Rheotechnologies in well drilling

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Abstract

The principles of quality assessment of well drilling operations have been reviewed and four-grade evaluation system (very high, high, satisfactory, unsatisfactory) has been suggested. The model for interpretation of rotational viscosimetry data using criteria of transformed disreptancy and results of analysis of matrices of rheological properties estimates covariations has been summarized. The article describes how to build equations of state of rheological properties on the basis of the results of rotational viscosimetry data treatment for the plan of experiment. General formulas for calculation of biviscosity fluids steady flow in circular cylindrical and annular pipes have been presented.

Keywords: *biviscosity fluids, equation of state, quality assessment system, rheotechnology, rotational viscosimetry data interpretation model, stationary rheological model, steady flow.*

Drilling fluids systems are widely used during the construction of oil and gas wells. They help operators to implement important functional requirements of related technologies. The efficiency of drilling significantly depends on the dynamic characteristics of process fluids flow, defining the criteria of optimality and system of certain limitations and needs research, control and regulation of rheological properties.

To address the problem issues of oil and gas production due to the laws of flow of fluids, gases and its mixtures, A.Kh. Mirzadzhanzade coined the term "rheotechnologies" as the targeted use of non-equilibrium properties of fluid systems, process fluids systems and physical fields with regard to their interaction on the basis of synergy effects [1–3].

In this respect scientific principles of drilling technologies are based in particular on the study of the rheological properties of the drilling process liquids that relate to complex rheological systems [4–6]. Rheological properties form the functional purpose of the drilling process fluid as dispersed system to perform hydrodynamic, filtration and other requirements.

Currently, the rheological properties of drilling fluids are defined mainly by rotational viscosimetry data. Meanwhile different methods of measurement results treatment are used [4–12], which are based on relevant rheological models and assumptions. There is no appropriate justification for the choice of rheological model of the state. It is important in terms of the application to construct equations of state of drilling fluids rheological properties, depending on temperature, pressure, concentrations of reagents.

This article on the basis of previously completed studies [9, 11, 13–18] develops certain issues related to reotechnologies in drilling, namely:

principles of quality assessment of technological operations;

synthesis of interpretation model of rotational viscosimetry data;

equations of state for rheological properties of drilling process fluids;

calculation of steady laminar flow of biviscosity fluids in pipes.

Quality assessment of technological operations

The quality of the well depends ultimately on the list and sequence of technological processes, accordance of its parameters upon mining and geological conditions of drilling etc. Thus, targeted monitoring and process control is an integral part of the system of quality assurance of wells construction.

Technology of deepening and completion of wells fed the appropriate combinations of basic operations. Each operation is characterized by the relevant parameters system and certain restrictions on their parameters that determine the quality of the operation.

Generally, quality assessment of technological operations is limited to defining basic and controlled parameters, formation of the system of restrictions in case of safe drilling and provision of the quality of well construction, stipulation of the criterion of optimality and parameters of operations [13].

The effectiveness of manufacturing operations, aimed at wells deepening is defined by criteria that meet minimum construction cost of wells.

Effectiveness criteria of wells completion operations should be aimed at improving the quality of

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productive horizons disclosure and reliability of a well as a technical facility.

The system of quality assessment of wells construction technology should include performance standards for each technological operation for the corresponding drilling conditions. Standards should contain recommendations on the selection of parameters, its monitoring and analysis, changes in the technological operation to improve its quality.

Parameters of technological operations $x=\left(x_1,x_2,\ldots,x_n\right)^T$ are selected out of safe drilling conditions, provision of restrictions $\varphi(x)$ to guarantee quality well and optimality of effectiveness criteria $K_l\left(x,a\right)$

$$\begin{cases} K_l\left(x,a\right)\to \min,\ l\in L,\ x\in D; \\ \varphi(x)\le 0, \end{cases} \tag{1}$$

where D is the range of definition of technological operations parameters; $a=\left(a_1,a_2,\ldots,a_m\right)^T$ is the model parameter vector.

Thus, on the basis of the abovementioned information, four-grade system for quality assessment of technological operations parameters can be suggested:

very high – the parameters of technological operations meet the adopted system of restrictions and reasonable optimality criterion;

high – parameters of manufacturing operations conform to the system of restrictions and at least one of them does not meet the criteria of optimality;

satisfactory – the parameters of manufacturing operations conform to the system of restrictions and at least one of them does not meet the criteria of well construction quality;

unsatisfactory – the parameters of technological operations conform to the system of restrictions being accepted and at least one of them doesn't meet the conditions of safe drilling operations.

