fluids

Article

Investigation of Non-Linear Rheological Characteristics of Barite-Free Drilling Fluids

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Abstract: Drilling fluids play an important role in the construction of oil and gas wells. Furthermore, drilling of oil and gas wells at offshore fields is an even more complex task that requires application of specialized drilling muds, which are non-Newtonian and complex fluids. With regard to fluid properties, it is necessary to manage the equivalent circulation density because its high values can lead to fracture in the formation, loss of circulation and wellbore instability. Thus, rheology of the used drilling mud has a significant impact on the equivalent circulation density. The aim of the present research is to develop compositions of drilling muds with a low solids load based on salts of formate acid and improve their rheological parameters for wells with a narrow drilling fluid density range. Partially hydrolyzed polyacrylamide of different molecular weights was proposed as a replacement for hydrolized polyacrylamide. The experiment was conducted on a Fann rotary viscometer. The article presents experimentally obtained data of indicators such as plastic viscosity, yield point, nonlinearity index and consistency coefficient. Experimental data were analyzed by the method of approximation. Analysis is performed in order to determine the most suitable rheological model, which describes the investigated fluids' flow with the least error.

Keywords: drilling mud; formate-based drilling fluids; rheology; rheological models; equivalent circulation density; partially hydrolyzed polyacrylamide

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1. Introduction

1.1. Review of the Current Trends in the Field of Research

Nowadays, construction of oil and gas wells is carried out under difficult geological and climatic conditions. In addition to ensuring environmental safety in drilling areas, technical requirements for selecting the optimal drilling fluid must be met: high temperature stability; necessary rheological and filtration characteristics to preserve reservoir properties; good inhibiting ability; effective bottomhole cleaning (especially in highly inclined and horizontal sections of the wellbore); resistance to contamination; compatibility with formation fluids; reusability [1–3].

When considering wells drilled offshore, complications arise from the fact that the allowable mud density range is quite narrow [4]. This narrow range is usually the result of abnormally high pore pressure and/or low fracture pressure, since rock layers are additionally under pressure from the seawater column. It requires more casings than in wells of a similar depth constructed onshore. Accordingly, under such conditions, one of the key factors of drilling operations success is the management of equivalent circulation density (ECD) [5,6]. Factors affecting the final ECD value include [7,8]: mud type (WBM/OBM); static density; rheological parameters of the mud; well design and profile; drilling mode (pump capacity and mechanical speed); applied DP and BHA; drilling bit type (number and flow section of each nozzle); well temperature; chemical composition of the mud (salinity, solid phase content).

With the use of drilling muds containing barite as a weighting agent, a relatively thick filter cake is formed on the wellbore wall. In case of long periods of circulation stoppage (e.g., tripping) and absence of proper gel strength values, barite settles and results in a decrease in backpressure in the wellbore, which creates probability for a well control loss [9–11].

High ECD during circulation of drilling fluids containing barite is a common cause of formation fracturing, especially where there is a narrow operating window between pore and fracture pressures.

Currently, inorganic and organic salts (chlorides, bromides, formates) are used as bases for creating barite-free high-density drilling fluids. Densities of drilling fluids based on salts are presented in Table 1.

Table 1. Maximum solubility of salts at room temperature [12].

Salt	Formula	Solubility (% on Weight)	Density, g/cm^3
Sodium chloride	NaCl	26	1.20
Potassium chloride	KCl	24	1.16
Calcium chloride	$CaCl_2$	40	1.41
Sodium bromide	NaBr	46	1.52
Potassium bromide	KBr	56	1.81
Calcium bromide	$CaBr_2$	57	1.83
Zinc bromide	$ZnBr_2$	78	2.52
Sodium formate	HCOONa	49	1.32
Potassium formate	HCOOK	76	1.59
Caesium formate	HCOOCs	81	2.29

Zinc bromide-based solutions can provide the highest density among other salts (Table 1) but are much more corrosive than chloride- and formate-based solutions [13–15].

Brine-based drilling muds are a good alternative to muds that contain a significant amount of solids and bentonite. The recipes usually consist of brine, a pH control additive, a structure builder (usually a biopolymer), a filtrate reducer and a bridging agent. This set of reagents provides favorable rheological and filtration characteristics [13]. Salt solutions assist in creating a high-density drilling system with a low solids concentration, which minimizes damage to reservoir properties and leads to a decrease in plastic viscosity. With the use of barite-free WBM, lower ECD and lower pressure losses in the well are achieved, which contributes to improved drilling efficiency [16,17].

