

Article

Rheological Properties and Prediction Method for Oil-Based Drilling Fluids Under High-Temperature and High-Pressure Conditions

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Abstract

The rheology of high-temperature and high-pressure oil-based drilling fluids is critical for managed pressure drilling in deep and ultra-deep wells. This study investigates the rheological behavior of high-temperature and high-pressure oil-based drilling fluid from the Tarim Basin under conditions of 60–160 °C and 60–140 MPa. Three oil-based drilling fluids with densities of 1.8, 2.0, and 2.2 g/cm³ were tested under 60 temperature–pressure–density conditions, and six rotational speeds were selected for each condition, resulting in 360 rheological data points for model evaluation and parameter prediction. Rheological models, including Bingham, Power law, Casson, and Herschel–Bulkley, were established and evaluated to identify the optimal model. An improved high-temperature and high-pressure rheological parameter prediction model was proposed. Unlike previous correlations mainly developed for Bingham rheological parameters, the proposed model directly predicts the three Herschel–Bulkley parameters and introduces a quadratic pressure term to describe the nonlinear pressure dependence under high-temperature and high-pressure conditions. The results indicate that the Herschel–Bulkley model best characterizes the fluid's rheological properties, with an average relative error of 2.64% in shear stress prediction and superior regression accuracy compared to Landmark WellPlan software, achieving an average error of 2.049%. Density significantly affects yield stress and consistency coefficient, while temperature and pressure have minimal impact on the flow index. Rheological parameters exhibit opposite trends under varying densities. The improved Herschel–Bulkley model enables precise rheological parameter predictions within the tested range, with average prediction accuracies of 81.40% for yield stress, 97.90% for flow index, and 87.05% for consistency coefficient, meeting engineering requirements. These findings provide theoretical support for managed pressure drilling in deep and ultra-deep wells.

Keywords: deep and ultra-deep oil and gas; managed pressure drilling; oil-based drilling fluids; Herschel–Bulkley flow model; multiple regression



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1. Introduction

China is endowed with abundant deep and ultra-deep oil and gas resources, which are important strategic resources for ensuring national energy security [1]. According to the

resource assessment reported in Ref. [2], China's deep and ultra-deep oil and gas resources reach 67.1 billion tons of oil equivalent, accounting for approximately 34% of the country's total oil and gas resources. Among them, 39% of the remaining oil resources and 57% of the remaining natural gas resources are distributed in deep formations [3], making them an important replacement field for future large-scale reserve growth and production enhancement in China. In recent years, the implementation of the 10,000 m-deep wells "TK1" [4] and "CK1" [5] has marked China's oil and gas exploration and development moving toward ultra-deep formations. However, the geological conditions of deep and ultra-deep oil and gas wells are extremely complex, with high-temperature and high-pressure environments being among the most prominent features [6]. In general, deep and ultra-deep reservoirs are characterized by high-temperature and high-pressure environments, where formation temperatures and pressures may exceed 150 °C and 130 MPa, respectively, imposing stringent requirements on the thermal stability, rheological control, and filtration performance of drilling fluids [7,8]. Under such extreme conditions, conventional water-based drilling fluids often fail to maintain their performance under high temperature and high pressure, showing problems such as viscosity reduction, increased filtration loss, and difficulty in maintaining rheological properties. As a result, they can hardly meet the requirements for wellbore stability and safe drilling. In contrast, oil-based drilling fluids have obvious advantages in high-temperature and high-pressure stability, lubrication and sticking prevention, rate of penetration improvement, wellbore stability, and reservoir protection [9]. Therefore, they have become an important drilling fluid system for complex drilling conditions such as deep and ultra-deep wells. Nevertheless, the application of oil-based drilling fluids is not without challenges. Common problems in deep and ultra-deep drilling include formation lost circulation, differential sticking, drill pipe twist-off, kicks, and losses [10]. These downhole pressure control issues can significantly increase non-productive time and drilling costs. Therefore, accurate regulation of downhole pressure has become one of the key requirements for deep and ultra-deep drilling [11].

Managed pressure drilling (MPD) is a closed-loop drilling technology used to precisely control the annular pressure profile, especially when drilling within a narrow pressure window [12,13]. During MPD operations, the bottom hole pressure is dynamically regulated by adjusting surface backpressure, flow rate, and equivalent circulating density [12,13], so that the annular pressure can be maintained between the pore pressure and fracture pressure. Therefore, accurate hydraulic calculation is essential for MPD design and real-time pressure control. However, the annular pressure distribution is affected by multiple factors [14], including drilling fluid density, flow rate, annular geometry, wall roughness, and drilling fluid rheology. Among these factors, density and flow rate can be obtained in real time through surface monitoring, while annular geometry and wall roughness are determined through the bottom hole assembly. In contrast, the rheological properties of drilling fluids continuously vary under the high-temperature and high-pressure conditions encountered in deep and ultra-deep wells. Moreover, oil-based drilling fluids exhibit a typical non-Newtonian behavior, with viscosity and shear stress showing nonlinear variations with shear rate. This poses a major challenge to the accurate prediction and control of pressure profiles in deep and ultra-deep wells [15–17].

Scholars in China and abroad have conducted a series of studies on the rheological properties of oil-based drilling fluids under high-temperature and high-pressure conditions. Politte [18] performed high-temperature and high-pressure rheological tests on emulsified oil-based drilling fluids and identified the variation patterns of plastic viscosity and yield stress under different temperatures and pressures. Fisk et al. [19] compared the differences in the temperature-dependent plastic viscosity between oil-based and water-based drilling fluids. Wang et al. [20] compared and optimized different rheological models under ambient

temperature and pressure and pointed out that the Herschel–Bulkley model provides the best description of the rheological behavior of oil-based drilling fluids. Sun et al. [21] developed an experimental methodology for determining drilling fluid rheology under high-temperature and high-pressure conditions. Zhang et al. [22] established a calibration model for drilling fluid rheological parameters in variable temperature environments based on support vector machine. Yan [23] measured the rheological properties of oil-based drilling fluids with different densities and base fluid compositions under varying temperatures and pressures and analyzed the variation patterns of plastic viscosity, yield stress, and apparent viscosity with temperature and pressure. Zhao et al. [15] established a unified mathematical model for predicting the plastic viscosity, apparent viscosity, and dynamic shear force of oil-based drilling fluids under high-temperature and high-pressure conditions through multivariable linear regression analysis. Ye et al. [24] proposed a parameter-free method for predicting the rheological properties of oil-based drilling fluids under high-temperature and high-pressure conditions. Zhou [25] proposed a viscometer reading prediction model applicable to various rheological models.

Although scholars have conducted a series of experimental and theoretical studies on the rheological properties of oil-based drilling fluids under high-temperature and high-pressure conditions, some limitations remain. Previous studies have reported rheological measurements under relatively high maximum temperature and pressure conditions; however, many of them mainly focused on experimental characterization or the prediction of conventional rheological parameters [26], such as apparent viscosity, plastic viscosity, and yield stress. The integration of multi-density high-temperature and high-pressure experiments, rheological equation selection, Herschel–Bulkley parameter prediction, and model validation remains insufficient. In particular, the effects of density, temperature, and pressure on the Herschel–Bulkley yield stress, flow index, and consistency coefficient of oil-based drilling fluids still require further systematic investigation. Therefore, oil-based drilling fluids from deep high-temperature and high-pressure wells in the Tarim Basin were used in this study to conduct rheological tests within the ranges of 60–160 °C and 60–140 MPa. Based on the experimental data, regression algorithms were established for the Bingham plastic, power law, Casson, and Herschel–Bulkley rheological equations. The mean relative error (MRE) between the experimental values and the calculated values of the regression models was used as the criterion for selecting the optimal rheological characterization equation. The accuracy of the regression method was then validated through comparison with Landmark WellPlan software. Furthermore, the effects of density, temperature, and pressure on the Herschel–Bulkley parameters were analyzed, and an improved model incorporating a quadratic pressure term was developed to directly predict these parameters, which differs from previous Bingham-based correlations. The results provide theoretical support for managed pressure drilling technology in deep and ultra-deep wells.