The model (1) of the selection of manufacturing operations parameters suggests confirming the concept of rheotechnologies, the parameters of which meet performance criteria $K_l\left(x,a\right)$ on the basis of process fluids rheological properties. For example, drilling mud formulation for directional and horizontal wells drilling can be selected by criteria of cuttings removal capacity [14], tamping (buffer) system for wells cementing, drilling fluid displacement, process fluids for discovery and development of productive strata according to the criterion of rheological propertiest of filtrate – oil emulsions [15, 16] etc.

Rotational viscosimetry data interpretation model

Couette equation of flow between coaxial cylinders serves as a the retical basis for rotational viscosimetry data treatment [4–7, 9, 11]

$$\omega=\frac{1}{2}\int_a^{\tau}\frac{\dot\gamma(\xi)}{\xi}d\xi, \tag{2}$$

where ω is the angular velocity of the outer cylinder; τ, a are the shear stress on the internal and external cylinders;

$$a=\begin{cases}\alpha^2\tau,\ \text{if}\ \ \tau\ge\tau_0/\alpha^2; \\ \tau_0,\ \text{if}\ \ \tau=\left[\tau_0,\tau_0/\alpha^2\right[; \end{cases} \tag{3}$$

$\alpha=R_в/R_з$; $R_в$, $R_з$ are the radii of the inner and outer cylinders; τ_0 is the dynamic shear stress of the fluid; $\dot\gamma(\cdot)$ is the rheological model of the fluid.

Viscosimetry data treatment comes to choosing (on the basis of measurements) of $\tau=\{\tau_i\}$ and $\omega=\{\omega_i\}$, $i=\overline{1,N}$ (N – number of velocities of outer cylinder rotation) of $\hat\nu$ model of the fluid under investigation out of certain a priori known class ϑ and building of estimates $\hat a_\nu$ of rheological properties.

Class ϑ is built out of rheologically stationary models (Newton $\dot\gamma=\tau/\eta$, Bingham $\dot\gamma=\left(\tau-\tau_0\right)/\eta$, Ostwald $\dot\gamma=\left(\tau/k\right)^{1/n}$, Herschel–Bulkley $\dot\gamma=\left(\left(\tau-\tau_0\right)/k\right)^{1/n}$, Schulman–Casson $\dot\gamma=\left(\tau^{1/n}-\tau_0^{1/n}\right)^n/\eta$ etc.), which allow explicit analytical solution of $\dot\gamma(\tau)$, as well as biviscosity models

$$\dot\gamma=\begin{cases}\dot\gamma\left(\tau,a^{(1)}\right),\ \tau\le\tau^*; \\ \dot\gamma\left(\tau,a^{(2)}\right),\ \tau>\tau^*, \end{cases} \tag{4}$$

where η, τ_0, k, n are the parameters of rheological properties of models; $a^{(1)}, a^{(2)}$ are the rheological properties of biviscosity models respectively for low and high shear rate gradients $\dot\gamma$; τ^* is the the threshold voltage shift, which is determined from the solution of equation $\dot\gamma\left(\tau^*, a^{(1)}\right)=\dot\gamma\left(\tau^*, a^{(2)}\right)$. Models (4) allow any combination of the abovementioned rheological models.

Assuming that the difference between the vector of experimental shear stress measurements τ and its theoretical field $\mathrm{A}(\omega,a_\nu)$ is additive, the task of rotary viscosimetry data treatment can be formalized as follows:

$$\tau=\begin{cases}\text{either}\ A(\omega,a_1)+\varepsilon_1, \\ \ldots\ \ldots\ \ldots\ \ldots, \\ \text{or}\quad A(\omega,a_\nu)+\varepsilon_\nu,\ \nu\in\vartheta, \\ \ldots\ \ldots\ \ldots\ \ldots, \end{cases} \tag{5}$$

where ε_ν is the random component vector due to measuring errors with normal distribution of their probabilities.

