The Evaluation of Rheological Parameters of non-Newtonian Fluids by Rotational Viscosimetry

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Received: 30.1.2012, Final version: 23.4.2012

Abstract:
The methodology of evaluation of rheological parameters of non-Newtonian fluids on the basis of rotational viscosimetry data has been described, which is based upon rigorous solution of Couette flow equation and considers informational content of experiments. Class of models is formed for rheologically stationary systems, biviscosity ones included. Functional features of methodology and its generalization for the interpretation of rheological properties measurements results according to plans of experiments have been outlined.

Zusammenfassung:
Die Methode zur Auswertung der rheologischen Parameter von nicht-newtonischen Fluiden durch Daten aus der Rotationsviskosimetrie basierend auf der genauen Lösung der Couette-Strömungsgleichung wird beschrieben und liefert die inhaltliche Substanz der Experimente. Die Modellklasse beinhaltet rheologische stationäre Systeme, einschließlich der Biviskosität. Funktionsmerkmale der Methoden sowie die Verallgemeinerung für die Interpretation der rheologischen Eigenschaften resultieren aus der dargelegten Planung der Experimente.

Résumé:
On a décrit la méthodologie d'évaluation des paramètres rhéologiques liquides non-newtoniens selon les doneés de la viscosimétrie rotative, basée sur une équation courante d'interprétation stricte Couette. Cette méthodologie prend en compte le contenu informatif des expériences. On a formée la classe des modèles pour les systèmes rhéologiquement stationnaires, y compris bi-visqueux. On a montré les possibilités fonctionnelles de la méthodologie et sa généralisation pour l'interprétation des résultats des mesures des propriétés rhéologiques selon les plans d'expérience.

Key words: rotational viscosimetry, Couette flow equation, informational content, biviscosity rheological models

1 INTRODUCTION

Fluids with non-Newtonian rheological properties are widely used in the technological processes of different industries, such as chemical industry, oil and gas production etc. Efficient management of these processes requires reliable information about rheological properties of fluids and influence of state parameters and other factors upon them. Rotational viscosimeters with coaxial cylinders are most widely used for measuring rheological properties of fluids on practice. Rotational viscosimetry data processing is based upon the use of equation which describes Couette flow in a gap between coaxial cylinders

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

where ω is the angular velocity of rotation of outer cylinder, τ and a are the shear stresses on inner and outer cylinders, $\dot{\gamma}(\tau)$ the fluid rheological model, and $\dot{\gamma}$ the shear rate. The relation between stresses on the outer and inner cylinders is determined as follows

$$a = \begin{cases} \alpha^2 \tau, & if \quad \tau \geq \tau_o/\alpha^2 \\ \tau_o, & if \quad \tau_o \leq \tau < \tau_o/\alpha^2 \end{cases} \tag{2}$$

where τ_o is the yield point, $\alpha = R_1/R_2$, while R_1, R_2 are the radii of the inner and outer cylinders. In Equation 1 the class of rheologically stationary models of non-Newtonian fluids permits clear analytical solution $\dot{\gamma} = \dot{\gamma}(\tau)$ and includes the models of Bingham [1] $\dot{\gamma} = (\tau - \tau_o)/\eta$, Ostwald [2] $\dot{\gamma} = (\tau/k)^{1/n}$, Herschel-Bulkley [3] $\dot{\gamma} = ((\tau - \tau_o)/k)^{1/n}$,

DOI: 10.3933/ApplRheol-22-32381

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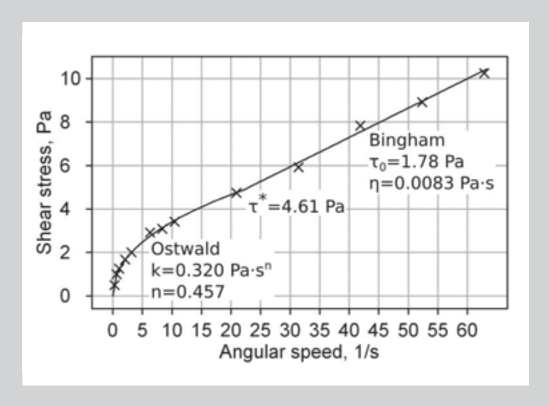