2. Experiments Under High-Temperature and High-Pressure Conditions

2.1. Experimental Apparatus and Sample Preparation

The rheological experiment was conducted using a Chandler 7600 high-temperature and high-pressure rheometer equipped with a PID controller (Chandler Engineering, Tulsa, OK, USA), as shown in Figure 1a. The apparatus measures the torque generated between the rotor and the fluid using a precision torsion spring and a high-resolution encoder and converts the measured torque into shear stress. A stepping motor and magnetic drive are used to generate the shear rate, ensuring high measurement accuracy and stability. The sample temperature and pressure are automatically controlled via PID controller (Chandler Engineering, Tulsa, OK, USA), with maximum operating limits of 275 MPa (40,000 psi) and 315 °C (600 °F). The oil-based drilling fluid sample (China Petroleum Engineering

Technology Research Institute Co., Ltd., Beijing, China) was collected from Xinjiang, China, as shown in Figure 1b. Its main components included diesel, primary emulsifier, secondary emulsifier, and other additives. According to the field operating conditions, three drilling fluid densities were prepared, namely 1.8, 2.0, and 2.2 g/cm³. The oil-based drilling fluids with different formulations were first aged. Considering the thermal resistance of oil-based drilling fluids with different densities, the oil-based drilling fluids were hot-rolled in a roller oven (China Petroleum Engineering Technology Research Institute Co., Ltd., Beijing, China) at 180 °C for 16 h. Subsequently, the aged oil-based drilling fluids were stirred at a high speed of 12,000 r/min for 20 min using a high-speed mixer (Jiangsu Hongbo Machinery Manufacturing Co., Ltd., Haian, Jiangsu, China). The sheared drilling fluids were then heated to 65 °C, and their rheological properties after aging were measured under laboratory atmospheric pressure, as shown in Table 1.

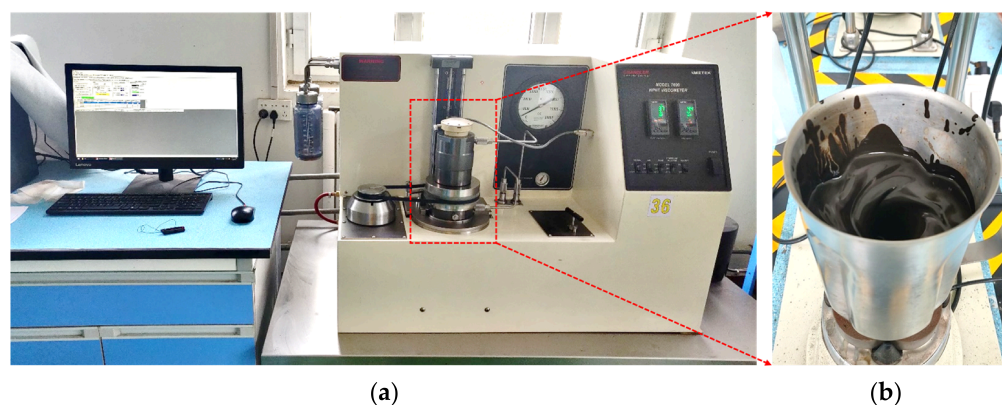


Figure 1. High-temperature and high-pressure rheological test device and oil-based drilling fluid samples. (a) High-temperature and high-pressure rheometer experimental apparatus; (b) oil-based drilling fluid.

Table 1. Rheological properties of oil-based drilling fluid at atmospheric pressure after aging.

Density /(g/cm ³)	Rotational Viscometer Readings						Apparent Viscosity/(mPa·s)	Plastic Viscosity /(mPa·s)	Yield Point /(Pa)
	600 r	300 r	200 r	100 r	6 r	3 r			
1.8	70	40	30	18	4	3	35.0	30.0	4.8
2.0	73	40	28	17	3	2	36.5	33.0	3.4
2.2	96	56	41	25	5	4	48.0	40.0	7.7

2.2. Experimental Scheme and Procedure

To obtain rheological data of oil-based drilling fluids with different densities under constant-pressure and variable-temperature conditions, five pressure points, namely 60, 80, 100, 120, and 140 MPa, were set according to the field drilling conditions. The corresponding formation temperature ranges at each pressure point were calculated based on the geothermal gradient in the Tarim Basin and the corresponding drilling fluid densities [27]. The temperature and pressure test points for oil-based drilling fluid samples with different densities are listed in Table 2. In the actual experiments, due to the nonlinear variations in temperature and pressure, slight deviations existed between the data acquisition conditions and the designed test scheme. Therefore, the temperature and pressure values monitored during the actual experiments were used for subsequent data processing. To improve the standardization and reproducibility of the rheological tests, the selection of rotational speeds was based on the conventional six-speed rotational viscometer testing scheme commonly used for drilling fluid rheological measurements. Considering that the

present experiments were conducted under high-temperature and high-pressure conditions, this conventional testing scheme was adapted to the Chandler 7600 high-temperature and high-pressure rheometer. The experimental procedure was as follows: (1) The aged oil-based drilling fluid samples were stirred at high speed and heated to 65 °C and then poured into the high-temperature and high-pressure rheometer. (2) The test pressure of the high-temperature and high-pressure rheometer was set. Then, according to the experimental scheme, the test temperature was gradually increased from a low temperature. For each oil-based drilling fluid density, five groups of rheological experiments were conducted under different pressures. In each group, six rotational speeds, namely 600, 300, 200, 100, 6, and 3 r/min, were selected. The control program automatically monitored and recorded the values at different rotational speeds. (3) Based on the experimental data, the rheological parameters of the oil-based drilling fluids at each temperature–pressure coupling point were calculated and recorded.

Table 2. Rheological test scheme for oil-based drilling fluids with different densities under high-temperature and high-pressure conditions.

Density/(g/cm ³)		1.8, 2.0, and 2.2		
Pressure/MPa		Temperature/(°C)		
60	60	70	80	90
80	80	90	100	110
100	100	110	120	130
120	110	120	130	140
140	130	140	150	160

Note: The same pressure–temperature scheme was applied to oil-based drilling fluids with densities of 1.8, 2.0, and 2.2 g/cm³.

3. Raw Experimental Results and Rheological Equation Optimization

3.1. Raw Experimental Results

Figures 2–4 present the raw experimental relationship between shear rate and shear stress for oil-based drilling fluids with different densities under high-temperature and high-pressure conditions. For all three fluid densities, the shear stress increases with increasing shear rate at different temperature and pressure conditions, indicating typical non-Newtonian flow behavior. In general, at a given shear rate, the shear stress tends to decrease with increasing temperature, suggesting that elevated temperature weakens the internal structural strength of the oil-based drilling fluid and reduces its resistance to flow. In contrast, increasing pressure generally leads to higher shear stress, reflecting enhanced viscosity and structural interactions under high-pressure conditions. Moreover, as the fluid density increases from 1.8 to 2.2 g/cm³, the shear stress at comparable temperature, pressure, and shear rate generally becomes higher, indicating that the increased weighting material content strengthens particle interactions and increases the overall rheological resistance of the fluid.

3.2. Regression Methods for Rheological Equations

In this section, regression models were established for the widely used Bingham plastic, power law, Casson, and Herschel–Bulkley rheological equations. The experimental values obtained at different rotational speeds were then used in the regression models to calculate the corresponding rheological parameters for each rheological equation.

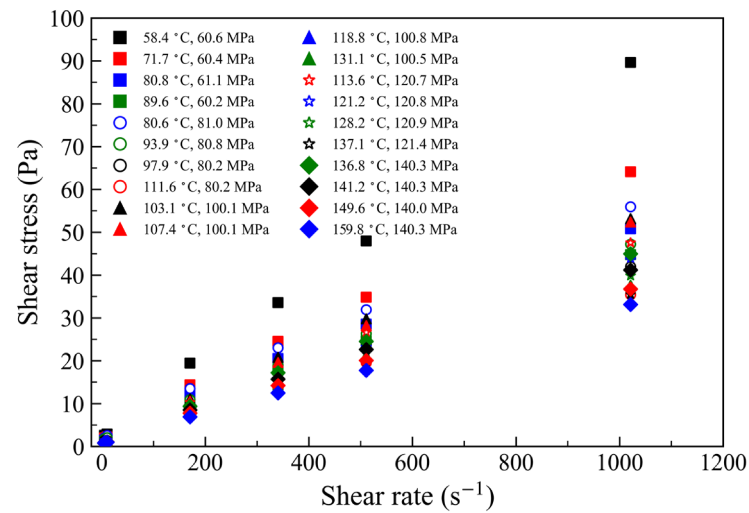


Figure 2. Experimental shear stress–shear rate relationships of the 1.8 g/cm³ oil-based drilling fluid under different temperature and pressure conditions.

