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ABOUT LOSS OF STRUCTURAL STABILITY DURING MOVEMENT OF DRILLING FLUIDS

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ABSTRACT

The analysis of scientific research conducted in recent years shows that the drilling fluids used in the drilling of oil and gas wells can be described by different rheological models. These models do not take into account structural stability and relaxation time of drilling fluids. Currently, in most cases, these drilling fluids are characterized by visco-plastic (pseudo-plastic) properties depending on the different basis and composition. Despite the above, considering the existence of the fact that they have structural stability which determines its internal characteristic and relaxation properties which determines how quickly the fluid responds to changes in stress or deformation during the movement of drilling fluids and the importance and relevance of their attention, the article deals with the issues of rheological modeling of such systems and taking into account the violation of their structural stability. These properties must be taken into account because problems of increasing the efficiency of technological processes during well drilling can be further complicated due to the complex structure and relaxation properties of the applied drilling fluids. In the article, it is proposed to use the generalized exponential model for the description of 10 different oil-based drilling fluids and 8 different water-based drilling fluids in the presence of shear deformation. As a result of the rheological test of oil-based drilling muds and water based drilling muds of different compositions on the basis of the mentioned model, the possibility of determining their structural stability coefficient and relaxation time has been shown.

Keywords: drilling fluid; rheological model; structural stability; relaxation time; viscosity; multiphase.

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Introduction

It is known that the rheological properties of the drilling fluids used in drilling oil and gas wells can vary in a very wide range. Such diversity is related to how they are prepared, what their basis is and what additives they contain [1-3]. Conducted experiments show that, in most cases, drilling fluids prepared using clays have viscoplastic or pseudoplastic properties and initial shear stress (τ_0) in addition to being characterized by structural viscosity. Research conducted in recent years shows that drilling fluids can even be nanoscale and have relaxation properties [4]. During the movement of such drilling fluids in the pipe, cases such as the loss of stability of the flow are also observed under certain conditions [5]. As a rule, the occurrence of these cases is related to the flexibility- elasticity of the system and internal structural changes. Such systems are rheologically non-equilibrium systems and their flow curves $\tau = f(\dot{\gamma})$ are mainly characterized by non-linear dependencies. Although the anomalies occurring in such systems are explained by various factors (for example, the presence of «black» emulsifiers – paraffin, asphaltenes in oils and their interaction, the occurrence of phase transformations, etc.), as a result of rheological studies conducted with a viscometer [6-9], certain it has been shown that in systems forming a structure before the critical value of the Reynolds number has been reached, cases such as flow instability occur. According to the results of the conducted scientific research [6, 8], the occurrence of the mentioned can cause not only quantitative, but also qualitative changes during their movement due to the occurrence of relaxation properties in those systems. Therefore, the reliable and efficient implementation of the transport of non-Newtonian systems forming the mentioned structure is closely related to the correct assessment of their relaxation properties [7, 10, 11].

Problem statement

The problems of increasing the efficiency of technological processes during well drilling can be further complicated due to the complex structure and relaxation properties of the applied drilling fluids. Therefore, based on rheological studies, it is important to first check whether these drilling fluids have relaxation properties. It is known that using the flow curves for rheologically complex systems, it is possible to determine whether the system has linear viscoelasticity or not, and if there is a relaxation property, using the Cross

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method [9]. For this purpose, obtaining the linear dependence $1/\eta^2=f(\tau^2)$ is an important condition.

As a result of the cross method of rheological studies conducted with different non-Newtonian oils, it was determined that the interpretation dependences of $1/\eta^2=f(\tau^2)$ are not straight lines, but non-linear dependences.

The existence of such dependencies can also be explained by the structural changes occurring in the system. It is for the rheological description of systems related to this kind of structural change that a model should be chosen to take into account their internal structural change. From this point of view, the use of exponential type rheological model can be considered suitable for the purpose [11-16]. According to that rheological model, the structural stability coefficient (χ) of the system can be estimated based on the following expression [12]:

$$\chi = \frac{\varphi_\infty - \varphi}{\dfrac{\partial\varphi}{\partial(\tau^2)}} \tag{1}$$

Here: χ – the structural stability coefficient of the system; $\varphi=1/\eta$ – fluidity of fluid (η – structural viscosity); φ_0 and φ_∞ are the fluidity at $\tau=0$ and the largest shear stress respectively.

