Based on the above processing results, the volume method is used to compute the volume, saturation and porosity of 11 hydrate sub-ore bodies to get the reserve of the sub-ore bodies and finally get the total reserve of this research area.

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Optimization of Rheology Models of Non-dispersed Polymer Drilling Fluid

LiFang[1], Pu Xiaolin[1]

1.Petroleum Engineering Institute, Southwest Petroleum University, Chengdu Sichuan610500,China

Abstract

The accurate calculation of rheological parameters and the optimization of rheology models of drilling fluid are the premise for the optimization design of drilling fluid. The conventional calculation methods and the regression analysis methods of the rheological parameters in common five rheological models are analyzed. We adopt rheological curve correlation, shear stress error correlation, correlated parameters analysis to optimize the rheology model of non-dispersed polymer drilling fluid, and analyze the calculation methods for rheological parameters of model. The results showed that the best rheology models of non-dispersed polymer drilling fluid should be Herschel-Bulkely Model, secondly, Power Law Model, Herschel-Bulkely Model is a three- parameters model, it is difficult and complicated to obtain these parameters, so we should be first selected Power Law Model when we describe rheological property of non-dispersed polymer drilling fluid.

Keywords: DRILLING FLUID, RHEOLOGY MODEL, RHEOLOGICAL PARAMETER, NON-DISPERSED POLYMER, CALCULATION METHODS

1. Introduction

Rheological property of drilling fluid is closely related to drilling work such as wellbore stability, carrying debris, increase in penetration rate and the annulus drilling hydraulic parameters, thus it is one of the most important properties of drilling fluid. Optimization of frilling fluid rheology mode is not only essential for the accurate calculation of the rheological parameters, but also plays an important role in the evaluation of the performance of the treatment agent, optimized drilling hydraulic parameters, analytical investigation of purification downhole and the stability of borehole etc. [1,2]. At present, in the drilling engineering, the commonly used rheology modes relatively close to flow conditions of drilling fluid are: Bingham Model, Power Law Model, Casson Model and Power-law Model with Yielding Point (also known as Herschel-Bulkely Model), Robertson-Stiff Model, Lin Boheng Model and the like. In this paper, the rheological model of a non-dispersed polymer drilling fluid system is optimized using rheological curve correlation, shear stress error correlation and regression analysis method in allusion to these types of models.

2. Common Rheological Models

2.1. Bingham Model

Bingham Model is a pattern used to describe plastic fluid model, able to be described by the following equation:

$$\tau=\tau_0+\mu_p\gamma \tag{1}$$

Among it: τ is the shear stress, Pa; τ0 is dynamic shear stress, Pa; μp is plastic viscosity, $mPa\cdot s$; γ is the shear rate, s^{-1}.

Usually, only at the middle and high shear rate, Bingham Model can better describe the rheological properties of the mud, and it can only describe the rheological model of non-Newtonian fluid. If the actual drilling fluid is not plastic, and then big problems will appear for continued use of Bingham Model and its unique parameters including static shear, plastic viscosity, dynamic shear force and dynamic plastic ratio, etc. to evaluate mud property and to guide on-site construction.

2.2. Power Law Model

Power Law Model is a rheology mode used to describe pseudoplastic fluid, able to be described by the following equation:

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

In the formula: τ is the shear stress, Pa; K is the consistency factor, $Pa\cdot s^n$; γ is the shear rate, s^{-1}; n is flow index, dimensionless quantity.

Power Law Model has reflected flow regularity of pseudoplastic fluid at the middle and high shear rates to some extent, but like Bingham Model, the Power Law Model can not reflect the flow regularity of fluid at low shear rates. And usually in the annulus, namely when carrying and suspending drillings, the shear rate is generally not high. Furthermore, the Power Law Model can not reflect thestatic shear properties of mud.

2.3. Casson Model

CassonModel can be described by the following equation:

$$\tau^{1/2}=\tau_c^{1/2}+\mu_\infty^{1/2}\gamma^{1/2} \tag{3}$$

In the formula: τ is the shear stress, Pa; τc is Casson dynamic shear force (or Casson yield value), Pa; μ_∞ is ultimate-high--shear viscosity, mPa•s; γ is the shear rate, s^{-1}.