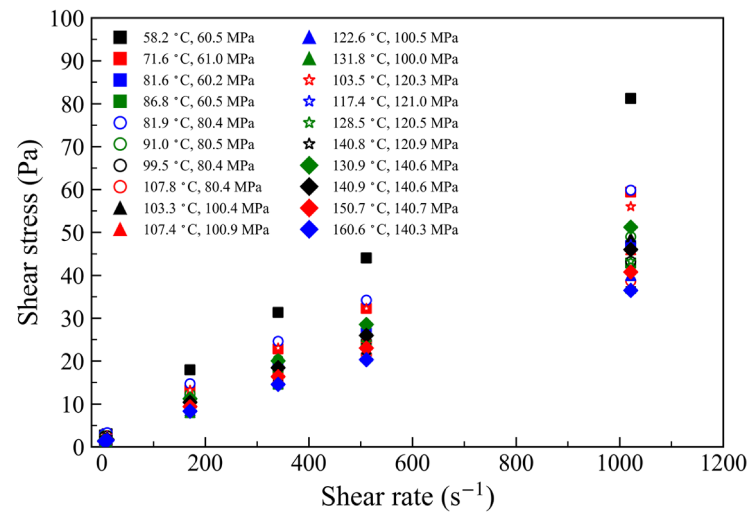


Figure 3. Experimental shear stress–shear rate relationships of the 2.0 g/cm³ oil-based drilling fluid under different temperature and pressure conditions.

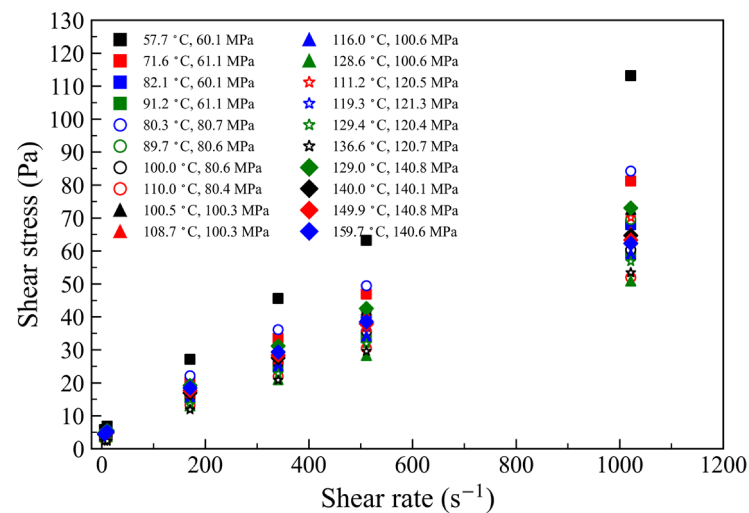


Figure 4. Experimental shear stress–shear rate relationships of the 2.2 g/cm³ oil-based drilling fluid under different temperature and pressure conditions.

3.2.1. Bingham Plastic Rheological Equation

The Bingham plastic rheological equation is one of the classical models in non-Newtonian fluid mechanics. It is suitable for describing fluids with yield behavior, that is, fluids that begin to flow only when the applied stress exceeds a certain threshold. This model contains two rheological parameters: yield stress τ_{yb} and plastic viscosity μ_{pb} . The equation is expressed as follows [28]:

$$\tau = \tau_{yb} + \mu_{pb}\gamma \quad (1)$$

where τ (Pa) is the shear stress, τ_{yb} (Pa) is the Bingham yield stress, γ (s^{-1}) is the shear rate, and μ_{pb} (Pa·s) is the Bingham plastic viscosity.

The linear regression form is:

$$\tau_{br} = \tau_{yb} + \mu_{pb}\gamma_{br} \quad (2)$$

where τ_{br} (Pa) is the actual shear stress, and γ_{br} (s^{-1}) is the actual shear rate.

The actual shear rate γ_{br} and actual shear stress τ_{br} can be calculated from the rotational speed N and reading of the rotational viscometer θ using the following equations:

$$\begin{cases} \gamma_{br} = 1.7023N \\ \tau_{br} = 0.50771\theta \end{cases} \quad (3)$$

where N (rpm) is the rotational speed of the rotational viscometer, θ (dimensionless) is the rotational viscometer reading.

Based on the linear regression form and the data obtained from Equation (3), the Bingham yield stress and plastic viscosity were determined through least-squares regression.

3.2.2. Power Law Rheological Equation

The power law rheological equation describes the power law relationship between shear stress and shear rate. It contains two rheological parameters: the consistency coefficient K_p and the flow index n_p . The equation is expressed as follows [28]:

$$\tau = K_p\gamma^{n_p} \quad (4)$$

where K_p ($Pa \cdot s^n$) is the power law consistency coefficient, and n_p (dimensionless) is the power law flow index.

After taking the natural logarithm of Equation (4), it can be transformed into the following linear regression form:

$$\ln\tau = \ln K_p + n_p \ln\gamma \quad (5)$$

For convenience in the subsequent regression calculations, $\ln\tau$ and $\ln\gamma$ are denoted as τ'_{pr} and γ'_{pr} , respectively. The processed actual shear rate γ'_{pr} and processed actual shear stress τ'_{pr} can then be calculated from the rotational speed N and reading θ of the rotational viscometer using the following equations:

$$\begin{cases} \gamma'_{pr} = \ln\gamma = \ln(1.7023N) \\ \tau'_{pr} = \ln\tau = \ln(0.50771\theta) \end{cases} \quad (6)$$

where τ'_{pr} (dimensionless) is the actual shear stress after natural logarithm transformation, and γ'_{pr} (dimensionless) is the actual shear rate after natural logarithm transformation.

Based on the linear regression form and the data obtained from Equation (6), the consistency coefficient and flow index can be determined through least-squares regression.

3.2.3. Casson Rheological Equation

The Casson rheological equation describes the nonlinear relationship between shear stress and shear rate after yielding. It can characterize the yield behavior under low shear stress and capture the nonlinear viscosity characteristics at high shear rates. This model contains two rheological parameters: Casson yield stress τ_c and Casson viscosity η_∞ . The equation is expressed as follows [28]:

$$\sqrt{\tau} = \sqrt{\tau_c} + \sqrt{\eta_\infty} \sqrt{\dot{\gamma}} \quad (7)$$

where τ_c (Pa) is the Casson yield stress, and η_∞ (Pa·s) is the Casson viscosity.

Equation (7) can be rewritten in the following linear regression form:

$$\tau'_{cr} = \sqrt{\tau_c} + \sqrt{\eta_\infty} \gamma'_{cr} \quad (8)$$

where τ'_{cr} (Pa^{1/2}) is the actual shear stress after square-root transformation, and γ'_{cr} (s^{-1/2}) is the actual shear rate after square-root transformation.

The processed actual shear rate γ'_{cr} and processed actual shear stress τ'_{cr} can be calculated from the rotational speed N and reading θ of the rotational viscometer using the following equations:

$$\begin{cases} \gamma'_{cr} = \sqrt{\dot{\gamma}} = \sqrt{1.7023N} \\ \tau'_{cr} = \sqrt{\tau} = \sqrt{0.50771\theta} \end{cases} \quad (9)$$

Based on the linear regression form and the data obtained from Equation (9), the Casson yield stress and Casson viscosity can be determined through least-squares regression.

3.2.4. Herschel–Bulkley Rheological Equation

The Herschel–Bulkley rheological equation is a mathematical model widely used to describe the flow behavior of complex non-Newtonian fluids. By incorporating yield stress, plastic flow characteristics, and power law behavior, this model can describe rheological properties that are more complex than those of Bingham fluids and power law fluids. It contains three rheological parameters: yield stress τ_{yh} , consistency coefficient K_h , and flow index n_h . The equation is expressed as follows [28]:

$$\tau = \tau_{yh} + K_h \dot{\gamma}^{n_h} \quad (10)$$

where τ_{yh} (Pa) is the Herschel–Bulkley yield stress, K_h (Pa·sⁿ) is the Herschel–Bulkley consistency coefficient, n_h (dimensionless) is the Herschel–Bulkley flow index.

Its linear regression form is expressed as follows:

$$\ln(\tau - \tau_{yh}) = \ln K_h + n_h \ln \dot{\gamma} \quad (11)$$

For convenience in subsequent regression calculations, $\ln(\tau - \tau_{yh})$ and $\ln \dot{\gamma}$ are denoted as τ'_{hr} and γ'_{hr} , respectively. The processed actual shear rate γ'_{hr} and processed actual shear stress τ'_{hr} can then be calculated from the rotational speed N and reading θ of the rotational viscometer using the following equations:

$$\begin{cases} \gamma'_{hr} = \ln \dot{\gamma} = \ln(1.7023N) \\ \tau'_{hr} = \ln(\tau - \tau_{yh}) = \ln(0.50771\theta - \tau_{yh}) \end{cases} \quad (12)$$

where τ'_{hr} (dimensionless) is the actual shear stress after natural logarithm transformation, and γ'_{hr} (dimensionless) is the actual shear rate after natural logarithm transformation.

