.6   | 5.2   | 5.2   | 4.8   | 4.9   | 4.8   | 4.7   | 4.3   |
| 10          | 4.0  |      | 3.8   | 3.6   | 3.7   | 3.0   | 3.0   | 3.0   | 3.0   | 2.9   |
| 6           | 3.4  |      | 3.3   | 3.2   | 3.1   | 2.7   | 2.7   | 2.6   | 2.7   | 2.6   |
| 3           | 2.5  |      | 2.2   | 2.1   | 2.0   | 1.8   | 1.8   | 1.8   | 1.8   | 1.7   |
| PV. cp      |     | 40.8 | 36.2  | 33.5  | 29.3  | 28.5  | 22.0  | 22.1  | 19.7  | 18.2  |
| DSS. lb/100 feet$^2$ (Pa)| 7.4  | (3.5)| 5.6   | 0.2   | 4.5   | 0.1   | 7.6   | 4.8   | 4.7   | 4.4   |
|             |     | (2.7)| (0.1) | (2.1) | (0.5) | (3.6) | (2.3) | (2.3) | (2.1) |       |

The dependence of the blend parameters on the blend composition and the temperature is presented in Tables 2–8 and Figures 2,3,4. The analysis of the data shows the following.
1. The increase of the content of organophilic clay, rheology modifier, fluid emulsifier mix, and NaCl in the oil-based mud (HEM 1,3,5) results in the increase of the plastic viscosity by 12-15%, DSS by a factor of 2.2-3.3, SSS by a factor of 1.2-3.1, and electrical stability by a factor of 2.

2. The increase of the reagent contents in the 60/40 oil-diesel oil blend (HEM2,4,6) has almost no influence on the drilling mud plastic viscosity (PV) and electrical stability, though it results in the increase of DSS by a factor of 1.8–2.1, and SSS by a factor of 1.87.

Table 5. Rheological parameters of HEM 3: test results for different temperatures.

| Spindle RPM | Rheological parameters at different temperatures, D.R. |
|-------------|-------------------------------------------------------|
|             | 5°C   | 10°C  | 15°C  | 20°C  | 25°C  | 30°C  | 35°C  | 40°C  | 45°C  |
| 600         | 264.4 | 258.0 | 215.8 | 116.8 | 143.6 | 141.8 | 128.5 | 112.9 | 100.1 |
| 300         | 150.1 | 145.9 | 123.7 | 66.7  | 83.7  | 81.5  | 73.4  | 65.2  | 58.8  |
| 200         | 107.2 | 104.9 | 89.9  | 48.8  | 63.6  | 59.8  | 54.1  | 49.0  | 44.8  |
| 100         | 60.8  | 60.8  | 53.0  | 29.9  | 39.3  | 38.0  | 35.0  | 31.9  | 29.5  |
| 60          | 41.3  | 42.2  | 37.5  | 21.5  | 29.3  | 28.6  | 26.5  | 24.3  | 22.9  |
| 30          | 25.7  | 27.3  | 25.7  | 15.0  | 20.7  | 20.6  | 19.3  | 17.3  | 16.5  |
| 20          | 20.2  | 22.0  | 20.4  | 12.8  | 17.3  | 17.0  | 16.2  | 15.2  | 14.3  |
| 10          | 14.3  | 17.1  | 15.1  | 9.8   | 13.6  | 13.5  | 13.1  | 12.2  | 11.7  |
| 6           | 11.9  | 13.6  | 13.2  | 8.6   | 12.3  | 12.0  | 11.7  | 11.2  | 10.9  |
| 3           | 9.2   | 10.3  | 10.5  | 7.3   | 10.1  | 10.0  | 9.4   | 9.1   | 8.6   |
| PV. cp      | 114.3 | 112.1 | 91.5  | 50.1  | 59.9  | 60.3  | 55.1  | 47.7  | 41.3  |
| DSS. lb/100 feet² (Pa) | 32.8 (17.2) | 33.8 (16.2) | 32.2 (15.5) | 23.8 (7.9) | 21.2 (10.8) | 18.3 (10.2) | 17.5 (8.8) | 17.5 (8.4) |