Norwegian energy company Statoil (now Equinor) drilled six horizontal wells in the Huldra offshore condensate field using cesium formate as a drilling fluid under high temperature and pressure conditions. Before the decision to replace the solution, a hydrocarbon-based solution was used, but precipitation of barite resulted in an influx. Drilling with the formate system provided wellbore stability, low equivalent circulating density (ECD), good well cleansing and high mechanical penetration rate (MPR). No signs of formation damage were found, so acidizing was not required [18].

Statoil (Equinor) also drilled seven wells with formate muds in the Kvitebyern condensate field in the North Sea. Complications included high pressure and temperature, frequent rock interlayering and high inclination of the wells. Following composition was developed for such difficult conditions: cesium formate, potassium formate, reagents for reducing fluid loss (modified starch and polyanionic cellulose (PAC)) and bridging/weighting agent ($CaCO_3$). The system based on a mixture of formic acid salts resulted in low ECD values, and MRP varied greatly in different locations and with different bit types. One well was completed in a record time of 12.7 days, while the average completion time was 20.9 days [19].

Formate-based drilling fluids are used in the North Sea as well as in other parts of the world, including Canada, Texas, the Gulf of Mexico, Argentina, Ecuador, Venezuela, Indonesia, Malaysia and Kazakhstan. Despite the fact that formate drilling systems are widely used outside the Russian Federation, it was only in 2017 that AKROS LLC and Gazpromneft PJSC carried out successful field tests using these drilling fluids at Yuzhno-Priobskoye and Prirazlomnoye (Pechora Sea shelf) fields [15]. Two horizontal sections were drilled with a formate-based solution in the Yuzhno-Priobskoye field. It contained potassium formate, biopolymer, PAC, modified starch and $CaCO_3$. Drilling time for horizontal sections using the formate system was reduced to 10 days compared with an average drilling time with other types of drilling mud of 26 days.

Thus, formate-based drilling fluids have been introduced in Canada, the North Sea, Germany, the Middle East, Russia and China since the 1990s. Initially, these fluids were developed for drilling high-temperature wells, as evidenced by successfully drilled wells: in the North Sea at temperatures up to 150 °C, in Saudi Arabia at temperatures up to 180 °C and in the Jidong field in China at temperatures up to 195 °C [18].

It should be noted that oil and gas reservoirs often have a complex structure, coupled with interlayering of clay rocks. Under these conditions, it is necessary that the drilling fluid also has an inhibiting and encapsulating effect. Potassium ions act as inhibitors in most solutions. Due to the inhibiting nature of these systems, clay hydration is reduced to a minimum, which leads to a decrease in the degree of cavernosity, a decrease in packing on the bit and stabilizer, a decrease in clay cavings and also lowers the permeability decrease in the pay zone. The potassium system works most effectively in the presence of polymers that provide encapsulation. Partially hydrolyzed polyacrylamide of various molecular weights (PHPA) is often used for these purposes [20]. Adsorbing on solid phase particles, creating insulating layers, these reagents prevent peptization, flocculate solid phase particles and generally create an inhibitory effect [21].

Synthetic polymers also affect the rheological characteristics of the drilling fluid and reduce the hydraulic resistance during circulation [20].

PHPA is a copolymer containing two or more different types of monomers (acrylate and acrylamide). Two monomers combine with each other to form a linear carbon chain. However, acrylamide is a water-insoluble compound, so to achieve solubility it is necessary to copolymerize with sodium acrylate. Carboxyl group in the polyacrylate facilitates the conversion of PHPA into an anionic polymer. Strong carbon–carbon bonds make PHPA thermally stable and resistant to bacterial degradation.

Few works studied the joint effect of formates and compositions of synthetic and biopolymers (biopolymer, starch or PAC and acrylic polymer) on the properties of drilling fluids. This work shows the possibility for the combined use of these substances and obtaining the technologically necessary parameters of drilling fluids for drilling in productive formations under complicated conditions [22].

Thus, the relevant direction for drilling deep formations is the development of water-based drilling fluid compositions, which should have not only high density, thermal stability and low corrosion activity, but also optimal rheological properties [5,23]. Modernization of the composition should be based not only on reducing the concentration of solids in the high-density mud, but also on finding a combination of polymer reagents that provide pseudoplastic rheology and transporting (“well-cleaning”) properties.

1.2. Rheological Models of Modern Drilling Fluids

Rheology is the study of deformation and flow of fluids, which evaluates the behavior of the drilling fluid in solving various theoretical and practical problems [24–26]. Rheological properties of drilling fluids influence almost all processes and indicators related to well drilling, so they are among the most important [27,28].