The efficient algorithms for $\tau=A(\omega,a_\nu)$ tasks solutions are presented in [4] for some on linear viscoplastic fluids (Herschel–Bulkley, Schulman–Casson). For biviscosity models (4) the main equation of rotational viscosimetry (2) can be written as:

$$\omega = \begin{cases} \dfrac{1}{2}\int\limits_a^{\tau} \dfrac{\dot\gamma_1(\xi)}{\xi} d\xi, \text{ if } \tau \le \tau^*; \\ \dfrac{1}{2}\left[\int\limits_a^{\tau^*} \dfrac{\dot\gamma_1(\xi)}{\xi} d\xi + \int\limits_{\tau^*}^{\tau} \dfrac{\dot\gamma_2(\xi)}{\xi} d\xi\right], \\ \qquad \text{if } \tau^* < \tau \le \tau^* / \alpha^2; \\ \dfrac{1}{2}\int\limits_a^{\tau} \dfrac{\dot\gamma_2(\xi)}{\xi} d\xi, \text{ if } \tau > \tau^* / \alpha^2. \end{cases} \quad (6)$$

Here there are three typical flows in the viscometer gap: for the $\dot\gamma_1(\tau)$ if $\tau \le \tau^*$; for the fluids $\dot\gamma_1(\tau)$ and $\dot\gamma_2(\tau)$ if $\tau^* < \tau \le \tau^*/\alpha^2$; for the fluid $\dot\gamma_2(\tau)$ if $\tau > \tau^*/\alpha^2$.

From (2), (3) and (6) in particular, it follows that generally for non-Newtonian fluids there is no strict assessment of shear gradient $\dot\gamma = \dot\gamma(\omega, \alpha)$. Such an assessment $\dot\gamma = 2\omega / \left(1 - \alpha^2\right)$ could be applied to viscous and viscoplastic fluids (for $\tau > \tau_0 / \alpha^2$). For the other rheological models shear gradient value also depends on the properties $\dot\gamma = \dot\gamma(\omega, a_\nu, \alpha)$ of the fluid under investigation.

Use of the formula for the shear gradient of viscous fluids leads to inaccuracies in the assessment of the rheological properties of non-Newtonian fluids, which in some cases may be high [4, 7, 10]. Due to this, the model for treatment of rotational viscosimetry data with the use of cubic splines, suggested in [12]

$$\tau_j = c_{0j} + c_{1j}\dot\gamma + c_{2j}\dot\gamma^2 + c_{3j}\dot\gamma^3, \; j = 1,2,...$$

does not provide high accuracy data interpretation, as $\dot\gamma$ is assessed with the help of formulas for viscous fluids. Here c_j are j –spline parameters.

The procedure of rotational viscosimetry data treatment depends on the type of C matrix of random component covariations (5). It is necessary to consider the cases when the matrix is known from the experiment and determines the informational content of experiment and when random component is centered, stationary and independent at all points of observation. The latter case is associated with a rapid assessment of rheological properties with limited experimental material and also requires a joint evaluation of dispersion σ_ν^2 of random component in the matrix of covariations $C = \sigma_\nu^2 I$, where I is a single matrix.

With this considerationin mind, the algorithm of rotational viscosimetry data treatment is based on successive solution of $\hat a_\nu$ vector tasks, rheological properties for each model out of ϑ class and the subsequent recognition of $\hat\nu$ model index. It uses the principles of the maximum of likelihood function or, equivalently, the minimum of transformed discrepancy

$$\min_{a_\nu} \left\| C^{-1/2}\left(\tau - A(\omega, a_\nu)\right)\right\| \Rightarrow \hat a_\nu, \; \forall \nu \in \vartheta \qquad (7)$$

and optimality of accepted model assessment criterion

$$\min_{\vartheta} K(\hat a_\nu) \Rightarrow \hat\nu. \qquad (8)$$

The criteria for evaluation of rheological model index could be as follows: transformed discrepancy

$$K\left(\hat a_\nu\right) = \left\| C^{-1/2}\left(\tau - A(\omega, \hat a_\nu)\right)\right\|; \qquad (9)$$

geometric mean relative deviation of model parameters

$$K(\hat a_\nu) = \left(\prod_j \sigma_{\nu j} / \hat a_{\nu j}\right)^{1/M}; \qquad (10)$$

the average relative deviation of model parameters

$$K(\hat a_\nu) = \frac{1}{M}\sum_j \sigma_{\nu j} / \hat a_{\nu j}; \qquad (11)$$

maximum relative standard deviation of the parameter

$$K(\hat a_\nu) = \max_j\left(\sigma_{\nu j} / \hat a_{\nu j}\right), \qquad (12)$$

where $\sigma_{\nu j}$ is the evaluation of relative standard deviation of $\hat a_{\nu j}$ parameter of ν rheological model; M is the dimension of vector $\hat a_\nu$.

Matrix of covariations of rheological model parameters estimates is defined by inversion of Fisher information matrix

$$\text{O} = \left(A'^{*}\left(\omega, \hat a_\nu\right) C^{-1} A'\left(\omega, \hat a_\nu\right)\right)^{-1}, \qquad (13)$$

where $A'\left(\omega, \, a_\nu^n\right)$ is a matrix of derivatives; $A'*$ is a transponsed matrix A'.