If we integrate expression (1) at a constant value of χ, we get:

$$\varphi = \varphi_\infty - \left(\varphi_\infty - \varphi_0\right)e^{\left(-\tau^2/\chi\right)} \tag{2}$$

As can be seen from the last statement, since τ^2/χ is a dimensionless quantity, the coefficient χ characterizing the structural stability should be the same as the unit of measurement of the τ^2 parameter – Pa^2. In general, the coefficient χ can be interpreted as the deformation power per unit flow [8]. This case can be considered as an analogous case of determining the work of elastic deformation in Maxwell›s model.

Considering that $\varphi=1/\eta$, then expression (2) can be written as follows:

$$\dot{\gamma} = \tau\left[\varphi_\infty - \left(\varphi_\infty - \varphi_0\right)e^{\left(-\tau^2/\chi\right)}\right] \tag{3}$$

As can be seen, equation (2) can be written as follows:

$$\ln\overline{\varphi} = \ln\frac{\varphi_\infty - \varphi}{\varphi_\infty - \varphi_0} = -\frac{\tau^2}{\chi} \tag{4}$$

From the last linearized expression, the value of parameters φ_0 and φ_∞ should also be known to determine the coefficient χ. These parameters are determined according to the graph by establishing the dependence $\varphi=f(\tau^2)$ for each system tested. Thus, based on the extrapolation of rheological parameters (viscometer data) for systems undergoing structural change, the parameters φ_0, φ_∞ and χ can be determined using the dependence $\varphi=f(\tau^2)$.

The test of the mentioned rheological studies was carried out on the example of oil-based and water based drilling fluids with different compositions. The 10 different oil-based and 8 water based drilling fluids tested and their composition are shown in table 1 and table 2, respectively. Density of water based drilling fluids are same – 1200 kg/m^3, but density of oil based drilling fluids are different as shown in table 1.

Figure 1 and 2 shows the $\tau = f(\dot{\gamma})$ flow curves for each composition of oil based drilling fluids and water based drilling fluids, respectively, based on rheological testing of the mentioned drilling fluids at 120F or 49 °C. As can be seen from figure 1, the flow curves of $\tau = f(\dot{\gamma})$ for all drilling fluids are non-linear and significantly different from each other despite the tests conducted at a relatively high temperature (49 °C). These curves intersect the ordinate (stress) axis, almost none of them passing through the coordinate origin. At first glance, it can be accepted that oil-based, multiphase drilling fluids have pseudoplastic rheological properties.

Based on the results of the rheological test, it was determined that the dependences noted for the tested systems were not straight lines, but non-linear dependences, as a

Table 1

Oil-based drilling fluids and their composition

Drilling fluids, №	ρ,kg/m^3	Composition of Oil Based Drilling fluids
1	900	65% diesel, 35% water, 8ppb Lime, 6ppb OBM-VIS, 8ppb Versamul, 25% CaCl$_2$, 6.5 ppb OBM FLC
2	1190	70% diesel, 30% water, 8ppb Lime, 6.5ppb OBM-Vis, 7.5ppb Versamul, 25% CaCl$_2$, 151ppb Barite, 6ppb OBM FLC
3	1280	72% diesel, 28% water, 7.5ppb Lime, 6.5ppb OBM-Vis, 7.5ppb Versamul, 30% CaCl$_2$, 204ppb Barite, 7ppb OBM FLC
4	1370	70% dizel, 30% water, 7.5ppb Lime, 6.5ppb OBM-Vis, 7.5ppb Versamul, 28% CaCl$_2$, 255ppb Barite, 7ppb OBM FLC
5	1520	70% diesel, 30% water, 7.5ppb Lime, 6.5ppb OBM-Vis, 7ppb Versamul, 28% CaCl$_2$, 352ppb Barite, 7ppb OBM FLC
6	1600	75% diesel, 25% water, 10ppb Lime, 6.5ppb OBM-Vis, 7ppb Versamul, 2ppb Versawet, 30% CaCl$_2$, 425ppb Barite, 6ppb OBM FLC
7	1750	85% diesel, 15% water, 7ppb Lime, 5ppb OBM-Vis, 6ppb Versamul, 2ppb Versawet, 30% CaCl$_2$, 571ppb Barite, 6ppb OBM FLC
8	1800	82% diesel, 18% water, 10ppb Lime, 6.5ppb OBM-Vis, 8ppb Versamul, 2ppb Versawet, 30% CaCl$_2$, 602 ppb Barite, 7ppb OBM FLC
9	2100	80% base oil, 20% water, 10ppb Lime, 6ppb OBM-Vis, 9ppb Versamul, 2ppb Versawet, 30% CaCl$_2$, 660ppb Barite, 250ppb shale + sand, 8ppb OBM FLC
10	2230	90% diesel, 10% water, 10ppb Lime, 5.5ppb OBM-Vis, 9ppb Versamul, 2ppb Versawet, 30% CaCl$_2$, 705ppb Barite, 250ppb shale+sand, 8ppb OBM FLC