Viscoelastic properties of the drilling muds should also be considered, especially when calculating hydraulic programm of the well drilling. Startups and shutdowns of the pumps may cause pulse impact on the borehole bottom zone, which could damage the formation. Several models, such as Maxwell or Thomson-Thet, can be used to describe the behaviour of viscous fluid [29]. However, this article focuses on rheological properties of the drilling fluids.

Most drilling fluids refer to non-Newtonian fluids [30–32]. Therefore, this study is aimed at studying nonlinear behavior of rheological parameters of the fluid and influence of component composition of the drilling mud with increased density on this dependence.

Drilling muds can be classified by their rheological behavior. Fluids, whose viscosity remains constant as the shear rate changes, are known as Newtonian fluids. However, most drilling fluids are non-Newtonian, i.e., their shear stress is not directly proportional to shear rate.

The rheological parameters of a drilling fluid are used for: calculation of friction losses in the pipe or annular space; determining the equivalent circulation density; determining the flow regime in the annulus; evaluation of wellbore cleaning efficiency; determination of drilling cuttings settling rate in vertical wells [33–35].

The accuracy of fitting a rheological model to properties of real drilling mud minimizes errors of calculated technological parameters used in well drilling, so the problem of choosing the optimal rheological model is especially relevant.

However, it should be considered that till the present day, there is no rheological model that would give the required accuracy of approximation over the whole interval of shear rate changes corresponding to drilling fluid circulation in the well [36–38].

Thus, the correctly selected model and its applicability in a particular case will both influence the accuracy of calculated parameters [24]. The method developed and presented in the work by R. Wi'sniowski, K. Skrzypaszek and T. Małachowski allows selecting a rheological model for the drilling fluid. Models of Bingham plastic, Casson, Ostwald–de Waele and Newton consider the application of a linear regression method to determine the rheological parameters, and models of Herschel–Bulkley, Vom Berg and Hahn-Eyring propose to apply the non-linear regression method [38]. The hyperbolic model by C. Vipulanandan and A.S. Mohammed predicted the maximum shear stress of the drilling fluid, whereas two other models (Herschel–Bulkley and Casson) studied assumed infinite shear stress tolerance for the drilling fluid in this work [25].

There is a large number of rheological models (more than 30) used to predict the rheological behavior of modern drilling fluids over a wide range of shear rates. The following models are most commonly used by drilling fluid engineers: Newtonian, Bingham-Shvedov (Bingham Plastic), Ostwald–de Waele (power law), Herschel–Bulkley (modified power law), Schulman-Casson [25,33,39].

The equation of Bingham's rheological model is as follows:

$$\tau = \tau_0 + \eta_p \dot{\gamma} \tag{1}$$

where τ—shear stress, Pa;

τ_0—yield point, Pa;

η_p—plastic viscosity, mPa·s;

$\dot{\gamma}$—shear rate, s^{-1}.

The flow of these muds begins only after the tangential stress exceeds a critical threshold, which is called the yield point [23,40]. When tangential stresses exceed the yield point, stresses are proportional to shear rate with a coefficient of proportionality called plastic viscosity. The common use of the Bingham-Schvedov model is justified by its simplicity, but a significant drawback is that it describes the linear part of the rheological curve, which makes it impossible to predict the actual behavior of the fluid at low shear rates. In addition, more often than not, the value of the yield point is overestimated by several times.

The power model is another widely used rheology model for pseudoplastic drilling fluids. The model uses a power relationship between tangential stress and shear rate; hence, in logarithmic coordinates, this relationship is plotted as a straight line. The values of two parameters of this law, n and K, can be determined from observations at any two values of velocity.

The equation of the power model has the form [33]:

$$\tau = K\dot{\gamma}^n \tag{2}$$

where K—consistency index;

n—power law index.

The model can be applied to viscous shear fluids at $n < 1$, to Newtonian fluids at $n = 1$, or to shear-thinning fluids at $n > 1$. The more the index of degree n differs from the 1, the greater the degree of difference between the fluid and the Newtonian fluid.

The Herschel–Bulkley model is also widely used in the industry for pseudoplastic fluids. This model is called a modified power law because it is a combination of the Bingham and power law models, i.e., the dependence of shear stress on shear rate is expressed as a power function, taking into account the yield point that must be exceeded in order for the fluid to begin its flow.

The equation of the Herschel–Bulkley rheological model is [33]:

$$\tau = \tau_0 + K\dot{\gamma}^n \tag{3}$$

The American Petroleum Institute (API) recommends predicting fluid behavior using a Herschel–Bulkley model. One part predicts fluid behavior at low shear rates and the other part predicts fluid behavior at high shear rates. Figure 1 shows a graphical representation of the described rheological models [39].