Casson dynamic shear force τc represents the intensity of the grid structure that is dismantled available in drilling fluid, also the smallest dynamic shear force when fluid begins to flow, and it reflects the capacity of mud carrying and suspending drill cuttings. Ultimate-high--shear viscosity μ∞ indicates the strength of friction within the mud system. Ultimate-high--shear viscosity can be approximated as the resistance in a turbulent state when mud is in the drill nozzle, namely, the flow resistance of mud when the shear rate is infinite. The lower the ultimate-high--shear viscosity μ∞ is, the greater the pressure drop at high shear rates down will be, and the higher the water horsepower of drill is. Moreover, to improve the ultimate-high-shear viscosity helps to timely remove drilling cuttings from the cutting surface of drill, thereby improving rate of penetration.

2.4. Herschel-Bulkely Model

Herschel - Bulkley three-parameter rheological model is also known as Power Law Model with dynamic shear force, Power Law Model with yield value, or the amended Power Law Model. HELENA - Buckley can be described by the following equation:

$$\tau=\tau_s+K\gamma^n \quad (4)$$

In the formula: τ is the shear stress, Pa; τs is dynamic shear force (or yield value) of the model, Pa;

γ is the shear rate, s-1; n is the flow index, dimensionless quantity.

Dynamic shear force τs represents the actual dynamic shear of mud, indicating the minimum shear stress required when the fluid starts to flow, and different from Bingham Model, τs is not a extrapolated value. For dynamic shear τ0 of Bingham Model, it is an extrapolation value higher than the actual limit dynamic shear of mud. There is an ultimate dynamic shear force in the actual drilling fluid, while Power Law Model can not reflect that the fluid has ultimate dynamic shear force, thus both Bingham Model and Power Law Model can not reflect the real nature of the drilling fluid. Thus, H - B mode combines the features of Bingham Model and Power Law Model, an ideal rheological model.

2.5. Lin Boheng Model

Lin Boheng has proposed a new rheology mode according hyperbolic characteristics, which can fully reflect the curve characters possibility of the general drilling fluid and Lin Boheng pattern can be described by the following equation:

$$\tau=\tau_s+\mu_p\gamma \quad (6)$$

In the formula: τ is the shear stress, Pa; τs is static shear stress or gel strength, Pa;

μp is plastic viscosity, mPa • s; γ is the shear rate, s-1;

β is the specific parameters for this model, namely, the shear thinning factor, s-1.

Three independent parameters based on this mode can combine a practical parameter, namely, dynamic shear stress τ0,

$$\tau_0=\tau_s+ \quad (7)$$

Lin Boheng Model can not only describe rheological property of non-Newtonian plastic fluid, but also the non-Newtonian fluid rheology, but also reveals the relationship between the various fluids:

When β=0 describes Bingham fluid, $\tau=\tau_s+\mu_p\gamma$, and τ_s in the formula is namely the dynamic shear stressτ_0 in Bingham model.

In addition, when the shear rate γ is larger, there is the following relationship:

$$\tau=\tau_s+\mu_p\gamma\approx\tau_s+\mu_p\gamma=\tau_s+\mu_p\gamma=\tau_0+\mu_p\gamma \quad (8)$$

The above formula is actually Bingham Model. This has thus actually proved that only in plastic fluid at middle and high shear rates, Bingham Model can make accurate description of flow regularity of fluid, failed to reflect the flow pattern of the fluid at lower shear rate. How much should the minimum shearing speed reach in the end can be enough to describe the rheology of mud with Bingham Model requires taking into account the required accuracy. If the relative error is less than 2%, then when τ≥2β, Bingham model can be used to describe the drilling fluid rheology.

3. Preferred Method of Rheology Model

Currently, the preferred mathematical analytical methods of drilling fluid rheology model mainly include rheological curve correlation, shear stress error correlation, the regression analysis method, least squares technique and golden section search method etc.

