Experimental research and development of drilling fluid formulations to reduce the rate of the permafrost thawing

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Abstract. The paper is devoted to complex experimental studies of methods to reduce the rate of permafrost thaw during the construction of oil and gas wells in the fields of the Krasnoyarsk territory. Laboratory physical and chemical studies on the development of drilling fluid formulations for drilling in permafrost conditions were carried out. The most significant results were obtained for clay-polymer solutions with the addition of ethylene glycol and propylene glycol. It was shown that it is possible to control the thermal, hydration and filtration characteristics of drilling fluids by introducing ethylene glycol and propylene glycol without deterioration of their rheological properties.

1. Introduction

Conditions for drilling oil and gas wells in northern latitudes are determined by the presence of permafrost in these latitudes. Permafrost is defined as rocks that are constantly under negative temperatures. Construction and operation of oil and gas facilities in permafrost conditions is complicated by the problem of partial or complete thawing of soils near objects that are a source of heat. This leads to long-term repairs, idle wells and significant losses of drilling fluids [1,2].

Currently, the main part of the new oil and gas fields of the Krasnoyarsk territory is being developed in the northern latitudes in the conditions of permafrost. According to unofficial data, the impact on permafrost (thawing) as a result of drilling causes 23% of technical systems failure and 29% of oil and gas production losses. The problem of permafrost thawing during drilling and well operation is particularly acute for the Vankor field in the Krasnoyarsk territory, which is characterized by abnormally high temperatures of permafrost in the range of -0.5 to -0.2 °C. At such high temperatures, permafrost thawing occurs at a very high rate, which is not typical for other regions. Under the thawing of rocks, the well structure may lose its longitudinal stability and deform, which makes operation of the well worth hundreds of millions of rubles impossible. In this regard, the formulations of drilling fluids with reduced melting capacity developed in the framework of this study can be used in the fields of the Krasnoyarsk territory [3-5]. Frilling fluids for permafrost drilling have been developed for a long time both in Russia and abroad, and a large number of works are known in this area. In particular, the inhibitory ability of solutions with additives of various glycols is well known.
Thus, drilling fluids based on ethylene glycol were used to eliminate complications during drilling in Antarctic glaciers [8]. Solutions based on polyethylene glycol and propylene glycol (up to 10 wt.%) were used to inhibit clay shale and prevent the formation of gas hydrates in the borehole [9,10]. In contrast to previous studies on this topic, this is the first systematic laboratory study of the properties of drilling fluids based on ethylene glycol and propylene glycol for various polymer and clay-polymer compositions. As a result, formulations of drilling fluids with a high content of glycol have been developed without significant deterioration of rheological properties.

2. Preparation of drilling fluids

Laboratory physical and chemical studies on the development of drilling fluid formulations for drilling in permafrost conditions were carried out. During laboratory research, the main types of drilling fluids used for drilling in permafrost were considered. These were water-based solutions with various clay-polymer compositions, solutions based on diatomic alcohols (ethylene glycol and propylene glycol). The following polymer additives were considered: technical starch, high-molecular biopolymer Duo-Vis, gammaxan GAM (Mirrico, Russia), xanthan XAN, cationic flocculant FLOPAM™ AN934 VHM (SNF, France), polyanion cellulose PAC. The influence of these additives on the viscosity, rheology, filtration and swelling capacity, thermal conductivity and heat capacity of drilling fluids was studied.

The study of the rheology of the created drilling fluids was carried out using rotary viscometers OFITE HPHT and OFITE 900 at temperatures and pressures maximally close to the well conditions of the fields of the Krasnoyarsk territory. OFITE HPHT is a fully automated system designed to determine the rheological properties of drilling fluids and oil-well cements at elevated temperatures (up to 260°C) and pressures (up to 17 MPa). Shear stress range is 0-4000 dyne/cm². Range of rotation speed is: 0.01-600 rpm. Accuracy of speed maintenance is 0.001 rpm. The shear rate varies between 3 and 1022 s⁻¹.

For research on the hydration of clay rocks, tablets were made from bentonite of the PBMA brand of the Chernogorsky Deposit. Tablets were pressed on an OFITE compactor at a pressure of 20.68 MPa for 30 minutes, which allowed reaching tablet permeability of 2.08 MD. The research was carried out on a longitudinal swelling tester from OFITE. Tablets were placed in test cells and filled with the test solution. The software allows studying the hydration process automatically for a long time. The mineralogical composition of clays of the Chernogorsky Deposit was determined on the basis of data from x-ray diffraction analysis performed on a diffractometer manufactured by Shinadzu XRD-6000.

The thermal conductivity coefficient of the developed drilling fluids was measured using the hot wire method. The method of measuring the thermal conductivity coefficient using this method was implemented and tested by our team earlier. Its full description may be found in [11].