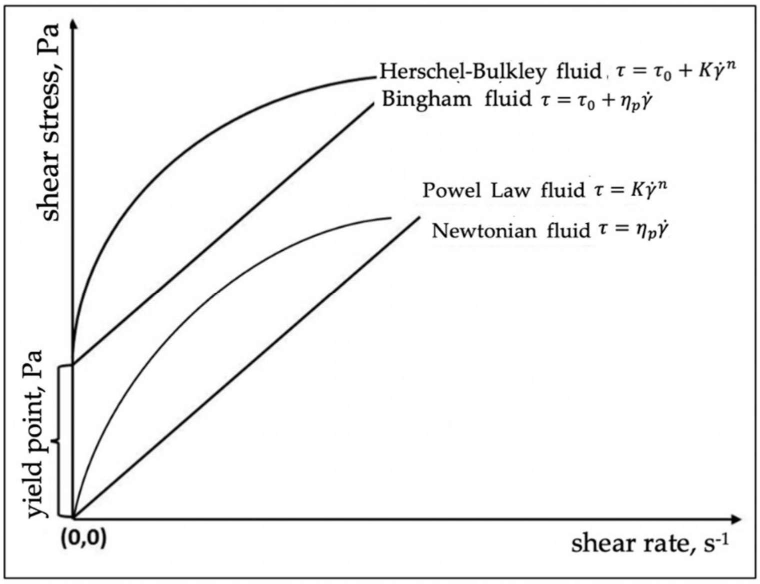

Figure 1. Flow curves of fluids obeying different flow models.

1.3. Aims and Tasks of the Research

In offshore drilling practice around the world, it is usually required to use environmentally friendly systems. Therefore, the formate-based drilling fluid, characterized by high density without or low solid phase content, was chosen for the study. With such fluid, as a rule, lower rheology, ECD and pressure losses in the well will be provided in contrast to traditionally used oil-based mud. It contributes to increasing drilling efficiency, especially in conditions of the narrow mud window [14,15,41]. It is also worth noting that the analysis of scientific literature proves that formate drilling systems are compatible with formation fluids, which creates conditions for increasing MPR and decreasing the contamination of bottomhole. In addition, such muds in combination with polymer reagents have good inhibiting ability in relation to unstable clay sediments [16,17,42,43].

The object of the study in this paper is a high-density, barite-free drilling mud based on sodium and potassium formats, with the addition of a composition of three polymeric reagents of different structure and properties (which has not been previously studied).

The novelty of the work is in the substantiation and development of weighted drilling fluid compositions based on formates and a composition of polymer reagents, as well as the assessment of their rheological parameters.

The purpose of the study is to establish the influence of the molecular weight of PHPA-polymer on the rheology of the formate drilling fluid and to provide the optimal composition of the drilling fluid, taking into account the nonlinear behavior of the rheological parameters of the fluid.

Research tasks:

1. Parametric study of the base solution used in the Arctic shelf of the Russian Federation (at high pressures in the reservoir);
2. Improving the formulation of the base solution by its treatment with PHPA of various molecular weights;
3. Evaluation of technological parameters of the obtained drilling fluids;
4. Choice of rheological model for the flow of drilling fluids;
5. Substantiation of the optimal rheological model for the developed compositions of high density drilling fluids.

2. Materials and Methods

2.1. Justification on Choice of the Research Object

Basic ecologically clean barite-free drilling mud of high density (1.45 g/cm^3) based on formic acid salts (sodium formate and potassium formate) for drilling a directional well with a horizontal ending, located on the Arctic shelf of the Russian Federation, was chosen as an object of study. Composition of the mud is presented in Table 2.

Table 2. Composition of the formate-based solution.

Component	Function	Concentration
HCOONa/sodium formate (dry)	Mud base	800 g/L
HCOOK/potassium formate (liquid)	Mud base, inhibitor	30% (ρ = 1.57 g/cm^3)
K_2CO_3/potassium carbonate	Buffer pH	20 g/L
Xanthan gum	Viscosifier	4 g/L
Starch	Filtration reducer	10 g/L
HPAM	Filtration reducer HT	4 g/L
$CaCO_3$ MEX-CARB F	Bridging agent	50 g/L
$CaCO_3$ MEX-CARB M	Bridging agent	20 g/L
$CaCO_3$ MEX-CARB VF	Bridging agent	10 g/L

Complicated conditions are associated with a narrow mud window and with the presence of unstable shale sediments, causing problems with wellbore stability.

2.2. Equipment and Experiment

Experimental investigations to develop formulations of drilling fluids based on salts of formic acid, containing polymer reagents and marble chips, were carried out on the basis of the laboratory for the study of drilling and cementing fluids of the Saint Petersburg Mining University.