In the regression calculation procedure for the Herschel–Bulkley rheological parameters, since the Herschel–Bulkley model is a three-parameter model, an initial value of yield stress must be specified for trial calculation. This initial value must be smaller than the shear stress corresponding to a rotational speed of 3 r/min, namely $0.50771\theta_3$. With a calculation step size of 0.001, the number of trials, num , and the yield stress $\tau_{yh-trial}$ in a given trial, denoted as j , can be expressed as follows:

$$num = \frac{0.50771\theta_3}{0.001} \quad (13)$$

$$\tau_{yh-trial} = 0.001 \times j \quad (14)$$

where θ_3 (dimensionless) is the rotational viscometer reading at a rotational speed of 3 rpm, num (dimensionless) is the number of trials, j (dimensionless) is the trial index, and $\tau_{yh-trial}$ (Pa) is the yield stress in a given trial. The trial calculation step for the yield stress was set to 0.001 to balance computational accuracy and efficiency. Preliminary calculations showed that further reducing the step size produced negligible changes in the regression results, whereas a larger step size could reduce the resolution of the optimal yield stress search.

The processed actual shear rate $\gamma'_{hr-trial}$ and processed actual shear stress $\tau'_{hr-trial}$ are further calculated as follows:

$$\begin{cases} \gamma'_{hr-trial} = \ln(1.7023N) \\ \tau'_{hr-trial} = \ln(0.50771\theta - \tau_{yh-trial}) \end{cases} \quad (15)$$

where $\tau'_{hr-trial}$ (dimensionless) is the actual shear stress after natural logarithm transformation in a given trial, and $\gamma'_{hr-trial}$ (dimensionless) is the actual shear rate after natural logarithm transformation in a given trial.

Based on the linear regression form and the shear rate and shear stress data under different trial yield stress values in Equation (15), different consistency coefficients $K_{h-trial}$ and flow indices $n_{h-trial}$ can be obtained through regression. The mean relative error corresponding to each trial yield stress value is then calculated. The yield stress, consistency coefficient, and flow index corresponding to the minimum mean relative error are selected as the final Herschel–Bulkley rheological parameters.

3.3. Regression Results and Selection of Rheological Equations

Using the established regression models for the Bingham plastic, power law, Casson, and Herschel–Bulkley rheological equations, regression and error analyses were performed on the high-temperature and high-pressure rheological data of oil-based drilling fluids with different densities. The mean relative error between the experimental values and the calculated values of the regression models was used as the error analysis criterion. Accordingly, the rheological parameters and mean relative errors of each rheological model under different temperature and pressure conditions were obtained. Due to the large amount of data, only the regression calculation and optimization results for the 2.2 g/cm³ oil-based drilling fluid are presented here, as shown in Table 3. The rheological curves of each model are shown in Figure 5. Taking shear stress as an example, the mean relative error is calculated as follows:

$$MRE = Average \left\{ \frac{|\tau_{model,i} - \tau_{test,i}|}{\tau_{test,i}} \times 100\%, i = 1, 2, 3 \dots m \right\} \quad (16)$$

where MRE (%) is the mean relative error, $\tau_{model,i}$ (Pa) is the shear stress of the i -th data point calculated by the regression equation, $\tau_{test,i}$ (Pa) is the shear stress of the i -th data point obtained from experimental tests, and m is the number of experimental data points.

Table 3. Experimental data and regression results for the 2.2 g/cm³ oil-based drilling fluid.

P	T	Bingham Plastic			Power Law			Casson			Herschel–Bulkley (H–B)				Best Fit
		τ_{yb}	μ_{pb}	MRE	n_p	K_p	MRE	η_∞	τ_c	MRE	τ_{yh}	n_h	K_h	MRE	
MPa	°C	Pa	Pa·s	%	/	Pa·s ⁿ	%	Pa·s	Pa	%	Pa	/	Pa·s ⁿ	%	
60.1	57.7	7.479	0.105	13.005	0.547	2.055	12.905	0.077	2.922	2.780	4.882	0.883	0.239	0.634	H–B
61.1	71.6	5.716	0.076	18.047	0.558	1.407	13.065	0.056	2.070	2.497	3.257	0.857	0.206	1.238	H–B
60.1	82.1	4.915	0.063	17.074	0.547	1.256	13.373	0.046	1.852	2.706	2.942	0.865	0.162	1.713	H–B
61.1	91.2	5.114	0.054	11.451	0.486	1.611	14.624	0.036	2.345	3.909	3.721	0.889	0.117	1.708	H–B
80.7	80.3	7.060	0.078	18.413	0.526	1.821	11.924	0.056	2.781	1.312	3.973	0.828	0.259	0.223	H–B
80.6	89.7	6.402	0.064	20.120	0.516	1.633	12.021	0.045	2.546	2.138	3.537	0.824	0.222	0.945	H–B
80.6	100.0	4.993	0.056	18.723	0.529	1.278	13.973	0.040	1.933	3.640	2.880	0.841	0.170	2.490	H–B
80.4	110.0	3.986	0.049	19.473	0.547	0.978	14.175	0.036	1.467	3.782	2.242	0.848	0.139	2.898	H–B
100.3	100.5	6.207	0.067	14.885	0.505	1.774	13.974	0.046	2.640	3.007	4.036	0.860	0.178	1.548	H–B
100.3	108.7	5.363	0.060	12.589	0.502	1.612	14.634	0.041	2.353	3.953	3.776	0.889	0.131	2.140	H–B
100.6	116.0	5.262	0.054	12.590	0.485	1.624	14.815	0.036	2.386	3.755	3.713	0.877	0.127	1.896	H–B
100.6	128.6	4.148	0.047	10.591	0.492	1.317	15.012	0.031	1.894	4.559	3.110	0.907	0.089	2.380	H–B
120.5	111.2	5.476	0.065	20.071	0.547	1.323	12.945	0.048	2.002	2.912	2.991	0.843	0.197	1.611	H–B
121.3	119.3	4.619	0.060	15.552	0.542	1.223	14.283	0.044	1.777	3.470	2.905	0.875	0.143	1.795	H–B
120.4	129.4	3.451	0.053	16.136	0.576	0.859	14.755	0.040	1.206	4.197	2.134	0.895	0.111	2.924	H–B
120.7	136.6	2.743	0.051	13.697	0.597	0.694	15.924	0.039	0.916	5.363	1.820	0.924	0.085	3.348	H–B
140.8	129.0	6.359	0.067	15.001	0.503	1.811	12.270	0.046	2.719	1.778	3.969	0.840	0.205	0.795	H–B
140.1	140.0	5.709	0.059	14.390	0.498	1.660	13.203	0.041	2.476	2.212	3.682	0.847	0.173	0.380	H–B
140.8	149.9	6.277	0.058	18.270	0.493	1.726	11.781	0.039	2.689	1.512	3.626	0.809	0.220	0.380	H–B
140.6	159.7	6.883	0.057	22.748	0.492	1.764	10.074	0.039	2.878	2.661	3.451	0.768	0.291	0.467	H–B

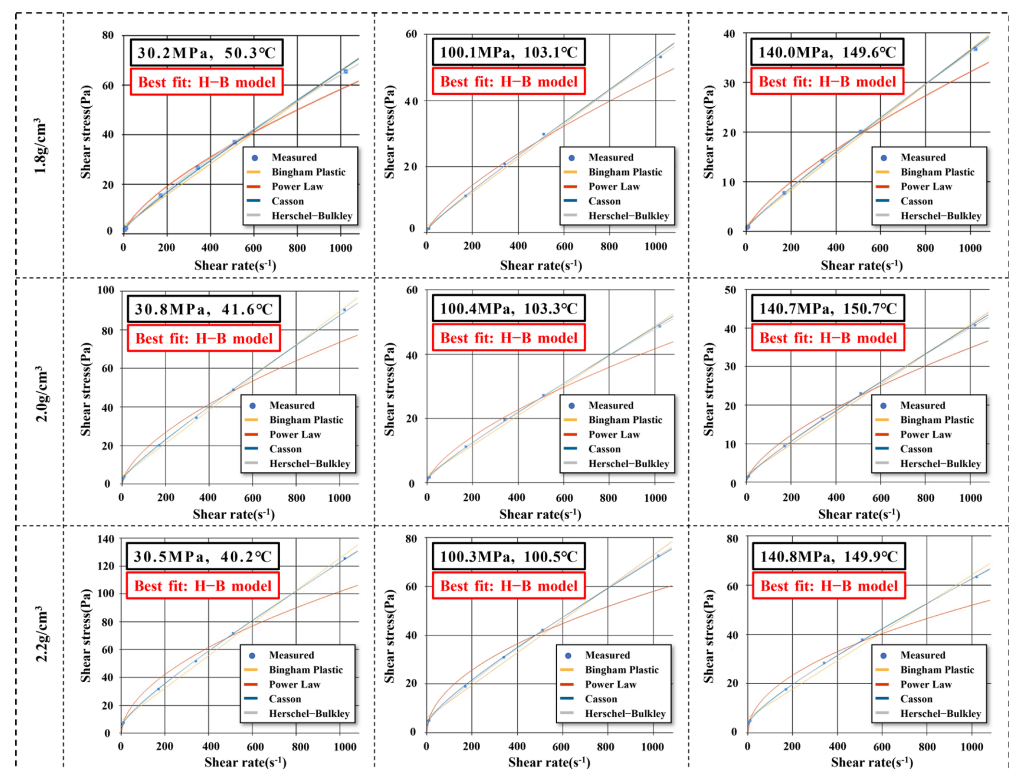


Figure 5. Comparison of rheological curve fitting results with different densities.