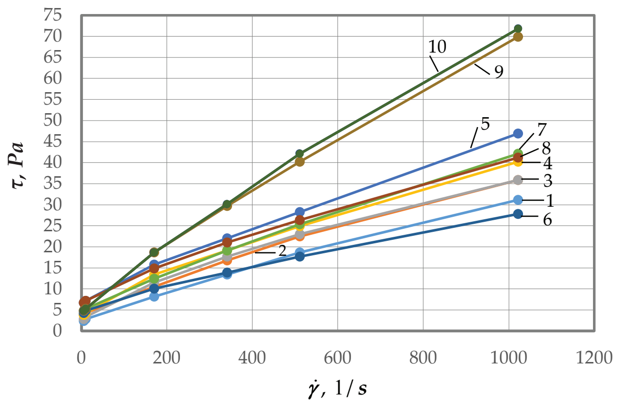
result of the interpretation performed by the Cross method [$1/\eta^2=f(\tau^2)$] for each drilling fluid. For example, as in №8 oil based drilling fluid in picture 3 and as in №6 water based drilling fluid in picture 4.

A $\varphi=f(\tau^2)$ dependence was then constructed for each drilling fluid tested. The values of the parameters φ_0, φ_∞ and χ from the obtained graphs representing the nonlinear dependencies are given for oil based mud in table 3 and for water based mud in table 4. The non-linear dependence for the mentioned №8 oil-based drilling fluid is shown in figure 5 and for water based drilling fluids in figure 6. The extrapolation of $\ln\bar{\varphi}=f(\tau^2)$ for the mentioned №8 oil-based drilling fluid is shown in figure 7 and for №6 water based drilling fluids in figure 8.

Table 2

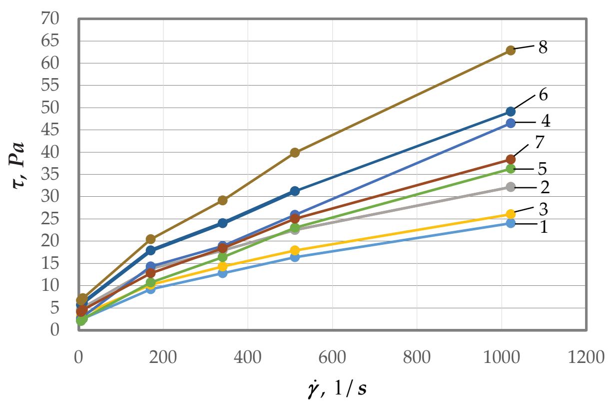
Water-based drilling fluids and their composition

Drilling fluids, №	Water based drilling fluids composition
1	1ppb caustic soda (NaOH), 2.5ppb soda ash (Na_2CO_3), 6ppb Pac LV (polyanionic cellulose), 0.6ppb duovis (Xhantan gum), 8ppb KCl, 0.2ppb Ultracap (PHPA), 2% Glydrill, 74ppb barite ($BaSO_4$)
2	1ppb caustic soda (NaOH), 2.5ppb soda ash (Na_2CO_3), 6ppb Pac LV (polyanionic cellulose), 1ppb duovis (Xhantan gum), 8ppb KCl, 0.2ppb Ultracap (PHPA), 2% Glydrill, 74ppb barite ($BaSO_4$)
3	1ppb caustic soda (NaOH), 2.5ppb soda ash (Na_2CO_3), 6ppb Pac LV (polyanionic cellulose), 0.6ppb duovis (Xhantan gum), 8ppb KCl, 0.6ppb Ultracap (PHPA), 2% Glydrill, 74ppb barite ($BaSO_4$)
4	1ppb caustic soda (NaOH), 2.5ppb soda ash (Na_2CO_3), 4ppb Pac LV (polyanionic cellulose), 2ppb PolyPac R, 0.6ppb duovis (Xhantan gum), 8ppb KCl, 0.2ppb Ultracap (PHPA), 2% Glydrill, 20ppb barite ($BaSO_4$), 68ppb sand (7faiz)
5	1ppb caustic soda (NaOH), 2.5ppb soda ash (Na_2CO_3), 4ppb Pac LV (polyanionic cellulose), 2ppb PolyPac R, 0.6ppb duovis (Xhantan gum), 8ppb KCl, 0.2ppb Ultracap (PHPA), 2% Glydrill, 54ppb barite ($BaSO_4$), 24ppb sand (3%)
6	1ppb caustic soda (NaOH), 2.5ppb soda ash (Na_2CO_3), 6ppb Pac LV (polyanionic cellulose), 0.6ppb duovis (Xhantan gum), 8ppb KCl, 0.2ppb Ultracap (PHPA), 2% Glydrill, 56ppb barite ($BaSO_4$), 20ppb drilled shale
7	1ppb caustic soda (NaOH), 2.5ppb soda ash (Na_2CO_3), 6ppb Pac LV (polyanionic cellulose), 0.6ppb duovis (Xhantan gum), 8ppb KCl, 0.2ppb Ultracap (PHPA), 2% Glydrill, 64ppb barite ($BaSO_4$), 10ppb drilled shale
8	1ppb caustic soda (NaOH), 2.5ppb soda ash (Na_2CO_3), 6ppb Pac LV (polyanionic cellulose), 0.6ppb duovis (Xhantan gum), 8ppb KCl, 0.2ppb Ultracap (PHPA),2% Glydrill, 5ppb barite ($BaSO_4$), 20ppb drilled shale, 68ppb sand (7%)