Table 6. Rheological parameters of HEM 4: test results for different temperatures.

| Spindle RPM | Rheological parameters at different temperatures, D.R. |
|-------------|-------------------------------------------------------|
|             | 5°C   | 10°C  | 15°C  | 20°C  | 25°C  | 30°C  | 35°C  | 40°C  | 45°C  |
| 600         | 83.7  | 69.6  | 62.1  | 59.2  | 59.2  | 53.6  | 49.4  | 44.8  | 40.8  |
| 300         | 46.8  | 39.6  | 36.1  | 35.6  | 35.6  | 32.6  | 30.3  | 28.1  | 25.6  |
| 200         | 33.8  | 29.2  | 26.8  | 26.6  | 26.7  | 24.5  | 23.4  | 21.4  | 19.9  |
| 100         | 20.1  | 18.1  | 16.8  | 16.9  | 17.0  | 16.3  | 15.6  | 14.5  | 13.6  |
| 60          | 14.6  | 13.3  | 12.6  | 13.3  | 13.4  | 12.8  | 12.4  | 11.3  | 10.1  |
| 30          | 9.9   | 9.3   | 9.0   | 9.4   | 9.4   | 9.2   | 8.9   | 8.5   | 8.1   |
| 20          | 8.2   | 7.9   | 8.1   | 8.4   | 8.3   | 8.0   | 7.9   | 7.8   | 7.5   |
| 10          | 5.9   | 6.0   | 6.0   | 7.2   | 7.1   | 7.0   | 6.8   | 6.8   | 6.6   |
| 6           | 5.5   | 5.5   | 5.6   | 6.8   | 6.7   | 6.6   | 6.5   | 6.4   | 6.2   |
| 3           | 4.6   | 4.6   | 4.6   | 6.2   | 6.1   | 5.9   | 5.8   | 5.8   | 5.8   |
| PV. cp      | 36.9  | 30.0  | 26.0  | 23.6  | 23.6  | 21.0  | 19.1  | 16.7  | 15.2  |
| DSS. lb/100 feet² (Pa) | 9.9 (4.8) | 9.6 (4.7) | 10.1 (4.8) | 12.0 (5.8) | 12.0 (8.5) | 11.6 (5.6) | 11.2 (5.4) | 11.4 (5.5) | 10.4 (5.0) |

3. The drilling mud made using clean oil has higher rheological and electrical stability indices than the oil-diesel oil mud. This is connected with the fact that the YTF petroleum blend includes natural
emulsifiers, as phaltenes, and resinous substances[2]. Thus, the use of this oil as the dispersion medium for the drilling mud makes it possible to achieve technologically reasonable rheological properties of HEM with a smaller amount of functional additives.

**Table 7.** Rheological parameters of HEM 5: test results for different temperatures.

| Spindle RPM | Rheological parameters at different temperatures, D.R. |
|-------------|--------------------------------------------------------|
|             | 5°C  | 10°C | 15°C | 20°C | 25°C | 30°C | 35°C | 40°C | 45°C |
| 600         | 283.2| 282.0| 234.3| 191.0| 180.2| 158.4| 137.3| 123.9| 114.8|
| 300         | 173.0| 171.4| 145.0| 122.0| 115.6| 102.0| 91.0 | 84.0 | 79.0 |
| 200         | 132.0| 129.0| 111.3| 94.3 | 89.5 | 80.4 | 73.0 | 68.0 | 64.7 |
| 100         | 83.0 | 82.0 | 72.0 | 63.5 | 61.0 | 57.4 | 53.0 | 49.9 | 48.3 |
| 60          | 62.0 | 61.9 | 54.7 | 50.2 | 48.7 | 46.8 | 43.5 | 41.5 | 40.5 |
| 30          | 44.8 | 45.1 | 40.5 | 39.0 | 38.0 | 37.0 | 34.8 | 33.1 | 32.0 |
| 20          | 38.9 | 39.1 | 35.6 | 34.7 | 34.4 | 33.7 | 32.0 | 30.1 | 30.0 |
| 10          | 32.0 | 32.4 | 30.4 | 30.0 | 29.7 | 29.4 | 28.1 | 26.7 | 26.6 |
| 6           | 29.5 | 29.9 | 28.4 | 27.9 | 27.9 | 27.6 | 26.2 | 25.1 | 24.5 |
| 3           | 24.8 | 24.7 | 24.0 | 23.5 | 23.5 | 23.4 | 22.9 | 22.4 | 21.3 |
| PV. cp DSS. | 110.2| 110.6| 89.3 | 69.0 | 64.6 | 56.4 | 46.3 | 39.9 | 35.8 |
| lb/100 feet² | (30.1) | (29.2) | (26.7) | (25.4) | (24.4) | (21.9) | (21.5) | (21.2) | (20.7) |