The main properties of the drilling fluid include density determined by the balance weigher (Mud balance Fann), specific Marsh funnel viscosity, filtration index measured by API filter press and rheological parameters (plastic viscosity (PV), dynamic shear stress (DSS) and static stress shear (SSS)) obtained on Fann 35A.

The experiment was conducted on a Fann 35A 6-speed viscometer (Figure 2) at rotor speeds of 3, 6, 100, 200, 300 and 600 rpm in order to establish the rheological flow model of the various formulations developed. The obtained results allowed determining the rheological parameters of the studied solutions and construct rheograms in Cartesian coordinates.

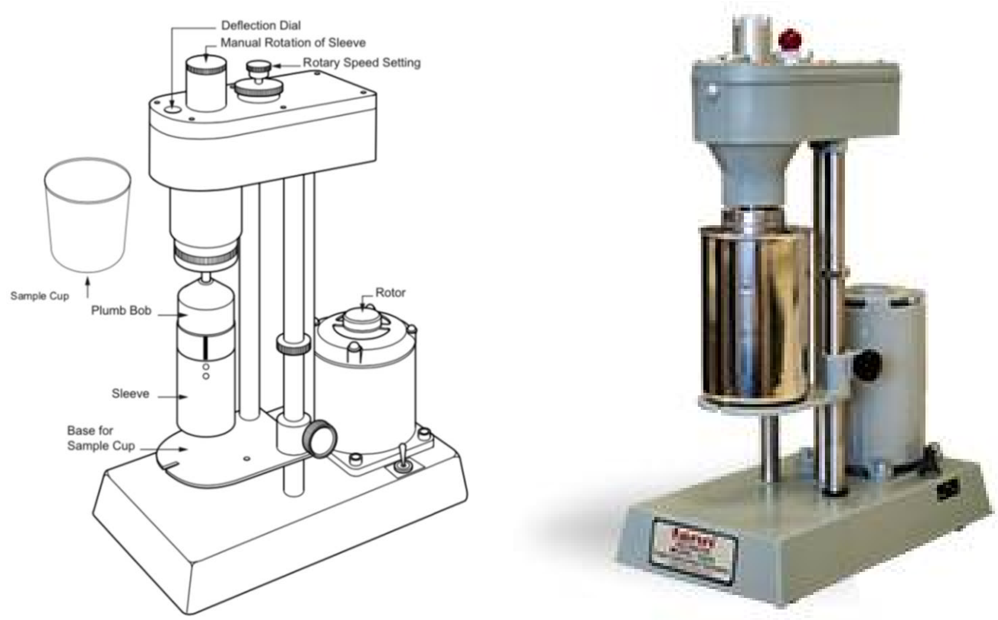

Figure 2. Fann rotary viscometer.

The plastic viscosity in centipoise (cP) or millipascals per second (mPa·s) is calculated as the difference of Fann viscometer readings (θ) at 600 and 300 rpm [44]:

$$PV = \theta_{600} - \theta_{300} \text{ [cP]}, \tag{4}$$

where θ_{600} and θ_{300}—values of viscometer scale angles at rotation frequencies, respectively, equal to 600 and 300 rpm.

The yield point in lb/100 ft^2 is calculated from the data of the viscometer Fann by the formula [14,17]:

$$YP = \theta_{300} - PV; \tag{5}$$

where θ_{300}—reading of the instrument at 300 rpm;

PV—plastic viscosity.

According to the API standard, Gel 10 s/10 min values of the system are obtained on a rotary viscometer, creating a speed of 3 rpm after 10 s and 10 min [44].

Parameters of the developed drilling fluids were measured three times and the average values of the corresponding indicators were calculated. The averaged error of the tests is 1.2%.

3. Results and Discussion

3.1. Parameters of the Investigated Drilling Fluids

Partially hydrolyzed polyacrylamide (PHPA) with various molecular mass (from 12 to 27 million—PHPA12, PHPA15, PHPA20, PHPA27) was proposed as a replacement for HPAM to improve the basic formulation. The concentration of the PHPA in each solution is 1 g/L. When increasing the concentration of PHPA up to 2 g/L, the Weissenberg effect was observed (the mud was winding up on the mixing element), so it was decided to reduce the amount of PHPA. The main parameters of the developed drilling fluids are presented in Table 3.