Using the mean relative error between the experimental values and the calculated values of the regression models as the optimization criterion, error analysis was performed on the regression results of each model. The calculation results are shown in Figure 6. It can be seen that the high-temperature and high-pressure rheological characteristics of this oil-based drilling fluid formulation are more consistent with the three-parameter Herschel–Bulkley rheological equation. Under different temperature and pressure conditions, the mean relative error between the shear stress calculated by the Herschel–Bulkley model and the experimental values is only 2.64%, which is much lower than those of the other three rheological equations. Therefore, the Herschel–Bulkley model exhibits excellent fitting performance and satisfies the requirements of engineering calculations.

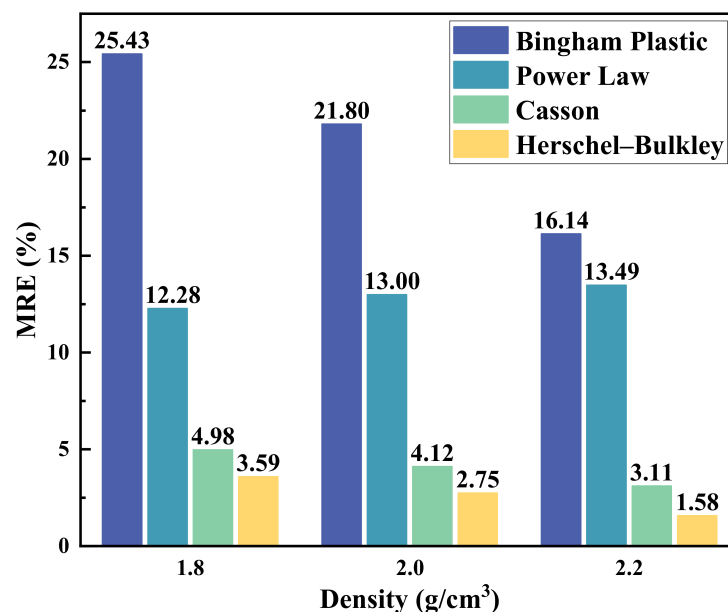


Figure 6. Comparison of regression accuracy of different rheological equations.

3.4. Verification of the Regression Method for Rheological Equations

To further verify the correctness of the rheological equation regression method described in Section 3.2, part of the experimental data was imported into the Landmark WellPlan software (version 5000.14; Halliburton Landmark, Houston, TX, USA). The Herschel–Bulkley rheological parameters calculated by the commercial software were obtained through regression. The commercial software shear stresses at different rotational speeds, namely different shear rates, were then further calculated and compared with the values calculated using the regression algorithm proposed in this study and the experimental measured values. The validation results are shown in Table 4, and the relative error (RE) in the table is calculated as follows:

$$RE = \frac{|\tau_{\text{Landmark or model}} - \tau_{\text{Measured value}}|}{|\tau_{\text{Measured value}}|} \times 100\% \quad (17)$$

where RE (%) is the relative error, $\tau_{\text{Landmark or model}}$ (Pa) is the shear stress obtained using Landmark or regression algorithm, and $\tau_{\text{Measured value}}$ (Pa) is the shear stress obtained by experimental testing.

As shown in Table 4, the regression algorithm established in Section 3.2 has a mean relative error of only 2.049%, which is lower than that of the Landmark WellPlan software. This indicates that the proposed regression algorithm provides higher computational accuracy in rheological parameter regression and satisfies the requirements of engineering calculations. This is because the Landmark WellPlan software determines rheological pa-

rameters for different rheological models using multi-speed dial readings from a rotational viscometer through empirical formulas for the Bingham plastic and power law models and nonlinear fitting for the Herschel–Bulkley model, which results in limited accuracy. In contrast, the regression algorithm established in this study is based on shear rate–shear stress data calculated from rotational viscometer readings. The rheological equations are transformed into linear regression forms, and the rheological parameters are determined using the least-squares method. For the Herschel–Bulkley model, an additional three-parameter regression procedure of “yield stress trial calculation–linear regression–error optimization” is adopted, and the optimal rheological parameters are obtained according to the mean relative error. This method can significantly improve the regression stability and computational accuracy of the model. In summary, the Herschel–Bulkley model was selected as the optimal characterization equation for the high-temperature and high-pressure rheological properties of this oil-based drilling fluid formulation, and its applicability was validated through algorithm verification.

Table 4. Error comparison between regression algorithm and Landmark algorithm.

Experimental Conditions	Measured Values	Regression Algorithm		Landmark	
	τ/Pa	τ/Pa	RE/%	τ/Pa	RE/%
1.8 g/cm ³ 120.8 MPa 121.2 °C	43.97	44.981	2.305	44.392	0.965
	24.27	24.029	0.989	24.193	0.312
	16.96	16.774	1.079	17.062	0.616
	9.19	9.265	0.821	9.547	3.890
	1.52	1.614	5.952	1.560	2.406
	1.37	1.330	2.989	1.240	9.569
2.0 g/cm ³ 100.4 MPa 103.3 °C	48.64	48.635	0.007	49.054	0.854
	27.21	26.998	0.791	27.444	0.847
	19.50	19.244	1.294	19.638	0.727
	11.17	10.959	1.888	11.237	0.601
	1.68	1.858	10.906	1.846	10.180
	1.57	1.471	6.521	1.434	8.874
2.2 g/cm ³ 80.7 MPa 80.3 °C	84.23	84.296	0.079	83.684	0.647
	49.50	49.213	0.582	49.015	0.984
	36.15	36.309	0.443	36.202	0.148
	22.19	22.186	0.005	22.119	0.306
	5.74	5.745	0.141	5.551	3.246
	4.98	4.971	0.086	4.757	4.399
MRE/%			2.049	MRE/%	2.754

4. Analysis of Rheological Parameters

4.1. Variation Pattern of Herschel–Bulkley Yield Stress

Based on the established regression algorithm, the Herschel–Bulkley yield stress under different densities, temperatures, and pressures can be calculated. During the experiments, slight fluctuations existed between the measured pressures and the pressure values designed in the experimental scheme. However, the variation range was small, only 0.14–1.00%. Therefore, for convenient plotting and intuitive comparison, the measured pressures at the same designed pressure but different temperatures were uniformly replaced by their average values. The results are shown in Figure 7.

As shown in Figure 7, the density of the oil-based drilling fluid has a significant influence on the Herschel–Bulkley yield stress. When the density increases from 1.8 g/cm³ to 2.2 g/cm³, the average Herschel–Bulkley yield stress under different temperature and pressure conditions increases from 0.79 Pa to 3.33 Pa, representing an increase of 319.85%. In ad-