Selection of criteria for rheological model assessment is based on additional information regarding the intended use of rheology measurement results in the technological operations.

Transformed discrepancy (9) is used under the principle of likelihood function maximum and implemented in rotational viscosimetry data treatment models [4, 9, 11]. In some situations, this principle allows for the formation of the class of equivalent or statistically equivalent rheological models to justify a rheological model by criteria (10)–(12) on the basis of the analysis of the matrix of competitive models parameters estimates covariations (13). Also the independence of criteria (10)–(12) in the models of rotational viscosimetry data interpretation (7) and (8) must be noted as they are valuable in applied tasks of rheological technologies.

The example of rotational viscosimetry data interpretation

In order to illustrate the suggested procedures (7) and (8) let's consider the interpretation of measurements data of the plug-back slurry RTM-75 PV with the density of 1920 kg/m^3 at 22 °C. Plug-back slurry has been prepared with the help of Chandler 3060 mixer with the rotation speed of 9000 min^{-1} within 180 s. After conditioning in consistometer for 10 min rheological properties were determined using a rotary viscometer 35SR / SA-12 with a relative clearance of $\alpha = 0.9365$.

Measurements results: the rotation frequency of the external cylinder $\omega = \{0.9, \; 1.8, \; 3, \; 6, \; 30, \; 60, \; 90, \; 100, \; 180, \; 200, \; 300, \; 600\}$ min^{-1}, shear stress $\tau = \{0.48, \; 0.96, \; 1.20, \; 1.44, \; 4.79, \; 10.05, \; 11.97, \; 13.41, \; 21.07, \; 22.50, \; 34.47, \; 60.33\}$ Pa. Matrix of covariations of random

Table 1 – Data processing results of rotational viscometry of RTM-75 PV plug-back slurry

Rheological properties model ν evaluations $\hat{a}_\nu$	Root-Mean-Square deviation $\sigma_{\nu j}$ of rheological properties of model ν	σ_ν^2, Pa^2	Criteria $K(\hat{a}_\nu)$ for formulas		
			(10)	(11)	(12)
$\nu=1$ (Herschel – Bulkley) $\hat{\tau}_0=0.48$ Pa, $\hat{k}=0.1488$Pa·s^n, $\hat{n}=0.8643$	$\sigma_{11}=0.3639$ Pa, $\sigma_{12}=0.0203$ Pa·s^n, $\sigma_{13}=0.0189$	0.5493	0.1311	0.3047	0.7553
$\nu=2$ (Schulman – Casson) $\hat{\tau}_0=0.23$ Pa, $\hat{\eta}=0.0445$Pa·s, $\hat{n}=2.500$	$\sigma_{21}=0.3332$ Pa, $\sigma_{22}=0.0067$ Pa·s, $\sigma_{23}=0.8287$	0.5716	0.4217	0.6539	1.4790
$\nu=3$ (biviscosity Ostwald and Ostwald) $\hat{k}_1=0.2881$ Pa·s^n, $\hat{n}_1=0.7439, \hat{\tau}^*=16.358$ Pa $\hat{k}_2=0.1475$ Pa·s^n, $\hat{n}_2=0.8672$	$\sigma_{31}=0.0786$ Pa·s^n, $\sigma_{32}=0.0562$, $\sigma_{33}=0.0309$ Pa·s^n, $\sigma_{34}=0.0319$	0.5830	0.0126	0.1485	0.2728
$\nu=4$ (Ostwald) $\hat{k}=0.1707$ Pa·s^n, $\hat{n}=0.8453$	$\sigma_{41}=0.0172$ Pa·s^n, $\sigma_{42}=0.0157$	0.5856	0.0433	0.0598	0.1010
$\nu=5$ (biviscosity Newton and Bingham) $\hat{\eta}=0.0977$Pa·s, $\hat{\tau}^*=8.958$ Pa, $\hat{\tau}_0=3.86$ Pa, $\hat{\eta}=0.0556$Pa·s	$\sigma_{51}=0.3150$ Pa·s, $\sigma_{52}=0.5717$ Pa, $\sigma_{53}=0.0013$ Pa·s	0.7852	0.4296	1.1791	3.2230
$\nu=6$ (biviscosity Bingham and Bingham) $\hat{\tau}_{01}=0.69$ Pa, $\hat{\eta}_1=0.0788$Pa·s, $\hat{\tau}^*=12.024$ Pa, $\hat{\tau}_{02}=4.07$ Pa, $\hat{\eta}_2=0.0553$Pa·s	$\sigma_{61}=0.3259$ Pa, $\sigma_{62}=0.0048$ Pa·s, $\sigma_{63}=0.9542$ Pa, $\sigma_{64}=0.0018$ Pa·s	0.9859	0.1222	0.2001	0.4717
$\nu=7$ (Bingham) $\hat{\tau}_0=1.93$ Pa, $\hat{\eta}=0.0590$ Pa·s	$\sigma_{71}=0.5307$ Pa, $\sigma_{72}=0.0016$ Pa·s	2.3870	0.0852	0.1506	0.2747