The OFITE HPHT 171-01 filter press, designed specifically to simulate well conditions, was used to study the filtration losses of drilling fluid. 500 ml of the test solution was placed in the press filter. Then a pressure of 7atm was applied to the suspension, and it was filtered through an appropriate filter. At the same time, according to the API standard (American Petroleum Institute), the volume of filtered fluid was measured in a time equal to 30 minutes. The volume of fluid leaked during this time through the filter is called filtration losses. Each experiment was repeated three times. The data spread across the three dimensions does not exceed 5%.

3. Experimental study

3.1. Study of drilling fluid rheology

The effect of the mass content of ethylene glycol (EG) and propylene glycol (PG) in a water-polymer solution with 2.0 wt% starch and 0.5 wt% GAM on the rheology of drilling fluids is studied. The mass concentration of glycols varies from 0 to 80%. It is shown that the viscosity of these solutions
decreases with increasing shear rate for all ethylene glycol concentrations (Table 1). Thus, these solutions are pseudoplastic fluids. The dependence of the effective viscosity on the concentration of ethylene glycol shows that at low values of the shear rate, the viscosity of the solution has a minimum at a concentration equal to 35 wt%. At the same time, the decrease in viscosity to the minimum is not very significant and is about 15%. With a further increase in the concentration of EG, the viscosity of the solution increases. At high values of the shear rate, the viscosity increases monotonously with increasing EG concentration. From a practical point of view the effect of ethylene glycol on the effective viscosity of the polymer solution is found to be insignificant, except for a very high concentration of 80 wt%. The rheology of the solutions was described using the most common power-law and Bingham models. The analysis of confidence coefficients allows us to conclude that at low EG contents rheology is better described by the power model, and at high concentrations-by the Bingham model. Analysis of the behavior of rheological parameters of drilling fluids shows that the consistency index is weakly dependent on the concentration of EG. The power model index increases slightly with increasing EG concentration. The plastic viscosity and limit shear stress at EG concentrations below 35 wt% are slightly reduced compared to the base solution. With a further increase in the concentration of EG, these characteristics monotonously increase. However, in absolute terms, except for the concentration of 80%, these changes are insignificant. Thus, it can be argued that the addition of ethylene glycol up to high concentrations (65 wt%) does not impair the rheological properties of polymer solutions. Qualitatively similar results were obtained when studying the properties of drilling fluids with propylene glycol additives (see Table 2). It was shown, that the increase in the content of PG in the drilling fluid increases the plastic viscosity and limit shear stress. At the same time, it was found that in general, the effect of PG additives on the rheological characteristics of drilling fluids is stronger than with EG additives, due to the higher viscosity of pure propylene glycol.

Table 1. Rheological and thermophysical properties of drilling fluids based on an aqueous mixture of ethylene glycol with additives of 2.0 wt.% starch and 0.5 wt.% gammexane.

| ϕ, % | PV   | YP   | $R_1^2$ | n   | $R_2^2$ | $G_1$ | $G_2$ | $\lambda$ | $C_p$ |
|------|------|------|---------|-----|---------|-------|-------|-----------|-------|
| 0    | 30.26| 11.71| 0.948   | 0.279| 4.94    | 0.983 | 8     | 10        | 0.624 | 4.18  |
| 20   | 29.35| 10.94| 0.950   | 0.283| 4.59    | 0.980 | 8     | 10        | 0.550 | 3.80  |
| 35   | 24.23| 10.98| 0.960   | 0.242| 5.29    | 0.967 | 8     | 10        | 0.495 | 3.52  |
| 50   | 30.37| 11.64| 0.960   | 0.270| 5.17    | 0.968 | 9     | 10        | 0.430 | 3.25  |
| 65   | 37.03| 11.90| 0.969   | 0.298| 4.90    | 0.968 | 9     | 11        | 0.371 | 2.99  |
| 80   | 61.18| 13.71| 0.984   | 0.354| 4.95    | 0.964 | 10    | 14        | 0.324 | 2.74  |
### Table 2. Rheological and thermophysical properties of drilling fluids based on an aqueous propylene glycol mixture with additives of 2.0 wt. % starch and 0.5 wt. % gamma-xane.

| φ, % | PV       | YP   | $R_1^2$ | n  | K | $R_2^2$ | $G_1$ | $G_2$ | λ   | $C_p$ |
|------|----------|------|---------|----|---|---------|-------|-------|-----|-------|
| 0    | 30.26    | 11.71| 0.279   | 4.94| 8 | 10      | 0.624 | 4.18  | 30.26| 11.71 |
| 20   | 38.25    | 13.27| 0.292   | 5.450| 10| 11      | 0.536 | 3.81  | 38.25| 13.27 |
| 35   | 38.43    | 14.78| 0.268   | 6.609| 11| 12      | 0.475 | 3.59  | 38.43| 14.78 |
| 50   | 41.20    | 12.49| 0.307   | 5.027| 9 | 11      | 0.414 | 3.34  | 41.20| 12.49 |
| 65   | 51.14    | 12.94| 0.336   | 4.846| 9 | 12      | 0.352 | 3.08  | 51.14| 12.94 |
| 80   | 91.17    | 11.02| 0.591   | 1.595| 3 | 5       | 0.291 | 2.83  | 91.17| 11.02 |