3.1. Rheological Curve Correlation

Rheological curve correlation is theoretical and practical flow curve plotted based on experimental data, thereby performing intuitive curve fitting contrast to determine rheological model. Specific methods are: six groups of data are measured using rotational viscometer and recorded as θ, θ_6, θ_{100}, θ_{200}, θ_{300}, θ_{600}. According to these six groups of data and the given formula, parameters of drilling fluid are calculated including plastic viscosity μp, flow index n, consistency coefficient K, ultimate shear viscosity μ∞, Casson dynamic shear force τc and others, and then brought into Bingham and Power Law and other modes, theoretical values τ theory at six shear rates γ for each mode are determined respectively. According to the obtained parameters, γ-τ theory curves of each model are drawn, namely, the theoretical flow curve. Then, according to τ = 0.511θ, the six actual drilling fluid shear stress τ real are obtained to draw γ-τ actual curves in the same coordinate axes as the theoretical flow curve, namely the actual flow curve. Contrast is made in difference between the actual flow curve and the theoretical flow curve to select the fit rheological model, which is namely the optimal rheological model.

Rheological curve correlation is a relatively straightforward way to judge. Using this method requires very complicated calculation, and calculation accuracy cannot be guaranteed. If there are several curves very close to each other, it would be not easy to judge by the naked eye.

3.2. Shearing Stress Error Correlation Method

The principle of shearing stress error correlation method is that: the calculated theoretical shear stress value and the actual value of the shear stress of the various rheology models are calculated to figure out relative error and mean relative error, and the selected pattern with the smallest average relative error is the preferred rheological model.

Computational formula of shearing stress error correlation method is

Relative error

$$e=(\tau_1-\tau_0)/\ \tau_0\times 100\% \qquad (9)$$

Average relative error

$$\bar{e}=\left(|e_1|+|e_2|+|e_3|+\ldots+|e_n|\right)/n \qquad (10)$$

In the formula, n is the number of data.

Shearing stress error correlation method is very simple in calculation. If the data are disturbed by outliers, the accuracy will be greatly reduced.

3.3 Regression Analysis Method

Regression analysis is a linear regression method, and data obtained from drilling fluid rheology experiments are recorded as: (x_1,y_1) (x_2,y_2)……(x_n,y_n) , and x, y are random variables. When there is a linear relationship between x and y to certain degree, it shall be returned to equation with one unknown quantity:

$$y=\hat{a}+\hat{b}x \qquad (11)$$

Parameters calculations in five rheological model formulas after linear regression are shown in Table 1 below.

Table 1. Regression model of regression analysis

Rheological models	Rheological equations
Bingham Model	$\tau=\tau_0+\mu_p\gamma$
Power Law Model	$\tau=K\gamma^n$
Casson Model	$\tau^{1/2}=\tau_c^{1/2}+\mu_\infty^{1/2}\gamma^{1/2}$
Herschel-Buckley Model	$\tau=\tau_s+K\gamma^n$
Lin Boheng Model	$\tau=\tau_s+\mu_p\gamma$

Rheological models	Regression models
Bingham Model	$\tau=\tau_0+\mu_p\gamma$
Power Law Model	$\tau_1=\tau_n+\mu_n\gamma_n$ $\tau_1=\lg\tau$, $\tau_n=\lg k$ $\mu_n=n, \gamma_n=\lg\gamma$
Casson Model	$\tau_1=\tau_n+\mu_n\gamma_n$ $\tau_1=\tau^{1/2}$, $\tau_n=\tau_c^{1/2}$ $\mu_n=\mu_\infty^{1/2}, \gamma_n=\gamma^{1/2}$
Herschel-Buckley Model	$\tau_1=\tau_n+\mu_n\gamma_n$ $\tau_1=\lg(\tau-\tau_s)$, $\tau_n=\lg k$ $\mu_n=n, \gamma_n=\lg\gamma$
Lin Boheng Model	$\tau_1=\tau_n+\mu_n\gamma_n$ $\tau_1=\tau$, $\tau_n=\tau_s$ $\mu_n=\mu_p, \gamma_n=\gamma(1+\beta/\gamma)^{1/2}$