component is accepted as $C=\sigma_\nu^2 I$. Class ϑ is formed out of Bingham, Ostwald, Herschel–Bulkley and Schulman–Casson rheological models and biviscosity models (4), presented as combinations of Newton, Bingham and Ostwald models.

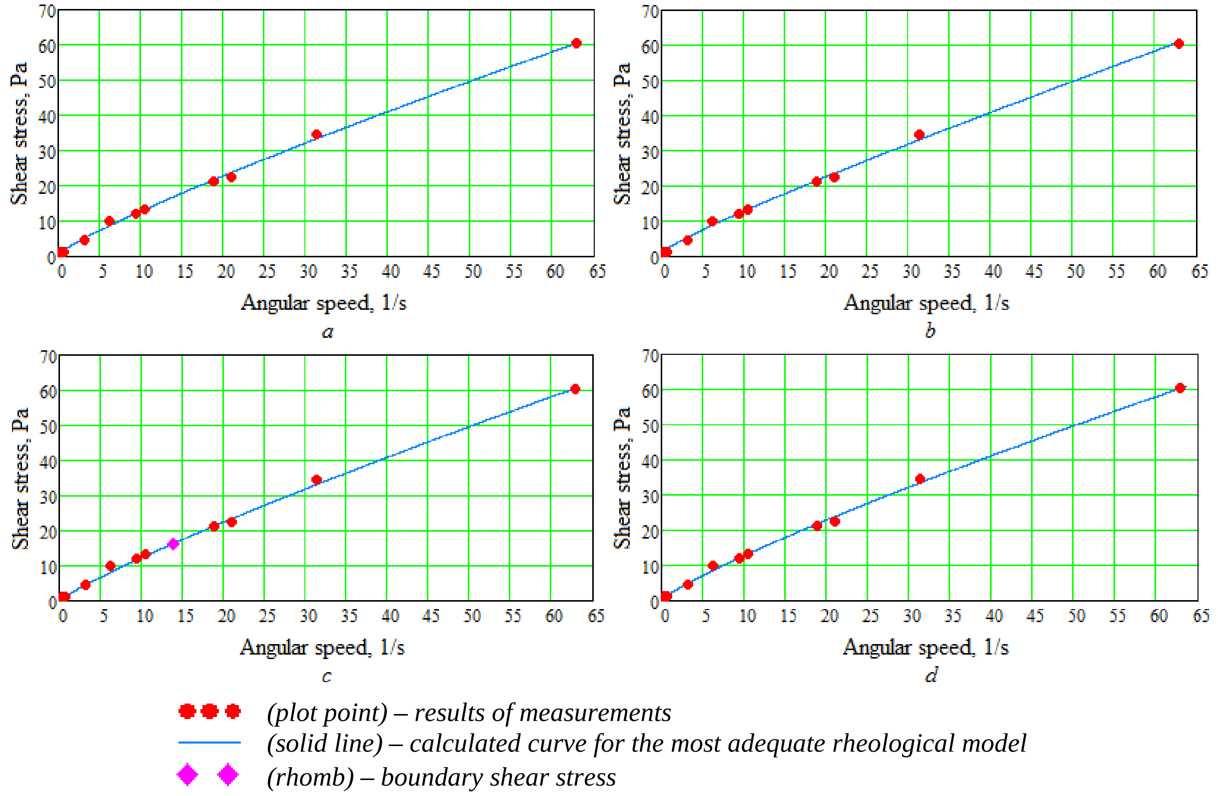
The table 1 gives fragments of data interpretation results in accordance with procedures (7) and (8). Rheological models are systematized by transformed discrepancy criterion (9), or in the case of stationary uncorrelated random component covariations matrix C (5) by its equivalent adequacy dispersion σ_ν^2. According to the criterion (9) Herschel – Bulkley rheological model is the most adequate one ($\sigma_\nu^2=0.5493$ Pa^2).