dition, high temperature and high pressure have significant effects on the Herschel–Bulkley yield stress of oil-based drilling fluids with different densities. However, low-density and high-density oil-based drilling fluids exhibit different variation patterns. Compared with the condition of 65 °C and atmospheric pressure, the Herschel–Bulkley yield stress of the 1.8 g/cm³ oil-based drilling fluid decreases from 1.10 Pa to 0.54 Pa under 160 °C and 140 MPa, corresponding to a decrease of 51.05%. In contrast, the Herschel–Bulkley yield stress of the 2.2 g/cm³ oil-based drilling fluid increases from 1.34 Pa to 3.45 Pa, corresponding to an increase of 156.75%. This indicates that the yield stress of low-density oil-based drilling fluids (≤ 1.8 g/cm³) tends to decrease with increasing temperature and pressure, whereas that of high-density oil-based drilling fluids (≥ 2.0 g/cm³) tends to increase. This means that high-density oil-based drilling fluids possess greater structural strength. When the shear stress applied to the oil-based drilling fluid is lower than the yield stress, the fluid does not flow and behaves as a solid or quasi-solid. As temperature and pressure increase, the structural strength is further enhanced, enabling the fluid to better resist the gravitational settling of solid particles, such as cuttings and weighting materials. This helps maintain the uniform distribution of cuttings, barite, and other solid particles when the drilling fluid is static. It also provides stronger support for the wellbore wall and can reduce the risk of wellbore collapse. Therefore, high-density oil-based drilling fluids have important application advantages in deep and ultra-deep drilling. Furthermore, within the pressure range of 60–100 MPa, when pressure remains basically stable, the Herschel–Bulkley yield stress of oil-based drilling fluids with different densities decreases with increasing temperature. However, when the pressure reaches approximately 120 MPa or higher, the influence of temperature on yield stress gradually weakens, and the decrease becomes smaller. For example, for the 1.8 g/cm³ oil-based drilling fluid at 60 MPa, when the temperature increases from 58.4 °C to 89.6 °C, the yield stress decreases by 62.13%. However, when the pressure increases to 120 MPa and the temperature rises from 113.6 °C to 137.1 °C, the yield stress decreases by only 5.11%. This indicates that, under high-pressure conditions, the yield stress of this oil-based drilling fluid formulation is less sensitive to temperature, which is beneficial for maintaining strong structural stability and particle suspension capacity under high-temperature and high-pressure conditions.

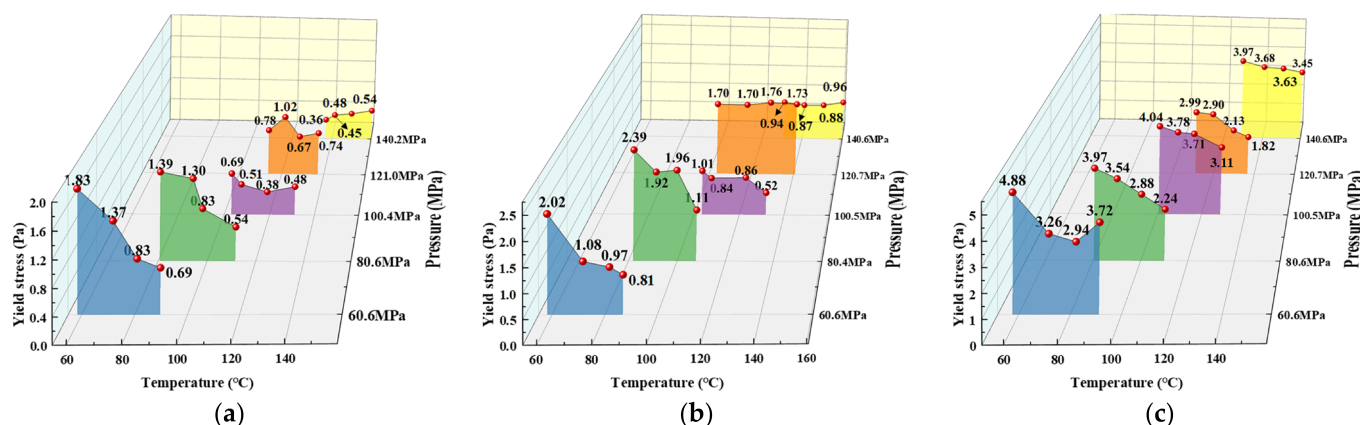


Figure 7. Herschel–Bulkley yield stress distribution of oil-based drilling fluid under different density, temperature and pressure conditions. (a) 1.8 g/cm³; (b) 2.0 g/cm³; (c) 2.2 g/cm³. Different colors are used to distinguish different pressure groups, and the labeled data points represent the yield stress values calculated using the fitted equation.

4.2. Variation Pattern of Herschel–Bulkley Flow Index

The variation pattern of the Herschel–Bulkley flow index of oil-based drilling fluids under different densities, temperatures, and pressures is shown in Figure 8. As shown

in Figure 8, the Herschel–Bulkley flow index of the oil-based drilling fluid is less than 1 under different density, temperature, and pressure conditions. This indicates that this oil-based drilling fluid formulation is a shear-thinning non-Newtonian fluid, also known as a pseudoplastic fluid, whose viscosity decreases with increasing shear rate. This rheological behavior enables the oil-based drilling fluid to maintain good flowability under different operating conditions. For example, under low shear rates, such as pump shutdown or low annular flow rate conditions, the drilling fluid has a relatively high viscosity, which is beneficial for carrying cuttings and suspending solids, thereby preventing particle settling. Under high shear rates, such as near the drill bit or during pumping, the viscosity decreases, reducing flow pressure loss and pumping energy consumption.

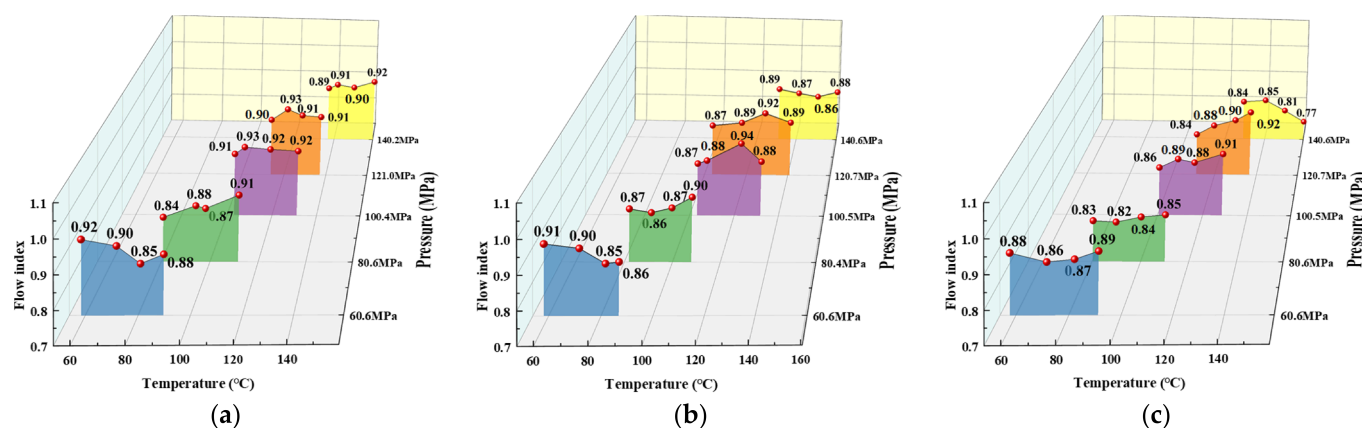


Figure 8. Herschel–Bulkley flow index distribution of oil-based drilling fluid under different density, temperature and pressure conditions. (a) 1.8 g/cm³; (b) 2.0 g/cm³; (c) 2.2 g/cm³. Different colors are used to distinguish different pressure groups, and the labeled data points represent the flow index values calculated using the fitted equation.

In addition, unlike the positive correlation between Herschel–Bulkley yield stress and density, the density of this oil-based drilling fluid formulation shows a negative correlation with the Herschel–Bulkley flow index, although the influence is relatively weak. For example, when the density increases from 1.8 g/cm³ to 2.2 g/cm³, the average Herschel–Bulkley flow index under different temperature and pressure conditions decreases only from 0.90 to 0.86, corresponding to a decrease of 4.58%. Moreover, high temperature and high pressure also have a relatively minor effect on the Herschel–Bulkley flow index of oil-based drilling fluids with different densities. Low-density and high-density oil-based drilling fluids also exhibit different variation patterns. Compared with the condition of 65 °C and atmospheric pressure, the Herschel–Bulkley flow index of the 1.8 g/cm³ oil-based drilling fluid increases from 0.81 to 0.92 under 160 °C and 140 MPa, corresponding to an increase of 13.28%. In contrast, the Herschel–Bulkley flow index of the 2.2 g/cm³ oil-based drilling fluid decreases from 0.80 to 0.76, corresponding to a decrease of 3.8%. This variation may be attributed to differences in internal components, such as weighting material content. The 1.8 g/cm³ oil-based drilling fluid contains less weighting material, resulting in weaker interactions among internal particles. Increasing temperature and pressure may enhance intermolecular mobility, thereby increasing the Herschel–Bulkley flow index. In contrast, the 2.2 g/cm³ oil-based drilling fluid contains more weighting material, and the complex interactions among particles, such as particle–particle interactions and lubrication effects, may be suppressed under high-temperature and high-pressure conditions, resulting in a decrease in the flow index. On the other hand, high temperature can enhance molecular thermal motion in the oil-based drilling fluid and reduce liquid viscosity, thereby decreasing internal flow resistance and increasing the Herschel–Bulkley flow index. However, for high-density oil-based

drilling fluids with a relatively high particle content, such as 2.2 g/cm^3 , high temperature may change the dispersion state and interaction network of solid particles and rheological additives, leading to a more complex microstructure and consequently reducing the flow index [29]. High pressure may compress the molecular structure of the oil-based drilling fluid and increase the fluid density and viscosity. For higher-density oil-based drilling fluids, such as 2.2 g/cm^3 , high pressure may enhance interparticle contact forces or form a more stable network structure, thereby inhibiting fluid flowability and reducing the flow index. This also explains the contrasting temperature dependence of the Herschel–Bulkley flow index at different pressure levels: at approximately constant pressure, the flow index of oil-based drilling fluids with different densities increases with temperature within the pressure range of 60–120 MPa, whereas it decreases with temperature at 140 MPa.