A related parameter R is used to measure the degree of linear correlation between the variable x and y.

$$R=\frac{\sum_{i=1}^{n}(xi-\bar{x})(yi-\bar{y})}{\left[\sum_{i=1}^{n}(xi-\bar{x})^2\sum_{i=1}^{n}(yi-\bar{y})^2\right]^{1/2}}\quad 0\le R\le 1 \qquad (12)$$

If R is closer to 0, the degree of correlation between x and y is also smaller, the worse the effect of linear regression will be. On the contrary, if R is closer to 1, the degree of correlation between x and y is higher, the higher, the better the effect of the linear regression will be. Hence, we can determine the exact rheology model most consistent with the experimental data based on the value of correlation coefficient R. The value of correlation coefficient is a comprehensive measure for various flow patterns to calculate error, thus being very important. Regression analysis also can accurately describe the extent of integration between variables in each flow pattern, and its calculation is simple. In general, however, differences in R value would appear on the third or fourth decimal place of that number.

4. Measurement and Calculation of Non-dispersible Polymer Drilling Fluid Rheological Parameters.

In this study, the most common paradigm of six-speed rotational viscometer is used. The six rotational speeds and corresponding shear rates are as follows: 600r/min(1022 s^{-1}), 300r/min(511 s^{-1}), 200r/min(340.7 s^{-1}), 100r/min(170.3 s^{-1}), 6r/min(10.22 s^{-1}) and 3r/min(5.11 s^{-1}).

4.1. Computational Formula of Rheological Parameters

Dial reading $\overline{F_i}$ is the dial reading when speed is N. Shear rate γ refers to increment in flow velocity at unit distance perpendicular to the direction of flow velocity.

$$\gamma=\theta\times 1.703 \qquad (13)$$

Dynamic shear stress τ_0 is the intersection between extending line segment of plastic fluid flow curve and shear stress axis.

$$\tau_0=0.511\times(2\theta_{300}-\theta_{600}) \qquad (14)$$

Plastic viscosity μ_p is the slope of the line segment in plastic fluid flow curve.

$$\mu_p=\theta_{600}-\theta_{300} \qquad (15)$$

Flow index n represents the non-Newtonian levelmanifested by pseudoplastic fluid within a certain range of shear rate.

$$n = 3.322\lg\left(\theta_{600}/\theta_{300}\right) \quad (16)$$

Consistency coefficient K is the parameter relatedto viscosity and shearingforce of drilling fluid.

$$K = \left(0.511\theta_{300}\right)/511^{n} \quad (17)$$

Casson dynamic shear strength τ_c represents the intensity of the grid structure that is dismantled available in drilling fluid.

$$\tau_c^{1/2} = 0.493\left[\left(6\theta_{100}\right)^{1/2} - \theta_{600}^{1/2}\right] \quad (18)$$

Ultimate-high--shear viscosity μ_∞ represents strong velocity of internal friction within the drilling fluid system, used to approximatelyindicate the flow resistance when drill nozzle is in turbulent state.

$$\mu_\infty^{1/2} = 1.195\left(\theta_{600}^{1/2} - \theta_{100}^{1/2}\right) \quad (19)$$

Flow index n_h in Herschel-Buckley Model has the same significance with the flow indexn in Power Law Model.

$$n_h = 3.322\lg\left((\theta_{600} - \theta_3)/(\theta_{300} - \theta_3)\right) \quad (20)$$

Consistency coefficient K_h in Herschel-Buckley Model has the same significance with that in Power Law Model

$$K_h = 0.511(\theta_{300} - \theta_3)/511^{n_h} \quad (21)$$

Dynamic shear force in Herschel-Buckley Model is the actual dynamic shear force in drilling fluid, representing the minimum shear stress required when the fluid begins to flow.

$$\tau_s = 0.511 \times \theta_3 \quad (22)$$

Shearing dilution factor β is the specific parameter in Lin Boheng Model.

$$\beta = 2\tau_0/\mu_p \quad (23)$$

According to the formula (13) - (23), rheological parameter of this non-dispersed polymer drilling fluid system can be calculated, as shown in Table 2.