φ – mass content of ethylene glycol, %; PV – plastic viscosity, MPa·s; YP – yield point, Pa; $R_1^2$ – confidence coefficient for the Bingham model; n – power model index; K – consistency index; $R_2^2$ – confidence coefficient for the power model; $G_1$ – static shear stress after 10 seconds, Pa; $G_2$ – static shear stress after 10 minutes, Pa; λ – coefficient of thermal conductivity, W/(m·K); $C_p$ – specific heat capacity, kJ/(kg·K)

### 3.2. Investigation of the inhibitory ability of drilling fluids

An important factor affecting the stability of the well walls during permafrost drilling is the process of swelling of clay minerals. Penetration of water, formed as a result of permafrost thawing and contained in the solution, into rock beds composed of compacted clays, argillites or clay shales leads to their swelling, bulging into the well bore and, ultimately, to the failure of the well wall. As a result, extended cavities are formed, and the diameter of the well bore increases, which further creates problems when cementing the well walls. Therefore, to increase the stability of the well walls, it is necessary to use drilling fluids that have a low degree of clay swelling. Many works were devoted to the study of hydration of clay minerals, however, in the field of studying the interaction of clay rocks with drilling fluids of various compositions, this issue remains insufficiently studied. Figure 1 shows the graphical dependences of changes in the linear dimensions of clay tablets in the solutions with different ethylene glycol content and various polymer additives. It was shown that the degree of swelling of clay monotonously decreases with an increase in the concentration of ethylene glycol. At the same time, this decrease is quite significant. So when the content of ethylene glycol in the solution is 50 wt. % the degree of swelling is reduced by almost three times compared to the solution on water.
Figure 1. The curve of swelling of the tablets in polymer solutions (EG Water+2.0% starch+0.5% gammaxan) at certain mass content of ethylene glycol (a) and in solutions with various polymer additives at a mass content of 50% ethylene glycol (b).

Figure 1b shows data on the swelling of clay tablets in a solution containing 50% ethylene glycol and 1.0% starch with additives of various polymers with a mass concentration of 0.25%. Studies have shown that the type of polymer additive also affects the dynamics of the swelling process. Duo-Vis and GAM polymers have a lower degree of swelling at initial times, so they are more preferable. In the final stage of the process, the degree of swelling of clay in different polymer solutions is approximately the same. However, regardless of the type of polymer additive, the degree of swelling of clay in a solution with ethylene glycol is significantly lower than in aqueous solutions. According to modern studies, the main mechanism of action of glycols on the swelling of clay is that they prevent the formation of hydrogen bonds between water and clay plates. Ethylene glycol can also form hydrogen bonds with clay minerals and displace water from silica and alumina groups, thereby preventing hydration. Another important and poorly understood issue in stabilizing clay with water-based drilling fluids containing ethylene glycol is the role of salts. The most important influence of salt (for example, potassium or sodium ions) occurs due to the interaction of exchange ions on the clay surface and adsorbed glycol molecules. This interaction leads to the formation of agglomerates. Agglomerates with glycol molecules (larger than a water molecule) are less mobile than agglomerates formed by water. It also leads to a decrease in the speed of the process of swelling.

Investigation of the effect of the inhibitory ability of solutions with propylene glycol additives (see Fig. 2 and Fig. 3.) shows that propylene glycol also reduces the rate of clays swelling significantly. It has been shown that the additive of 65 wt.% propylene glycol reduces the swelling rate 4.7 times compared to pure water and 3.2 times compared to the base polymer solution. Comparison of solutions with ethylene glycol and propylene glycol additives shows that the inhibitory ability of propylene glycol is about 1.5 times higher than that of ethylene glycol.
3.3. Study of filtration characteristics of drilling fluids