Analyzing these results, we can see that by replacing HPAM with PHPA, it was possible to reduce filtration. Filtration index decreases with increasing molecular weight of partially hydrolyzed polyacrylamide, which helps to reduce the probability of differential pipe stuck. Moreover, such drilling mud is able to form a thin, impermeable filter cake that will prevent filtrate invasion into the formation. The increase in molecular weight of PHPA contributes to increase of YP, but has no effect on the value of plastic viscosity. Obtained values of gel indicate that the structure of the studied fluids appears after 10 s of being still and changes by an average of 1.4 Pa after 10 min of being still.

Table 3. Parameters of the investigated drilling fluids.

Property	Sample 1 (HPAM)	Sample 2 (PHPA 12)	Sample 3 (PHPA 15)	Sample 4 (PHPA 20)	Sample 5 (PHPA 27)
Density, g/cm^3	1.45	1.45	1.45	1.45	1.45
Specific viscosity, s/quarter	45	40	40	41	42
Plastic viscosity, mPa·s	19	16	16	16	16
YP, Pa	5.3	5.3	6.7	8.1	9.6
Gel (10 s/10 min), Pa	2.4/3.8	2.4/3.8	2.4/3.8	2.4/3.8	2.4/3.8
Filtration, mL/30 min	3.8	3	2.7	2.6	2.2

3.2. Selection of a Rheological Model for the Drilling Mud

The experimental data were analyzed using the approximation method. The approximation error of these models of real WBM flow curves does not go beyond 10–11%, which is quite enough for solving engineering tasks. Obtained relationships between shear stress and shear rate, as well as the method of selecting the optimal rheological model, are shown in Figures 3–5.

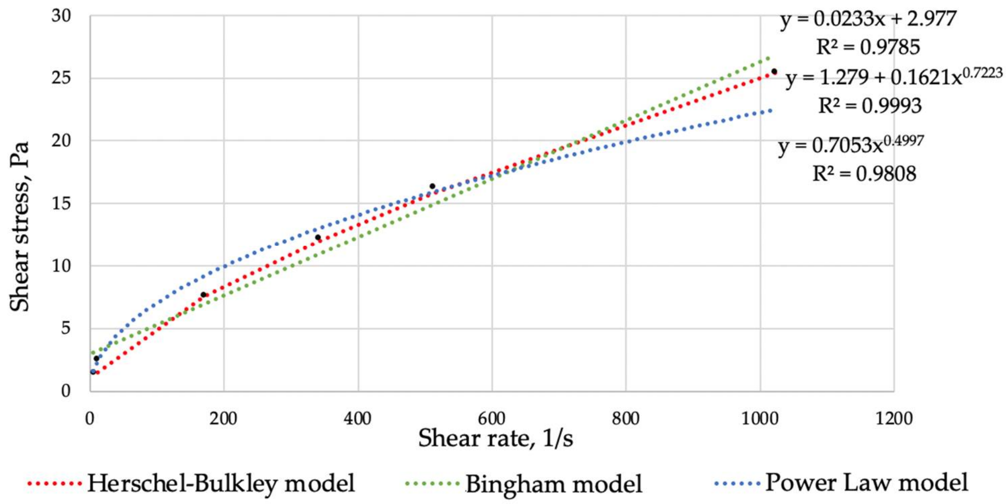

Figure 3. Selection of the rheological model for basic mud 1.

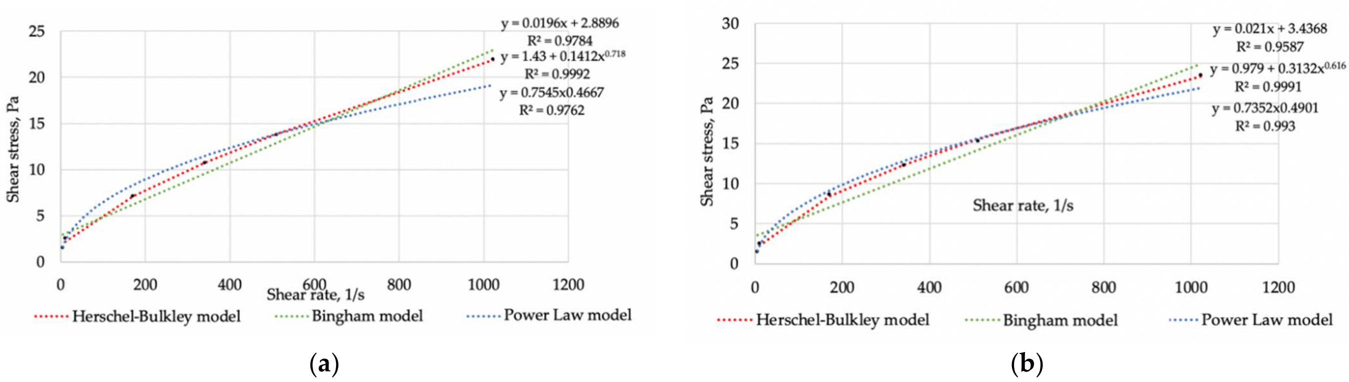

Figure 4. Selection of the rheological model for sample 2 with PHPA MM = 12 million (**a**) and for sample 3 with PHPA MM = 15 million (**b**).