Note: non-dispersed polymer drilling fluid is composed of 4% bentonite slurry + 0.2% FA367 + 0.7% KPHP + 0.3% XY-27 + 0.1% JT888;

4.2. Optimal Selection of Drilling Fluid Rheology Model

In this paper, analysis and optimal selection of rheology model for each kind of drilling fluid can be made using rheological curve correlation, shearing stress error correlation method and regression analysis method respectively.

Table 2. Non-dispersed polymer drilling fluid system rheological parameters list

Parameter	Non-dispersed polymer drilling fluid		
θ(r/min)	600	300	200
γ(s^{-1})	1022	511	340.7
value	48	29	22
T_0	24.53	14.82	11.24
T_{bin}(Pa)	24.53	14.82	11.58
T_{mi}(Pa)	24.51	14.81	11.03
T_{ka}(Pa)	24.66	14.34	10.65
T_{he}(Pa)	24.53	14.82	11.12
T_{lin}(Pa)	25.01	14.93	11.42
τ_0(Pa)	5.11		
μ_p(Pa.s)	0.019		
n	0.727		
K(Pa.s^n)	0.159		
$\tau_c^{1/2}$($Pa^{1/2}$)	0.938		
$\mu_\infty^{1/2}$$(Pa.s)^{1/2}$	0.126		
n_h	0.769		
K_h	0.114		
τ_s(Pa)	1.022		
β(s^{-1})	537.89		

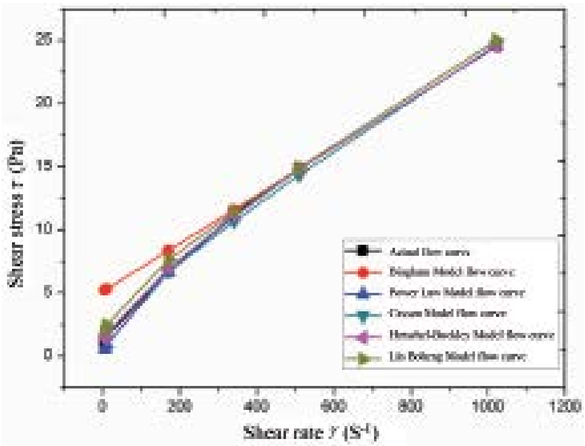
Parameter	Non-dispersed polymer drilling fluid		
θ(r/min)	100	6	3
γ(s^{-1})	170.3	10.22	5.11
value	13	3	2
T_0	6.64	1.53	1.02
T_{bin}(Pa)	8.35	5.3	5.21
T_{mi}(Pa)	6.66	0.86	0.52
T_{ka}(Pa)	6.67	1.80	1.50
T_{he}(Pa)	6.95	1.70	1.42
T_{lin}(Pa)	7.62	2.44	2.02
τ_0(Pa)	5.11		
μ_p(Pa.s)	0.019		
n	0.727		
K(Pa.s^n)	0.159		
$\tau_c^{1/2}$($Pa^{1/2}$)	0.938		
$\mu_\infty^{1/2}$$(Pa.s)^{1/2}$	0.126		
n_h	0.769		
K_h	0.114		
τ_s(Pa)	1.022		
β(s^{-1})	537.89		

4.2.1. Rheological Curve Correlation

According to the data in Table 1, γ-τ theoretical curve of each model, namely the theoretical flow curve, is drawn. Meanwhile, in the same coordinate axis as theoretical flow curve, γ-τ_{actual} curve, namely the actual flow curve, is plotted. Contrast is made in difference between the actual flow curve and the theoretical flow curve, and the selected most fit rheological model is the optimal rheological model.

According to Figure 1, it can be seen at low shear rates, Bingham Model curve has the lowest degree of fitting the actual flow curve of drilling fluid, while for other several flow curves, they are very close to the actual flow curve, hard to distinguish and optimize, so they are plotted respectively in order to find the flow curve with the highest degree of fitting.