1÷10 – oil-based drilling fluids of different composition

Fig. 1. Flow $\tau=f(\dot{\gamma})$ curves of oil-based drilling fluids



1÷8 – water-based drilling fluids of different composition

Fig. 2. Flow $\tau=f(\dot{\gamma})$ curves of oil-based drilling fluids

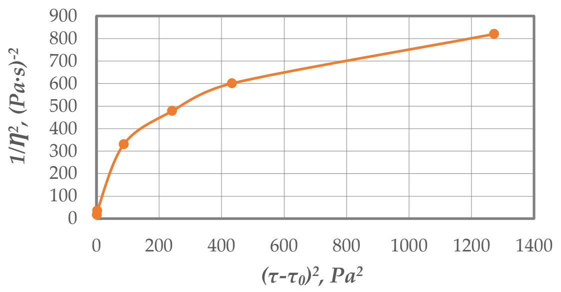


Fig. 3. Dependence of $1/\eta^2=f(\tau^2)$ for oil-based drilling fluids №8

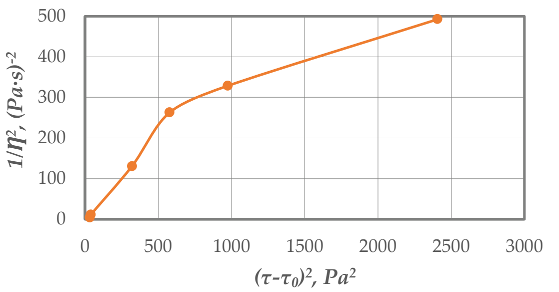


Fig. 4. Dependence of $1/\eta^2=f(\tau^2)$ for water-based drilling fluids №6

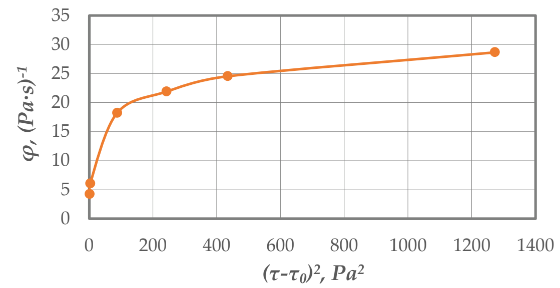


Fig. 5. Dependence of $\varphi=f(\tau^2)$ for oil-based drilling fluids №8

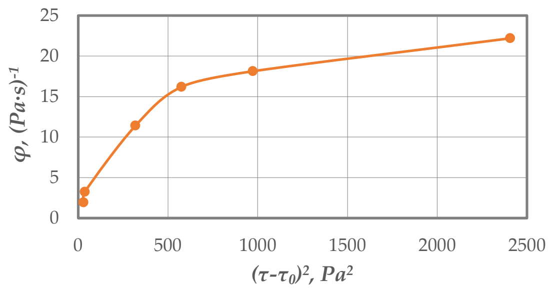


Fig. 6. Dependence of $\varphi=f(\tau^2)$ for water-based drilling fluids №6

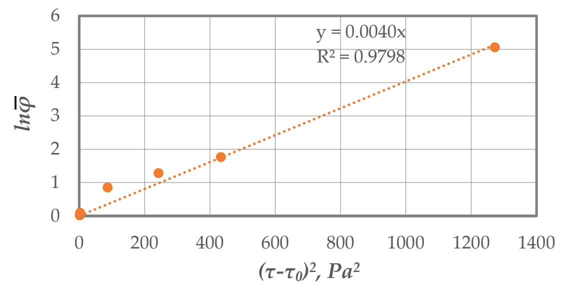


Fig. 7. Extrapolation of $\bar{\varphi}=f(\tau^2)$ for oil-based drilling fluids №8