The table 1 shows that, depending on the reliability likelihood level, one can justify the equivalent class of rheological models on the basis of criterion (9) using statistical hypotheses. For instance, formodels $\nu=\{1,2,3,4\}$ adequacy dispersions σ_ν^2 differ in significantly in terms of statistics and rheological curves clearly illustrate their equivalence (Fig. 1). The analysis of selection criteria of rheological models indicates that Ostwald – Ostwald ($\nu=3$) biviscosity fluid model is the most adequate for criterion (10), and Ostwald ($\nu=4$) for the criteria (11) and (12).

Building of rheological properties state equations

In practice, there are often situations caused by the need to assess the rheological properties of the fluid under investigation for some plan of experiment X (batch processing). For instance, building of barothermal or $p-T$ state equations $a(p,T)$, investigation of the influence of chemical agents upon rheological properties $a(c)$ (p – pressure, T – temperature, c – vector of chemical agents concentrations) etc. The task of rheological properties evaluation is meaningful for the most appropriate rheological model in terms of X experiment plan.

Batch processing of data is the best variant for the matrix of covariations $C=\sigma_\nu^2 I$ and can be formalized as (3). Then assessment procedures (7) and (8) can be generalized as follows:



a – Herschel–Bulkley model; b – Schulman–Casson model; c – biviscosity fluid model (Ostwald and Ostwald); d – Ostwald model

Figure 1 – Rheograms of RTM-75 PV plug-back slurry for equivalent models at a temperature of 22 °C

$$\min\left\|A(\omega,a_{\nu s})-\tau_s\right\| \Rightarrow \hat{a}_{\nu s},\ \ \nu\in\vartheta,\ \ s=\overline{1,N_s}; \quad (14)$$

$$\min\ \mathrm{K}(\hat{a}_{\nu s}) \Rightarrow \hat{\nu}. \quad (15)$$

In this case transformed discrepancy criterion (9) is equivalent to adequacy dispersion

$$\mathrm{K}(\hat{a}_{\nu s}) = \left(N_s\left(N-r_\nu\right)\right)^{-1}\sum_{s=1}^{N_s}\sum_{i=1}^{N}\left(A(\omega_i,\hat{a}_{\nu s})-\tau_{si}\right)^2, \quad (16)$$

where r_ν is the number of parameters under assessment of the ν – rheological model. Criteria, based upon the analysis of covariations matrix of rheological properties estimates, taking in to consideration (16) are similar to (10) – (12) for the plan of the experiment.

Building of the equations of state of the rheological properties depending on the number of factors x_j change levels of matrix X can be made in the second or higher class of polynomials [17]

$$a_\nu(x)=Bb(x), \quad (17)$$

where $b(x)=\left(1,x_1,x_2,\ldots,x_1x_2,\ldots,x_1^2,x_2^2,\ldots\right)^T$ is the basis functions vector; B is the matrix of parameters.

Matrix of parameters B in (17) is being evaluated for the most appropriate in accordance with (14) and (15) rheological model $\hat{\nu}$ for different combinations E of basis functions in accordance with procedure

$$\min\left\{\left(Bb(x_i)-\hat{a}_\nu\right)^T Oj^{-1}\left(Bb(x_i)-\hat{a}_\nu\right)\right\}\Rightarrow$$
$$\Rightarrow\left\{\hat{B},\hat{\varepsilon}\right\},\ \mathrm{j}=\overline{1,\mathrm{r}_\nu},\ r_\varepsilon<N_s, \quad (18)$$

where Oj is the matrix of covariations of rheological properties parameters estimates in j – point of experiment plan; r_j^ε is the number of parameters being evaluated in models (17). One of the authors [17] demonstrates the application of the procedure (18) to build the equations of state of the rheological properties of biopolymer drilling fluid (Biocar system) depending on the temperature 25–150 °C and concentration of chemical agents (sodium chloride 5–25 %, organo-mineral colmatant Alevron® 0,5–1,5 %). The experiment results have been used in accordance with the Latin plan with with changing factors on 5 levels. The equations of state (17) for the most adequate for criterion (9) Herschel–Bulkley rheological model have been presented as second order polynomials.