4.3. Variation Pattern of Herschel–Bulkley Consistency Coefficient

The variation pattern of the Herschel–Bulkley consistency coefficient of oil-based drilling fluids under different densities, temperatures, and pressures is shown in Figure 9. As shown in Figure 9, the density of the oil-based drilling fluid has a significant influence on the Herschel–Bulkley consistency coefficient. When the density increases from 1.8 g/cm^3 to 2.2 g/cm^3 , the average Herschel–Bulkley consistency coefficient under different temperature and pressure conditions increases from $0.09 \text{ Pa}\cdot\text{s}^n$ to $0.17 \text{ Pa}\cdot\text{s}^n$, representing an increase of 87.08%. This is related to the increased concentration of weighting materials, such as barite. As the density increases from 1.8 g/cm^3 to 2.2 g/cm^3 , the interactions among internal particles in the fluid, such as van der Waals forces and frictional resistance, are enhanced. In addition, particle aggregation and distribution are more likely to form a stable network structure, resulting in greater viscous resistance during shearing and thus a significant increase in the Herschel–Bulkley consistency coefficient. In addition, high temperature and high pressure have significant effects on the Herschel–Bulkley consistency coefficient of oil-based drilling fluids with different densities. However, low-density and high-density oil-based drilling fluids exhibit different variation patterns. Compared with the condition of 65°C and atmospheric pressure, the Herschel–Bulkley consistency coefficient of the 1.8 g/cm^3 oil-based drilling fluid decreases from $0.12 \text{ Pa}\cdot\text{s}^n$ to $0.056 \text{ Pa}\cdot\text{s}^n$ under 160°C and 140 MPa, corresponding to a decrease of 55.09%. In contrast, the Herschel–Bulkley consistency coefficient of the 2.2 g/cm^3 oil-based drilling fluid increases from $0.19 \text{ Pa}\cdot\text{s}^n$ to $0.29 \text{ Pa}\cdot\text{s}^n$, corresponding to an increase of 55.60%. On the other hand, when pressure remains basically stable, the Herschel–Bulkley consistency coefficient of oil-based drilling fluids with different densities decreases significantly with increasing temperature. However, at a pressure of approximately 140 MPa, when the temperature exceeds 140°C , the Herschel–Bulkley consistency coefficient of the 2.2 g/cm^3 high-density oil-based drilling fluid increases sharply with increasing temperature. For example, when pressure remains basically stable, the consistency coefficients of the 1.8 g/cm^3 and 2.0 g/cm^3 oil-based drilling fluids decrease by 31.92–61.02% and 24.17–49.89%, respectively, for every 30°C increase in temperature. However, for the 2.2 g/cm^3 high-density oil-based drilling fluid, when the pressure is lower than 140 MPa, the consistency coefficient decreases by 46.13–56.58% for every 30°C increase in temperature. At approximately 140 MPa, once the temperature exceeds 140°C , respectively, the consistency coefficient changes from a decreasing trend to a sharp increasing trend as the temperature further rises. When the temperature increases by 20°C , the consistency coefficient increases by as much as 68.52%, indicating a significant increase. This is because increasing temperature enhances the molecular thermal motion of the fluid and weakens the viscous intermolecular interactions in the oil-based drilling fluid, resulting in a decrease in the Herschel–Bulkley consistency coefficient. For low-density oil-based drilling fluids, the interactions among particles are relatively

weak, so the consistency coefficient decreases more significantly with increasing temperature. For high-density oil-based drilling fluids, the effect of temperature below 140 °C is still dominated by the weakening of viscosity. However, when the temperature exceeds 140 °C, particle aggregation and structural reorganization may occur, causing the consistency coefficient to reverse from a decreasing trend to an increasing trend. In addition, high pressure compresses the fluid and can enhance interparticle interactions and fluid cohesion in the oil-based drilling fluid. For high-density oil-based drilling fluids, once the pressure exceeds a certain threshold, particle aggregation becomes more pronounced, forming a highly viscous network structure and thereby increasing the consistency coefficient.

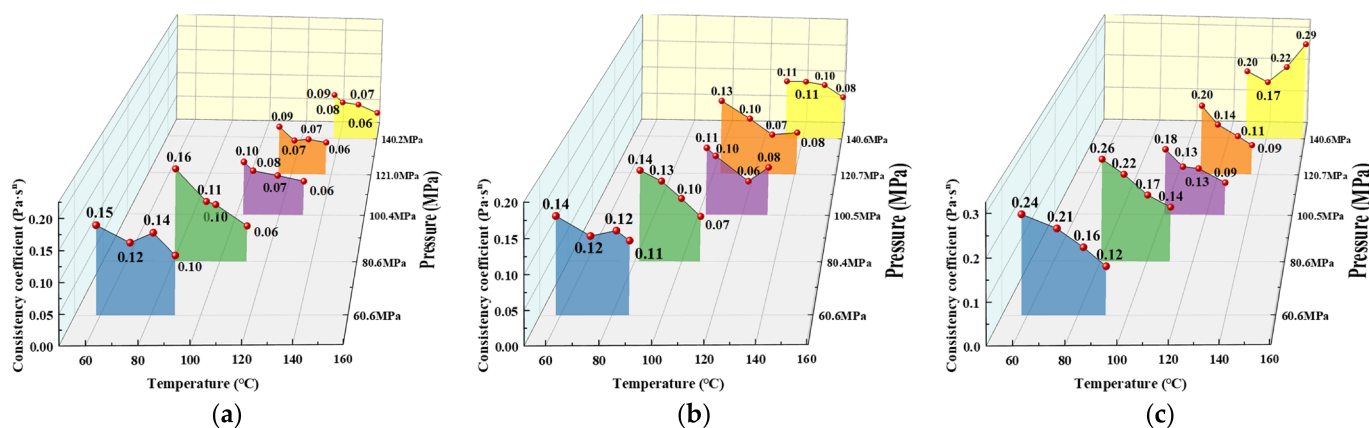


Figure 9. Herschel–Bulkley consistency coefficient distribution of oil-based drilling fluid under different density, temperature and pressure conditions. (a) 1.8 g/cm³; (b) 2.0 g/cm³; (c) 2.2 g/cm³. Different colors are used to distinguish different pressure groups, and the labeled data points represent the consistency coefficient values calculated using the fitted equation.

5. Discussion

Scholars in China and abroad have conducted experimental studies on the variation patterns of drilling fluid rheological parameters with temperature and pressure for different drilling fluid systems and under different temperature–pressure conditions. Based on these experiments, corresponding prediction models for rheological parameters have been proposed [28]. In 1985, Politte [18] developed a prediction model for the plastic viscosity of oil-based drilling fluids under different temperatures and pressures through linear regression based on the Bingham plastic rheological equation:

$$\mu = P(TP)^a 10^{(b+cT+dTP+eP+f\rho+g/\rho)} \quad (18)$$

where μ (Pa·s) is the plastic viscosity, T (°C) is the temperature, P (MPa) is the pressure, a, b, c, d, e, f and g (dimensionless) are the Politte model coefficients, and ρ (g/cm³) is the fluid density.

In 1988, Minton and Bern [30] introduced the reference temperature, reference pressure, and the plastic viscosity under these reference conditions, and developed a Bingham plastic viscosity prediction model for oil-based drilling fluids. This model can be used to predict the plastic viscosity under other temperature and pressure conditions based on the plastic viscosity at the reference temperature and pressure. The equation is expressed as follows:

$$\mu(T, P) = \mu_0 e^{\alpha(T-T_0) + \beta(P-P_0)} \quad (19)$$

where T_0 (°C) is the reference temperature, P_0 (MPa) is the reference pressure, μ_0 (Pa·s) is the plastic viscosity under the reference temperature and pressure conditions, and α (°C^{−1}) and β (MPa^{−1}) are the model coefficients.