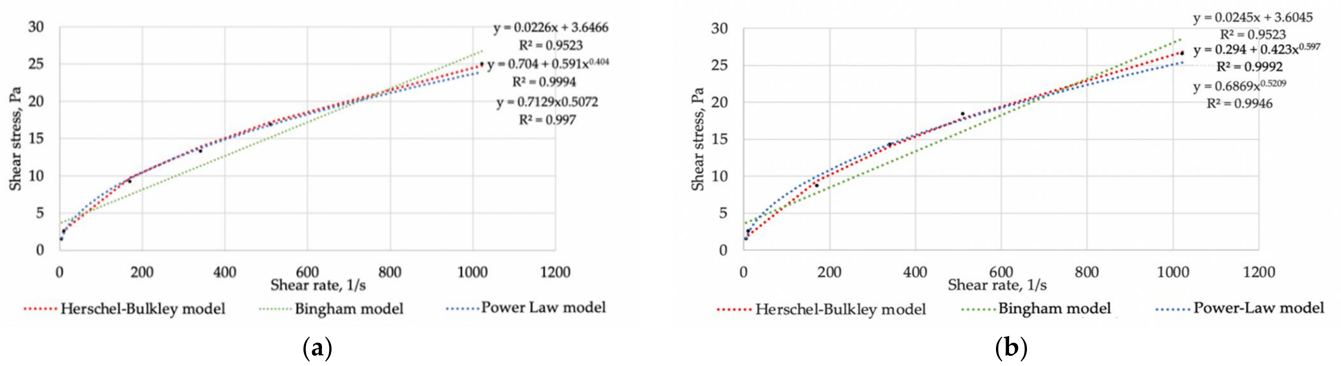

Figure 5. Selection of the rheological model for sample 4 with PHPA MM = 20 million (**a**) and for sample 5 with PHPA MM = 27 million (**b**).

According to the above diagrams, the results are summarized in Table 4.

Table 4. Rheological parameters of the studied drilling fluids.

Model	Regression Equation	R^2	τ_y, Pa	η_p, mPa·s	n	K, Pa·s^n
Parameters of the basic drilling mud 1						
Bingham-Shvedov	y = 0.0226x + 2.9606	0.9785	2.977	23.3		
Ostwald-de-Waele	y = 0.7156x$^{0.4936}$	0.9883	1.396	9.56	0.499	0.705
Herschel-Bulkley	y = 0.531 + 0.1857x$^{0.707}$	0.9993	1.279	18.53	0.722	0.163
Parameters of the drilling mud 2 (PHPA MM = 12 mln)						
Bingham-Shvedov	y = 0.0196x + 2.886	0.9784	2.884	19.59		
Ostwald-de-Waele	y = 0.7545x$^{0.4667}$	0.9874	1.432	6.55	0.467	0.755
Herschel–Bulkley	y = 1.43 + 0.1412x$^{0.718}$	0.9992	1.432	14.43	0.718	0.141
Parameters of the drilling mud 3 (PHPA MM = 15 mln)						
Bingham-Shvedov	y = 0.021x + 3.437	0.9587	3.437	21.13		
Ostwald-de-Waele	y = 0.7352x$^{0.4901}$	0.9957	1.396	9.5	0.490	0.735
Herschel–Bulkley	y = 0.979 + 0.3132x$^{0.616}$	0.9991	0.979	13.62	0.616	0.313
Parameters of the drilling mud 4 (PHPA MM = 20 mln)						
Bingham-Shvedov	y = 0.0224x + 3.9841	0.9363	3.9841	22.4		
Ostwald-de-Waele	y = 0.7171x$^{0.511}$	0.9976	0.378	12.83	0.511	0.717
Herschel–Bulkley	y = 0.723 + 0.541x$^{0.548}$	0.9994	0.704	14.84	0.591	0.404
Parameters of the drilling mud 5 (PHPA MM = 27 mln)						
Bingham-Shvedov	y = 0.0245x + 3.6045	0.9523	3.6045	24.53		
Ostwald-de-Waele	y = 0.6869x$^{0.5209}$	0.9945	0.287	13.81	0.521	0.687
Herschel–Bulkley	y = 0.294 + 0.439x$^{0.564}$	0.9992	0.294	16.13	0.564	0.439

A statistical approach was applied to choose the optimal model, in which rheology of drilling fluid is characterized by indicators of the model under review, that describes its rheological behavior most adequately (with less error).