Figure 2 is a graph of comparison among Power Law, Casson, Herschel-Buckley Model and the actual drilling fluid rheology curve. It is observed that there is quite small difference in flow curve between several models and the actual drilling fluid, but Herschel-Buckley Model has better degree of fitting. Figure 3 is chart of comparison in flow curve among Herschel-Buckley Model, Lin Boheng Model and the actual drilling fluid, and we can see that the degree of Herschel-Buckley Model fitting actual drilling fluid flow curve is higher than that of Lin Boheng Model. Therefore, the optimal rheology model is Herschel-Buckley Model.



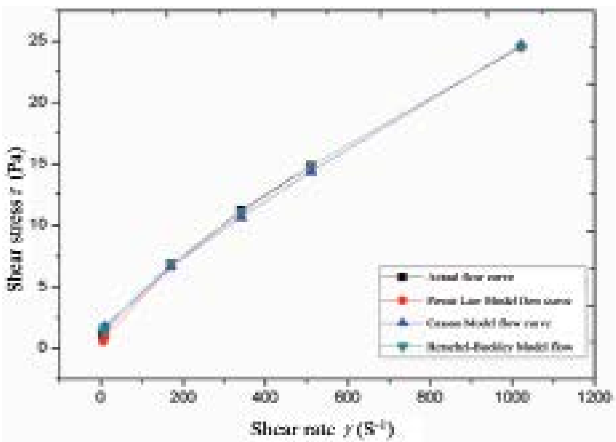


Figure 2. Non-dispersed polymer drilling fluid rheological model and the actual power law curve comparison of present Carson

4.2.2. Shearing Stress Error Correlation Method

According to equation (9), (10), relative error and mean relative error of stress value for each non-dispersed polymer drilling fluid rheology mode are calculated, as shown in Table 3.

Table 3. Non-dispersed polymer drilling fluid relative error table for each rheology model

Relative error (%)	e_1	e_2	e_3	e_4
Bingham Model (%)	0	0	3.02	25.75
Power Law Model (%)	0.08	0.07	-1.87	0.30
Casson Model(%)	0.53	3.24	-5.25	0.45
Herschel-Buckley Model (%)	0	0	-1.07	4.67
Lin Boheng Model (%)	1.96	0.74	1.6	14.76

Relative error (%)	e_5	e_6	$\bar{e}$
Bingham Model (%)	246.41	393.14	111.39
Power Law Model (%)	-43.79	-49.02	15.86
Casson Model(%)	17.65	47.06	12.36
Herschel-Buckley Model (%)	11.11	39.22	9.35
Lin Boheng Model (%)	59.48	98.04	29.43

It can be drawn from the data in Table 3:

$\bar{e}_{he}<\bar{e}_{ka}<\bar{e}_{mi}<\bar{e}_{lin}<\bar{e}_{bin}$

Hence, Herschel-Buckley Model has the highest degree of fitting the actual drilling flow curve, while Bingham Model Bingham has the worst degree of fitting the actual drilling flow curve.

4.2.3. Regression Analysis Method

As shown in regression model in Table 1, data analysis of non-dispersed polymer drilling fluid is shown in Table 4.

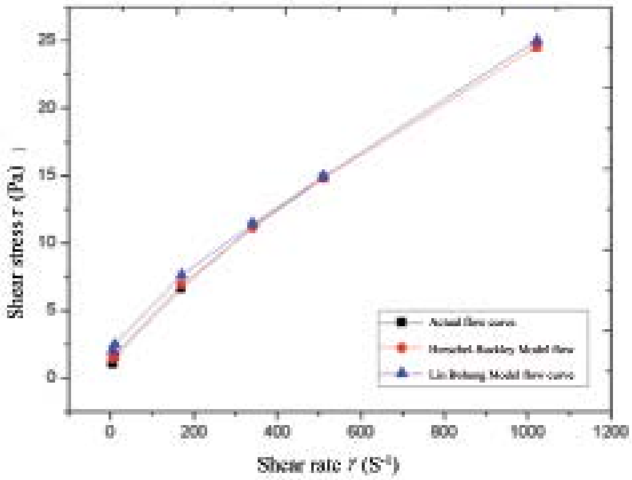


Figure 3. Non-dispersed polymer drilling fluid rheological model and the actual curve comparison of Bahrain Hector beugen