**Table 8.** Rheological parameters of HEM 6: test results for different temperatures.

| Spindle RPM | Rheological parameters at different temperatures, D.R. |
|-------------|--------------------------------------------------------|
|             | 5°C  | 10°C | 15°C | 20°C | 25°C | 30°C | 35°C | 40°C | 45°C |
| 600         | 88.1 | 88.2 | 73.2 | 62.8 | 53.1 | 48.2 | 45.3 | 44.0 | 42.7 |
| 300         | 50.1 | 47.4 | 42.0 | 36.9 | 31.7 | 29.0 | 27.4 | 27.1 | 26.5 |
| 200         | 35.8 | 34.5 | 30.7 | 27.6 | 23.6 | 22.1 | 21.3 | 21.3 | 21.0 |
| 100         | 21.8 | 21.0 | 19.2 | 17.7 | 15.4 | 14.5 | 14.0 | 14.0 | 13.9 |
| 60          | 15.6 | 17.2 | 14.2 | 13.3 | 11.8 | 11.5 | 11.2 | 11.2 | 11.2 |
| 30          | 10.7 | 10.4 | 10.1 | 9.6  | 8.9  | 8.5  | 8.3  | 8.6  | 8.7  |
| 20          | 9.1  | 8.2  | 8.6  | 8.2  | 7.2  | 7.2  | 7.2  | 7.2  | 7.3  |
| 10          | 6.8  | 6.8  | 6.6  | 6.5  | 5.8  | 5.9  | 5.9  | 6.1  | 6.3  |
| 6           | 5.6  | 5.6  | 5.8  | 5.7  | 5.2  | 5.4  | 5.4  | 5.5  | 5.7  |
| 3           | 4.5  | 4.5  | 4.6  | 4.5  | 4.7  | 4.8  | 4.8  | 4.8  | 4.2  |
| PV. cp DSS. | 38.0 | 40.8 | 31.2 | 25.9 | 21.4 | 19.2 | 17.9 | 16.9 | 16.2 |
| lb/100 feet² | (5.8) | (3.2) | (5.2) | (5.3) | (4.9) | (2.0) | (4.6) | (4.9) | (4.9) |

4. Results and Discussion

The analysis of the research results presented in Figures 2, 3, 4 and Table 3 shows that the mud rheological properties characterizing the mud’s cutting-carrying and holding capacity change in a relatively wide range depending on the temperature.
When the temperature rises from 5°C to 45°C, the gel’s plastic viscosity, dynamic shear stress, and strength sharply decrease. This can degrade the quality of the borehole cleaning as the drilling mud loses its sedimentation capacity and cannot hold fine-dispersed solid phase.

At the temperatures below 15°C, the mud thickens to a very viscous, up to a non-fluid state, which hinders the mud circulation and can cause equivalent circulating density (ECD) overrun, fluid loss, hydrofrac, circulation loss, and oil-gas-water flow when drilling-in.

It is important to note that the structure rheological properties of the oil-based mud meet the project documentation requirements at temperatures not lower than 30°C.

![Figure 1. Dependence of HEM plastic viscosity on the temperature.](image1)

Some researchers state that the use of a shear-liquefied mud makes it possible to meet the requirements concerning the drilling mud rheological properties [3]. When the mud circulation stops, the mud structure becomes enough to hold the cuttings suspension, and with the mud flowing, the structure dissolves, and the mud becomes more fluid. The mud has a high ratio of the ultimate dynamic shear stress to the plastic viscosity (YP/PV), and a low non-linearity value. The practice shows that to achieve high YP/PV values, it is advisable to decrease the plastic viscosity rather than to increase the ultimate dynamic shear stress.