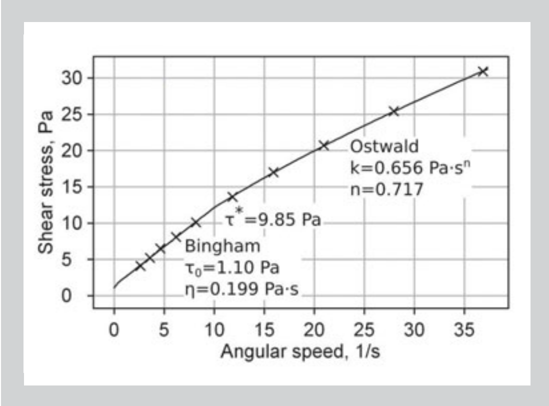

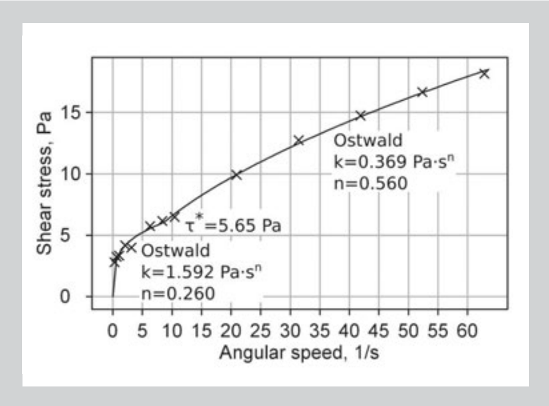

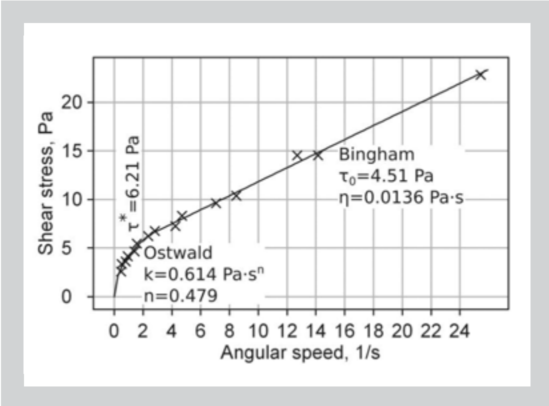

Figure 5 (left above): Rheogram for bentonite-lignite suspension (S5 [11, 16], α = 0.9365).

Figure 6 (right above): Rheogram for CMC-water solution (S33 [11, 17], α = 0.79384).

Figure 7 (left below): Rheogram for bentonite-lignite suspension (S7 [11, 16], α = 0.9365).

Figure 8 (right below): Rheogram for drilling fluid (clay 10 %, CMC 0.1 %) [7] (α = 0.981).

Table 4 (left): Rotational viscometry data for drilling fluid [18].

Table 5: The main results of rotational visosimetry data treatment for drilling fluid [18].

With the use of Procedure 9, evaluations of rheological properties of $\nu \in \vartheta$ models for each point *m* of experiment plan (which consists of *M* points) are built. Procedure 10 determines the adequate rheological model selection out of the condition of dispersion $\hat{\sigma}^2_{c\nu}$ minimum for experiment plan. Let us examine the results of treatment of rotational viscosimetry data (Fann 75, α=0.9365) of waterbased drilling fluid [18]. In Table 4 there are the results of shear stresses measurements for experiment plan with 5 pressure levels and 4 temperature levels. Class ϑ is formed by rheological models of Bingham, Ostwald, Herschel-Bulkley and Schulman-Casson. In Table 5 we list evaluations of dispersions of random component and highlight the most adequate rheological models for each point of experiment plan. In 16 points of experiment plan, the most adequate is Schulman-Casson rheological model, in 2 points – Herschel-Bulkley model and in 2 points – Bingham model. For experiment plan according to Procedure 10 the most adequate is Schulman-Casson rheological model (0.2325 Pa²), which rheological properties evaluations are listed in Table 5.