Calculation of steady laminar flow of biviscosity fluids

Decision-making in reotechnologies requires adequate modeling of hydrodynamic processes, due to the use of complex rheological models in fluid flow calculations, taking into account the effects of borehole information, informational uncertainty etc. Thus, it is important to calculate technological fluids flow at random cells of borehole circulation system. Hereafter there are the integral equations, used to calculate the laminar flow of biviscosity fluids in pipes [18]:

circular cylindrical pipes

$$Q=\begin{cases}\dfrac{\pi d^3}{8\tau_w^3}\displaystyle\int_{\tau_0}^{\tau_w}\tau^2\dot{\gamma}\left(\tau,a^{(1)}\right)d\tau, \text{ if } \tau_w\le\tau^*; \\ \dfrac{\pi d^3}{8\tau_w^3}\left(\displaystyle\int_{\tau_0}^{\tau^*}\tau^2\dot{\gamma}\left(\tau,a^{(1)}\right)d\tau+\int_{\tau^*}^{\tau_w}\tau^2\dot{\gamma}\left(\tau,a^{(2)}\right)d\tau\right), \text{ if } \tau_w>\tau^*;\end{cases} \quad (19)$$

concentric annular pipes

$$\begin{cases}d_2=d_1+4l\tau_0/\Delta p; \\ \tau_1=\Delta p\left(d_1d_2-d^2\right)/(4ld); \\ \tau_2=\Delta p\left(D^2-d_1d_2\right)/(4lD); \\ \Phi(d_1,d_2,\tau_1)=\Psi(d_1,d_2,\tau_2); \\ Q=\pi(l/\Delta p)^3\left[F(d_1,d_2,\tau_1)+G(d_1,d_2,\tau_2)\right],\end{cases} \quad (20)$$

where Q is the fluid flow in a pipe; $\tau_w=\Delta pd/(4l)$ is the shear stress on the wall of the circular pipe with the diameter of d and the length of l; Δp is the pressure drop in the pipe with in the length l; τ_1, τ_2 are the shear stress on the walls of internal and external pipes; d, D are the diameters of internal and external pipes; d_1, d_2 are the flow core diameters;

$$\Phi=\begin{cases}\displaystyle\int_{\tau_0}^{\tau_1}\dot{\gamma}\left(\tau,a^{(1)}\right)\left(1-\tau/f(\tau,d_1,d_2)\right)d\tau, \text{ if } \tau_1\le\tau^*; \\ \displaystyle\int_{\tau_0}^{\tau^*}\dot{\gamma}\left(\tau,a^{(1)}\right)\left(1-\tau/f(\tau,d_1,d_2)\right)d\tau+ \\ +\displaystyle\int_{\tau^*}^{\tau_1}\dot{\gamma}\left(\tau,a^{(2)}\right)\left(1-\tau/f(\tau,d_1,d_2)\right)d\tau, \text{ if } \tau_1>\tau^*;\end{cases}$$

$$\Psi=\begin{cases}\displaystyle\int_{\tau_0}^{\tau_2}\dot{\gamma}\left(\tau,a^{(1)}\right)\left(1+\tau/f(\tau,d_1,d_2)\right)d\tau, \text{ if } \tau_2\le\tau^*; \\ \displaystyle\int_{\tau_0}^{\tau^*}\dot{\gamma}\left(\tau,a^{(1)}\right)\left(1+\tau/f(\tau,d_1,d_2)\right)d\tau+ \\ +\displaystyle\int_{\tau^*}^{\tau_2}\dot{\gamma}\left(\tau,a^{(2)}\right)\left(1+\tau/f(\tau,d_1,d_2)\right)d\tau, \text{ if } \tau_2>\tau^*;\end{cases}$$

$$F=\begin{cases}\displaystyle\int_{\tau_0}^{\tau_1}\dot{\gamma}\left(\tau,a^{(1)}\right)\frac{\left(\tau-f(\tau,d_1,d_2)\right)^3}{f(\tau,d_1,d_2)}d\tau, \text{ if } \tau_1\le\tau^*; \\ \displaystyle\int_{\tau_0}^{\tau^*}\dot{\gamma}\left(\tau,a^{(1)}\right)\frac{\left(\tau-f(\tau,d_1,d_2)\right)^3}{f(\tau,d_1,d_2)}d\tau+ \\ +\displaystyle\int_{\tau^*}^{\tau_1}\dot{\gamma}\left(\tau,a^{(2)}\right)\frac{\left(\tau-f(\tau,d_1,d_2)\right)^3}{f(\tau,d_1,d_2)}d\tau, \text{ if } \tau_1\le\tau^*;\end{cases}$$