Table 4. Regression parameters and equations

Rheological models	τ_n	μ_n	Regression equations
Bingham Model	5.11	0.019	τ=5.11+0.019γ
Power Law Model	-0.798	0.727	τ_1= -0.799 +0.727γ_n
Casson Model	0.938	0.126	τ_1= 0.938 +0.126γ_n
Herschel-Buckley Model	-0.943	0.769	τ_1= -0.943 +0.769γ_n
Lin Boheng Model	1.022	0.019	τ_1= 1.022 +0.019γ_n

Then according to the regression equations and formula (12) in each mode, the correlation coefficient R values are calculated and filled in Table 5.

Table 5. Correlation coefficient computation sheet

Rheological models	Monadic equation parameters	Average	R
Bingham Model	X(γ)	343.22	0.999999894
	Y(τ)	11.63	
Power Law Model	X(γ)	2.03	0.99999689
	Y(τ)	0.68	
Casson Model	X(γ)	15.26	0.99965235
	Y(τ)	2.88	
Herschel-Buckley Model	X(γ)	2.03	0.999999701
	Y(τ)	0.62	
Lin Boheng Model	X(γ)	502.78	0.999999966
	Y(τ)	10.57	

Rheological models	Function points of monadic equation after linear regression					
	1	2	3	4	5	6
Bingham Model	5.11	10.22	170.3	340.7	511	1022
	5.21	5.30	8.35	11.58	14.82	24.53
Power Law Model	0.71	1.01	2.23	2.53	2.71	3.01
	-0.28	-0.06	0.82	1.04	1.17	1.39
Casson Model	2.26	3.20	13.05	18.46	22.61	31.97
	1.22	1.34	2.58	3.36	3.79	4.97
Herschel-Buckley Model	0.71	1.01	2.23	2.53	2.71	3.01
	-0.40	-0.17	0.77	1.00	1.14	1.37
Lin Boheng Model	52.68	74.84	347.28	547.12	732.11	1262.62
	2.02	2.44	7.62	11.42	14.93	25.01

Linear regression analysis method is used to conduct regression fitting of experimental data, and its rheological equation fitting results are shown in Figure 4 and Table 5. As shown in Figure 4 and Table 5, correlation coefficient of fitting equation in these types of rheological model is above 0.999 on average, of which correlation coefficients of fitting equation in Lin Boheng, Bingham, Herschel-Buckley and Power Law Models are higher, while correlation coefficient of fitting equation in Casson Model is relatively low. This suggests that models of Bingham, Lin Boheng, Herschel-Buckley and Power Law can well characterize rheological property of non-dispersible polymer drilling fluid, but judging from the flow curve, it is difficult for Bingham Model to characterize at low shear rates.

In summary, as for the non-dispersed polymer drilling fluid, Herschel-Buckley Model and Power Law Model can more accurately describe the rheological properties of the actual drilling fluid. But because Herschel-Buckley Model is a three-parameter model, the resolving of parameter values is more complex, which will reduce its practicability. Therefore, simple and accurate Power Law Model is the preferred rheology model to describe the rheological properties of the drilling fluid.

Conclusion

Optimal selection of non-dispersed polymer drilling fluid rheology model is implemented using rheological curve correlation, shear stress error correlation and regression analysis method. At low shear rates, there is great error between Bingham Model and the actual flow curve; Herschel-Buckley Model and Power Law Model can better describe rheological property of non-dispersed polymer drilling fluid, but for Herschel-Buckley Model, the resolving of parameters is complex and difficult. Hence, in describing non-dispersed polymer drilling fluid rheology, Power Law Model should be firstly selected.

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