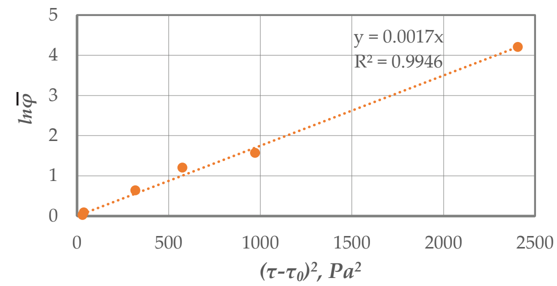


Fig. 8. Extrapolation of $\bar{\varphi}=f(\tau^2)$ for water-based drilling fluids №6

Solution of problem

It can be easily shown that the dependence (3) shown above is analogous to the following Maxwell-type rheological model, which is the basis of the Cross method–:

$$\dot{\gamma} = \tau\left(1+\frac{\tau^2}{4G^2}\right)^{1/2} / \eta_0$$

So, if we divide the terms $exp(-\tau^2/\chi)$ and $\left(1+\frac{\tau^2}{4G^2}\right)^{1/2}$ into series and write them in the form of double terms, we get:

$$\dot{\gamma} = \frac{\tau}{\eta_0}\left(1+\frac{\varphi_\infty-\varphi_0}{\varphi_0\chi}\tau^2-\frac{\varphi_\infty-\varphi_0}{\varphi_0\chi}\tau^4+\ldots\right) \tag{5}$$

$$\dot{\gamma} = \frac{\tau}{\eta_0}\left(1+\frac{1}{8G^2}\tau^2-\frac{1}{128G^4}\tau^4+\ldots\right) \tag{6}$$

If we combine formulas (5) and (6) and consider that $G=\eta_0/\theta$ (θ – is the relaxation time), then we get the following mathematical expression in the first approach for determining the relaxation time for structure-forming systems:

$$\theta = \sqrt{\frac{8\left(\varphi_\infty-\varphi_0\right)}{\chi\varphi_0^3}} \tag{7}$$

According to the last statement, the relaxation time was calculated for the tested oil-based and water based drilling fluids. These calculated values for oil based and water based mud are listed in table 3 and 4, resepectively. As can be seen from Table 3 and 4, depending on the composition of the drilling fluids, the structural stability and relaxation time, as well as their density, change significantly. Thus, if it is not possible to determine the relaxation time by the Cross method, the possibility of determining the relaxation time based on the determination of the structural stability of such multiphase and multicomponent solutions is shown.

Table 3

Specified values of parameters φ_0, φ_∞, χ and θ for oil-based drilling fluids

Drilling fluids, №	φ_0, 1/Pa·s	φ_∞, 1/Pa·s	χ, Pa²	θ, s
1	10.1	35.0	128.9	0.0387
2	8.5	31.5	215.7	0.0373
3	5.5	30.8	317.4	0.0619
4	9.5	28.0	336.8	0.0226
5	4.0	24.7	265.3	0.0988
6	3.8	41.5	122.2	0.0740
7	5.1	26.7	238.1	0.2121
8	4.0	28.8	252.2	0.1109
9	9.0	15.6	782.5	0.0096
10	10.4	15.3	1351.8	0.0050

Table 4

Specified values of parameters φ_0, φ_∞, χ and θ for water-based drilling fluids

Drilling fluids, №	φ_0, 1/Pa·s	φ_∞, 1/Pa·s	χ, Pa²	θ, s
1	6.0	45.0	100.337	0.1200
2	2.0	35.0	218.898	0.3883
3	4.5	43.0	135.264	0.1581
4	9.0	23.0	336.192	0.0214
5	6.5	29.5	279.769	0.0489
6	1.5	22.5	572.566	0.2949
7	5.0	29.2	256.597	0.0777
8	3.8	17.5	576.974	0.0588

Conclusion

It was determined that:

1. The exponential-type generalized rheological model, which takes into account the structural stability of the system, can be considered analogous to the Maxwell-type equation for linear viscoelastic fluids.
2. Based on exponential-type generalized rheological model extrapolation, it is possible to determine the structural stability and relaxation time during the movement of oil-based and water-based drilling fluids.

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