![Figure 2. Dependence of HEM static shear stress on the temperature.](image2)
The non-linearity value characterizes the degree of the drilling mud behavior deviation from the behavior of Newtonian fluids [9]. As it is known, the cleaning fluid with the non-linearity N<1 does not create additional hydrodynamic pressure on the permeable beds in the well tubing-casing annulus, i.e. the mud keeps the integrity of its structure [8]. This is especially important for the cutting transport and prevention of hydrofrac in case of the weakly cemented rocks, as well as for drilling-in. Such drilling mud is described by the rheological model of pseudo-plastic liquids (the Ostwald-de Waele model):

$$\tau = C \cdot \dot{\gamma}^N,$$

where $\tau$ is shear stress, Pa; $C$ is consistency index; $\dot{\gamma}$ is shear rate, s$^{-1}$; $N$ is non-linearity index that characterizes the degree of the fluid rheological behavior deviation from the Newtonian liquid.

$N$ is a measure of the inertness-to-viscosity ratio and is calculated by the formula:

$$N = 3.32 \cdot \lg(\frac{\varphi_{500}}{\varphi_{300}}).$$

The studies of the processes taking place during jetting show that it is most practical to use the pseudo-plastic fluid with the non-linearity index N<1 [6,7,8,9], which flattens the cleaning fluid flow rate curve and as a result, increases the fluid's carrying capacity. With $N>1$, abrupt loss of pressure needed for the mud circulation takes place.

The non-linearity index calculation was conducted for HEM 1-6 at the temperature of 25°C. The calculation results are presented in Table 9.

| Non-linearity index | $N_1$ | $N_2$ | $N_3$ | $N_4$ | $N_5$ | $N_6$ |
|---------------------|------|------|------|------|------|------|
| Calculation results | 0.893 | 1.002 | 0.778 | 0.733 | 0.64 | 0.743 |

The calculation shows that the drilling mud with $N<1$ does not create significant additional pressure on the permeable beds in the tubing-casing annulus of the well, which is important for the cutting transport, prevention of weakly cemented rock hydrofrac, as well as for drilling-in.

Figure 3. Dependence of HEM dynamic shear stress on the temperature.

With the temperature rise from 5°C to 45°C, there is a decrease of the plastic viscosity by 65% on the average, and of DSS, by 53% in case of the oil-based HEM (Table 3, Figures 2,3,4). In the case of the oil-to-diesel oil ratio of 60/40, there is a decrease of the above indices by 57% and 28%, correspondingly. The intensity of the plastic viscosity decrease is higher than that of DSS, thus the
ratio YP/PV does not decrease; on the contrary, it increases. Therefore, the studied HEM keeps the carrying capacity all along the wellbore with the temperature rise.

The YTF practice of drilling field wells clearly shows the necessity of minimizing the structure rheological indices of the drilling mud to provide partial load modes of the hydrodynamic influence on the opened rock mass [13].

The analysis of the geophysical studies (GIS) data for 2015-2015 has shown an abnormal growth of the rheological indices that could lead to fluid loss [8].

To minimize the ECD, the drilling mud was diluted with diesel oil before the settling; also, the cleaning technology allowed for starting the mud circulation with the minimal load of the slush pumps [11].

At present, on the territory of the YTF, there have been 15 field wells drilled using HEM, 10 of which have been already tested.

5. Summary and Conclusions
The YTF practice of welldrilling and the laboratory test results allow us to draw the following conclusions.

1. The crude-based HEM has heightened rheological indices reaching the upper limit of the specified values [10].
2. The HEM rheological characteristics depend on the percentage of diesel oil in the hydrocarbon base and on the drilling mud temperature [12,14].
3. The emulsion mud formulations based on oil only do not ensure stable optimal characteristics of the mud that ensure trouble-free well drilling. The average content of diesel oil in HEM should not be less than 40% of the total volume of the produced mud [15].
4. The cutting-carrying capacity of the drilling mud is one of the characteristics requiring special attention because of the significant Boycott effect in the inclined sections of the wellbore.

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