Pressure, MPa	Temperature, ºC	Shear stress τ (Pa) at rotational velocity ω, min^{-1}					
		3	6	100	200	300	600
0.1	50	7.50	8.00	14.50	20.50	25.50	40.00
	60	7.50	8.00	9.50	15.50	20.00	31.50
	90	7.66	8.14	10.05	13.89	16.76	24.42
	120	7.66	7.66	8.62	10.05	12.45	20.11
30	50	7.50	8.10	17.00	25.00	30.00	50.00
	60	8.00	8.00	15.00	20.50	26.00	43.00
	90	8.14	8.62	13.41	17.72	21.07	33.04
	120	7.66	7.66	12.93	15.80	18.19	27.29
35	50	8.10	8.50	17.00	25.50	32.00	55.00
	60	8.14	8.62	15.80	22.02	27.77	45.01
	90	8.62	8.62	14.36	18.19	22.02	33.99
	120	8.14	8.62	13.41	16.28	19.15	28.73
40	50	8.50	8.70	18.00	26.50	34.00	58.00
	60	8.62	8.62	16.76	22.98	29.21	49.32
	90	8.62	9.10	14.36	18.67	22.98	35.43
	120	8.62	8.62	14.36	16.76	19.87	31.12
45	50	8.50	8.50	18.50	27.00	35.50	59.00
	60	8.62	8.62	17.24	24.42	30.64	51.23
	90	9.10	9.10	14.84	19.15	23.46	37.83
	120	8.62	9.10	13.89	17.24	20.59	32.08

Pressure, MPa	Temperature, ºC	Evaluations of random component dispersion σ^2_ν (Pa^2) for rheological model ν				Evaluations of rheological properties of model $\hat{\nu}$		
		Bingham	Ostwald	Herschel-Bulkley	Schulman-Casson	$\hat{\tau}_0$, Pa	$\hat{\eta}$, Pa·s	$\hat{n}$
0.1	50	1.2400	11.91	**0.0201**	0.0288	6.515	0.0236	1.439
	60	**0.9866**	16.64	1.2590	1.1900	7.023	0.0258	0.883
	90	**0.2282**	8.59	0.2694	0.2809	7.241	0.0154	1.070
	120	0.8628	9.89	0.0418	**0.0148**	7.492	0.0179	0.517
30	50	2.5390	14.01	0.6382	**0.5149**	6.324	0.0306	1.508
	60	0.4194	16.36	0.1400	**0.0989**	7.110	0.0303	1.202
	90	0.3529	11.94	0.1185	**0.0937**	7.565	0.0201	1.231
	120	0.9807	6.28	0.3357	**0.2732**	6.733	0.0116	1.522
35	50	0.7364	19.67	0.2711	**0.2248**	7.185	0.0411	1.216
	60	0.7708	16.37	0.0461	**0.0155**	7.270	0.0299	1.296
	90	0.5831	11.80	0.1700	**0.1269**	7.728	0.0193	1.304
	120	0.6012	8.03	0.2366	**0.1887**	7.557	0.0141	1.359
40	50	0.7360	21.04	0.1231	**0.0770**	7.428	0.0433	1.225
	60	0.5227	20.47	0.3045	**0.2367**	7.687	0.0360	1.177
	90	0.3936	13.41	0.0392	**0.0215**	7.954	0.0214	1.249
	120	0.7908	10.77	0.7648	**0.6934**	7.952	0.0175	1.245
45	50	1.3600	19.25	**0.0495**	0.0533	7.123	0.0422	1.322
	60	0.9314	19.27	0.2285	**0.1594**	7.485	0.0357	1.272
	90	0.2301	17.21	0.1954	**0.1691**	8.368	0.0257	1.118
	120	0.2998	12.09	0.2213	**0.1891**	8.159	0.0195	1.176
$\sigma^2_{c\nu}$, Pa^2		0.7783	14.25	0.2736	**0.2325**			

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6 CONCLUSIONS

Methodology of evaluation of non-Newtonian fluids rheological properties is built in class ϑ of rheologically stationary models, which permit clear analytical solution $\dot{\gamma} = \dot{\gamma}(\tau)$. Methodology is based upon rigorous solution of the main rotational viscosimetry problem (Equations 1 and 2) and considers informational content of experiments. Class ϑ has been expanded due to piecewise approximation of measurements data by biviscosity rheological models. The methodology has been generalized for treatment of rotational viscosimetry data coming from plans of experiments. In such conditions the most adequate rheological model is selected for the whole plan of experiment (Procedure 10).

The above mentioned, in comparison with widely spread methodologies [5 – 8], ensures more adequate and accurate evaluations of rheological model and properties of investigated fluids. In petroleum industry the use of adequate rheological models (biviscosity ones included) and equations of their state is especially important for evaluation of cuttings transport properties of drilling fluid [19, 20] and replacement of one fluid with the other in the process of well cementing [21]. In applied aspect the important one is the information concerning covariations matrix *O* of rheological properties evaluations, which let us evaluate influence of different effects upon rheological properties with the use of statistical tests and use it in statistical modeling of technological processes, building of statistical decision making models etc. Practical implementation of the proposed methodology is connected with the use of computer systems for rotational viscosimetry data treatment [10].

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