The filtration characteristics of polymer and clay-polymer solutions with glycol additives are studied. In the process of drilling oil and gas wells, drilling fluid can penetrate into the rock through the well walls. This phenomenon is called filtration losses. At the same time, there is a loss of drilling fluid (absorption), which increases the cost of well construction. At the same time, filtration losses of drilling fluid in the rock bed are one of the main reasons for the formation of cracks and instability of the well bore. When drilling in permafrost conditions, it is necessary to use solutions with minimal filtration losses, since filtering the drilling fluid through the melted rock will lead to additional heat supply to the permafrost, thereby accelerating the rate of thawing. As a result of the study, it is shown that the addition of ethylene glycol and propylene glycol significantly reduces the filtration losses of drilling fluids. For example, adding 80 wt% ethylene glycol to an aqueous solution containing XAN of 0.3 wt % + starch of 2 wt % + clay of 5 wt % reduces filtration losses approximately 1.8 times and 2.5 times when adding it to a solution containing GAM of 1 wt % + starch of 2 wt % + clay of 5 wt %. At the same time, a decrease in filtration losses when adding glycols is observed for all the considered polymer additives. The minimum decrease observed for solutions with PAC additives is about 1.6 times. Comparison of solutions with ethylene glycol and propylene glycol additives shows that propylene glycol additive reduces filtration losses more significantly. So the addition of 50 wt % propylene glycol in an aqueous solution containing XAN of 0.3 wt. % + starch of 2 wt. % + clay of 5 wt. % reduces filtration losses more than 4 times, while a similar addition of ethylene glycol decreases it 2 times (see Fig. 4).
3.4. Thermophysical properties of drilling fluids

In terms of reducing the speed of the thawing process, the thermal conductivity and heat capacity of the drilling fluid play an important role in the drilling process. In this investigation, the thermal conductivity coefficient of solutions with additives of various polymers and clay is measured. As a result of the study of the thermal conductivity coefficient, the following conclusions are obtained. It is found that the coefficient of thermal conductivity of water solutions with additives of various polymers within the measurement error corresponds to the coefficient of thermal conductivity of water. It is shown that when adding clay, the thermal conductivity of water and polymer drilling fluids increases. So the addition of 5 wt% clay increases the thermal conductivity of the drilling fluid by about 6%. This increase within the experimental error range is described by the theoretical Maxwell dependence. A significant reduction in the thermal conductivity coefficient can be achieved by adding a hydrocarbon component to the drilling fluid. Measurements of the thermal conductivity coefficient show a significant decrease when ethylene glycol and propylene glycol are added to solutions. So at a concentration of EG in a solution of 80 wt% the coefficient of thermal conductivity is reduced 1.9 times, and with a similar addition of propylene glycol – 2.15 times. The thermal conductivity of the solution is shown to decrease with an increase in the mass content of glycols (Fig. 5a). The analysis shows that the obtained experimental values of the thermal conductivity coefficient with an error of 7% are described by theoretical data for water-ethylene glycol and water-propylene glycol mixtures. A decrease in the thermal conductivity of the drilling fluid when drilling in permafrost conditions is a favorable factor for reducing the rate of thawing, since in this case the value of the heat transfer coefficient from the solution to the well walls decreases.

The dependence of the specific heat capacity of drilling fluids with different ethylene glycol content is shown in figure 5b. As expected, the heat capacity of the solution also decreases monotonously. Reducing the heat capacity of the drilling fluid is also a favorable factor, since in this case the amount of heat entering the well with the drilling fluid is proportionally reduced.

The coefficient of heat transfer during the flow of drilling fluid in the well without its rheology can be estimated using the Mikheev formula $Nu = 0.021 \cdot Re^{0.8} \cdot Pr^{0.43}$, where Nu, Re, Pr are the Nusselt, Reynolds and Prandtl numbers. It is not difficult to show that in this case the heat transfer coefficient at a fixed value of the drilling fluid flow rate will be proportional to the complex $\tilde{\alpha} \approx \mu^{-0.37} \cdot \lambda^{0.57} \cdot C_p^{0.43}$. According to these estimates and data, a solution with 65 wt% of ethylene glycol, only by reducing the thermal conductivity and heat capacity of the drilling fluid, can reduce the coefficient of heat transfer from the solution to the well wall about 1.6 times. Preliminary calculations
of the permafrost thawing process using drilling fluids with the addition of ethylene glycol confirm these conclusions.

![Figure 5. Dependence of the thermal conductivity coefficient (a) and specific heat capacity (b) of drilling fluids on the mass concentration of glycols.](image)

**Conclusions**

A comprehensive experimental investigation of ways to reduce the speed of the permafrost thawing process during the construction of oil and gas wells in the fields of the Krasnoyarsk territory has been conducted. Laboratory physical and chemical studies on the development of drilling fluid formulations for drilling in permafrost conditions have been carried out. It is shown that it is possible to control the thermal, hydration and filtration characteristics of drilling fluids by introducing ethylene glycol and propylene glycol without deterioration of their rheological properties. Laboratory studies allow developing formulations of stable drilling fluids with a low melting capacity with a high content of the hydrocarbon phase. In general, according to the results of the experimental part of the study, the best results have been obtained for drilling fluids based on propylene glycol, which is less toxic compared to ethylene glycol (third hazard class).

**Acknowledgments**

The reported study was funded by RFBR, the Government of Krasnoyarsk Krai and enterprise of Krasnoyarsk Krai according to the research project № 18-48-242009.

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