Based on the obtained results and relations, we can conclude that the Herschel–Bulkley model describes the rheological behavior of the studied drilling muds more accurately than the Ostwald–de Waele model and the Bingham-Shvedov model. Analyzing graphical materials, we can state that the Herschel–Bulkley model describes the behavior of the studied muds in the whole range of shear rates with sufficiently high reliability.

Experience in directional and horizontal well construction shows that drilling fluids exhibiting pseudoplastic properties are characterized by ideal rheological behavior—at the exit from bit nozzles the fluid acquires viscosity close to that of water, and when moving in annulus increases its viscosity in order to sustain the cuttings.

The nonlinearity index (n) and consistency index (K) of the drilling fluid characterize the behavior of the system at both low and high shear rates. When xanthan polymer is introduced into the fluid, the fluid acquires pseudoplastic properties. Xanthan contributes to viscosity increase in drilling fluids due to its long-branched structure and relatively weak hydrogen bonds of side groups. The functional groups are represented by hydroxyl

(-OH), carboxyl (-COH), carbonyl (C=O) and other groups, which give this polymer its thickening properties.

Pseudoplasticity of the fluid is evaluated by the nonlinearity index in the range from 0 to 1. All solutions are characterized by the nonlinearity index in the range from 0.564 to 0.722. At the same time, a decrease in n happens with increasing molecular weight of PHPA, i.e., solution 5 exhibits pseudoplastic properties to a greater extent. Low value of nonlinearity index will contribute to equalization of flow speeds in annulus, thus avoiding undesirable migration of cuttings particles to borehole walls. Additionally, solution 5 is characterized by the lowest value of the yield point, which will reduce the amplitude of pressure fluctuations when starting and stopping the pumps and performing tripping operations, as well as the probability of stagnant zones formation with accumulation of cuttings in them.

The consistency index K represents the increasing viscosity of the fluid (the higher the K value, the more viscous the mud), which can achieve complete cuttings removal while reducing the nonlinearity index. When drilling mud is treated with partially hydrolyzed polyacrylamide, with increase in its molecular mass, an increase in consistency index is observed, which is associated with elastic properties and increased viscosity of PHPA.

4. Conclusions

The article deals with formate-based drilling fluids, which are low solids muds, more environmentally friendly than other widely used brine systems, as well as being compatible with reservoir fluids. This research presents investigations that assess the effect of partially hydrolyzed polyacrylamide of various molecular weights on the rheological parameters of the drilling fluids. The results of the work reflect the methods of selecting the optimal rheological model for the drilling mud flow.

1. The basic ecologically clean barite-free drilling mud of high density (1.45 g/cm^3) is based on sodium formate and potassium formate. As a replacement for HPAM, PHPA of different molecular mass (from 12 to 27 million) was proposed. It is not only an inhibitor but also an incapsulator (which creates preconditions for improving the quality of cleaning the well). The optimal concentration of PHPA was determined: in each solution it is 1 g/L.

2. It is recommended to use formic acid salts (sodium formate and potassium formate) and PHPA additive with a molecular weight of 27 million based on the results of the experimental data approximation and comparison of the obtained results.

3. Different rheological models were considered in the course of work: the Bingham Plastic model, the Ostwald–de Waele model and the Herschel–Bulkley model. It can be stated that the Herschel–Bulkley model reflects the behavior of the studied solutions in the whole range of shear rates with sufficiently high reliability. This will allow more accurate calculation of the pressure losses in the annulus and ECD at the next stage of the study.

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Conflicts of Interest: The authors declare no conflict of interest.

Nomenclature

ECD	Equivalent Circulating Density;
WBM	Water-based Mud;
OBM	Oil-based Mud;
DP	Drill Pipe;
BHA	Bottom Hole Assembly;
MPR	Mechanical Penetration Rate;
PHPA	Partially Hydrolyzed Polyacrylamide;
HPAM	Hydrolized Polyacrylamide;
PV	Plastic Viscosity;
PAC	Polyanionic cellulose;
YP	Yield Point.
DSS	Dynamic shear stress
SSS	Static shear stress
List of symbols	
ρ	fluids density, g/cm^3;
τ	shear stress, Pa;
τ_0	yield point, Pa;
η_p	plastic viscosity, mPa·s;
$\dot{\gamma}$	shear rate, s^{-1};
K	consistency index, Pa·s^n;
n	Power Law index.

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