$$G=\begin{cases}\displaystyle\int_{\tau_0}^{\tau_2}\dot{\gamma}\left(\tau,a^{(1)}\right)\frac{\left(\tau+f(\tau,d_1,d_2)\right)^3}{f(\tau,d_1,d_2)}d\tau, \text{ if } \tau_2\le\tau^*; \\ \displaystyle\int_{\tau_0}^{\tau^*}\dot{\gamma}\left(\tau,a^{(1)}\right)\frac{\left(\tau+f(\tau,d_1,d_2)\right)^3}{f(\tau,d_1,d_2)}d\tau+ \\ +\displaystyle\int_{\tau^*}^{\tau_2}\dot{\gamma}\left(\tau,a^{(2)}\right)\frac{\left(\tau+f(\tau,d_1,d_2)\right)^3}{f(\tau,d_1,d_2)}d\tau, \text{ if } \tau_2>\tau^*;\end{cases}$$

$$f(\tau,d_1,d_2)=\sqrt{\tau^2+d_1d_2\left(\Delta p/2l\right)^2},$$

where $\Phi=\Phi(d_1,d_2,\tau_2)$, $\Psi=\Psi(d_1,d_2,\tau_2)$, $F=F(d_1,d_2,\tau_2)$, $G=G(d_1,d_2,\tau_2)$.

The first equation (19) describes fluid flow of the rheological model $\dot{\gamma}\left(\tau,a^{(1)}\right)$ if $\Delta p\le 4\tau^* l/d$, while the second one describes biviscosity fluid flow of the rheological models $\dot{\gamma}\left(\tau,a^{(1)}\right)$ and $\dot{\gamma}\left(\tau,a^{(2)}\right)$ when $\Delta p>4\tau^* l/d$. The same applies to the fourth and fifth equations (20), the functions of which $\Phi(d_1,d_2,\tau_1)$, $\Psi(d_1,d_2,\tau_2)$, $F(d_1,d_2,\tau_1)$, $G(d_1,d_2,\tau_2)$ take into account these features. The system of equations (20) is presented in a convenient form of numerical solution (τ_1>0; τ_2>0).

The equations (19) and (20) summarize the solution of fluid flow tasks in a ϑ class of stationary rheological models which allow an explicit analytical representation of $\dot{\gamma}=\dot{\gamma}(\tau)$ type in case of biviscosity fluids flow (4) in circular cylindrical and concentric annular pipes [18]. The algorithms $Q=Q(\Delta p)$ for numerical solution of tasks have been developed ((19) and (20)) with a set accuracy and on its basis the algorithms $\Delta p=\Delta p(Q)$ have been developed. From (19) and (20) we can build flow velocity distributions of biviscosity fluids in the pipe cross section, which is important in tasks of fluid displacement and evaluation of laminar flow transport capacity.

Conclusions

The principles of evaluation of quality of well drilling operations, based on the decision-making model with a flexible choice of optimality criterion have been reviewed. Accounting for the compliance of technological operations with the system of constraints and optimality criterion four-grade evaluation system (very high, high, satisfactory, unsatisfactory) has been defined. The articles pecifies the concept of rheotechnology in drilling of wells that must meet the optimality criterion on the basis of rheological properties of process fluids.

The model for interpretation of rotational viscosimetry data treatment using criteria of transformed disreptancy and results of analysis of matrices of covariations of rheological properties estimates has been summarized. The class of stationary rheological models that allow explicit analytical solution of $\dot{\gamma}=\dot{\gamma}(\tau)$ type includes biviscosity fluids. The model can be used for batch processing in accordance with experiment plan and is characterized in comparison with known increased interpretative possibilities. It has been described how to build equations of state of rheological properties on the basis of the results of rotational viscosimetry data treatment for the plan of experiment.

General formulas for calculation of biviscosity fluids steady flow in circular cylindrical and annular pipes have been presented.

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Реотехнології в бурінні свердловин

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Розглянуто принципи і запропоновано чотирибальну (дуже висока, висока, задовільна, незадовільна) систему оцінювання якості технологічних операцій буріння свердловин. Узагальнено модель інтерпретації даних ротаційної віскозиметрії із використанням критеріїв трансформованої нев’язки та результататів аналізу матриці коваріацій оцінок реологічних властивостей. Описано процедуру побудови рівнянь стану реологічних властивостей за результатами обробки даних ротаційної віскозиметрії для плану експерименту. Наведено загальні формули для розрахунку усталених течій бів’язких рідин в круглих циліндричних і кільцевих трубах.

Ключові слова: *бів’язка рідина, модель інтерпретації даних ротаційної віскозиметрії, реологічно стаціонарна модель, реотехнологія, рівняння стану, система оцінювання якості, усталена течія.*