In 2009, Zhao et al. [15] expanded the output types of rheological parameter prediction models. Based on the Bingham plastic rheological equation, they established prediction models for the apparent viscosity, plastic viscosity, and yield stress of oil-based drilling fluids under high-temperature and high-pressure conditions. The main feature of their model is that the product term of temperature and pressure and the quadratic term of temperature were introduced on the basis of the Minton and Bern prediction model. The reference temperature and pressure were set as 23.9 °C and 0 Pa, respectively. The equation is expressed as follows:

$$f(P, T) = f(P_0, T_0)e^{[A(T-T_0)+B(P-P_0)+C(T-T_0)(P-P_0)+D(T-T_0)^2]} \quad (20)$$

where A (°C⁻¹), B (MPa⁻¹), C (°C⁻¹·MPa⁻¹), D (°C⁻²) are the model coefficients, and $f(P_0, T_0)$ has the same unit as the rheological parameter being predicted.

The above studies have promoted the development of drilling fluid rheology prediction and drilling pressure calculation. However, most existing prediction models have limited applicable temperature and pressure ranges, and the selected reference temperature and pressure differ from the values recommended by current standards. In addition, most prediction models are based on the Bingham plastic rheological equation and are used to predict Bingham rheological parameters. Although the Bingham plastic rheological equation has a simple form, it is difficult to accurately describe rheological behavior under high-temperature and high-pressure conditions, resulting in relatively large errors. Therefore, it is not suitable for predicting the Herschel–Bulkley rheological parameters selected as optimal in this study.

Therefore, based on the rheological parameter prediction model for oil-based drilling fluids proposed by Zhao et al. [15], an improved prediction model is proposed in this study. Let $F(P, T) = \ln f(P, T)$, $\Delta P = P - P_0$ and $\Delta T = T - T_0$. By performing a second-order Taylor expansion at the reference condition (P_0, T_0) , the following expression can be obtained:

$$F(P, T) \approx F_0 + F_T \Delta T + F_P \Delta P + \frac{1}{2} F_{TT} \Delta T^2 + \frac{1}{2} F_{PP} \Delta P^2 + F_{PT} \Delta P \Delta T \quad (21)$$

where $X_1 = T - T_0$ (°C) is the difference between the measured temperature and the reference temperature, $X_2 = P - P_0$ (MPa) is the difference between the measured pressure and the reference pressure, $X_3 = (T - T_0)^2$ (°C²) is the square of the difference between the measured temperature and the reference temperature, and $X_4 = (P - P_0)^2$ (MPa²) is the square of the difference between the measured pressure and the reference pressure.

Since the coupling term $(T - T_0)(P - P_0)$ is insignificant or may introduce multicollinearity and is unfavorable for extrapolation stability, whereas $(P - P_0)^2$ is significant and can systematically eliminate residuals at the high-pressure end, the quadratic term is used to replace the coupling term under the same level of model complexity. This approach can better fit the actual curvature of the variation surface of rheological parameters with temperature and pressure within the high-temperature and high-pressure range. Therefore, after removing the coupling term and retaining the individual quadratic terms, the following expression can be obtained:

$$F(P, T) \approx F_0 + F_T \Delta T + F_P \Delta P + \frac{1}{2} F_{TT} \Delta T^2 + \frac{1}{2} F_{PP} \Delta P^2 \quad (22)$$

To facilitate engineering interpretation, the coefficients are renamed as $\alpha = F_T$, $\beta = F_P$, $r = 0.5F_{TT}$ and $q = 0.5F_{PP}$. Taking the exponential of both sides yields:

$$f(P, T) = f(P_0, T_0)e^{\alpha(T-T_0)+\beta(P-P_0)+r(T-T_0)^2+q(P-P_0)^2} \quad (23)$$

In the equation, $f(P, T)$ represents the Herschel–Bulkley rheological parameter, namely the yield stress τ_{yh} , flow index n_h , or consistency coefficient K_h . The parameters α , β , r and q are undetermined coefficients, which can be obtained through multiple linear regression or linear programming algorithms. T_0 and P_0 are the manually selected reference temperature and pressure, respectively, and $f(P_0, T_0)$ denotes the corresponding drilling fluid rheological parameter under the reference temperature and pressure conditions. In this study, the rheological test temperature of 65 °C and atmospheric pressure of 0.1 MPa were used as the reference conditions. Using the optimized Herschel–Bulkley rheological parameters obtained under different densities, temperatures, and pressures, temperature and pressure were taken as independent variables, while the rheological parameters were taken as dependent variables. Prediction models for the Herschel–Bulkley rheological parameters of oil-based drilling fluids with specific densities were then established through regression. Taking the Herschel–Bulkley yield stress as an example, the workflow for prediction model development and prediction accuracy analysis is shown in Figure 10.

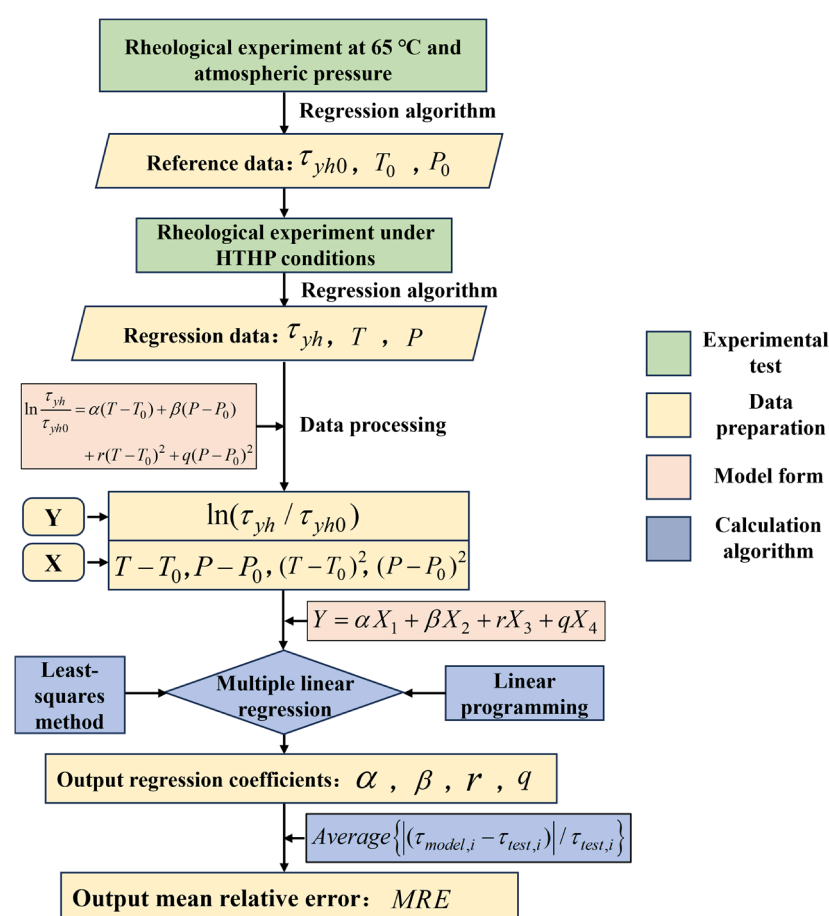


Figure 10. Prediction model and prediction accuracy analysis.

- (1) The rheological test data at 65 °C and atmospheric pressure in Table 1 were regressed using the Herschel–Bulkley rheological equation regression method described in Section 3.2. The Herschel–Bulkley yield stress at 65 °C and 0.1 MPa was obtained and used as the reference data, denoted as τ_{yh0} . The reference temperature and pressure were denoted as T_0 and P_0 , respectively.
- (2) All rheological test data under high-temperature and high-pressure conditions were regressed using the same method to obtain the Herschel–Bulkley yield stress under high-temperature and high-pressure conditions, denoted as τ_{yh} .

- (3) The dependent variable, yield stress, was processed by dividing the yield stress under each high-temperature and high-pressure condition by the reference yield stress and then taking the natural logarithm. A series of $\ln(\tau_{yh}/\tau_{yh0})$ values was obtained and denoted as Y .
- (4) The independent variables, temperature T and pressure P , were processed to obtain a series of values, including $T - T_0$, $P - P_0$, $(T - T_0)^2$ and $(P - P_0)^2$, which were denoted as X_1 , X_2 , X_3 and X_4 , respectively. Thus, a series of data in the linear form $Y = \alpha X_1 + \beta X_2 + r X_3 + q X_4$ was obtained.
- (5) Equation (23) was transformed into the linear form shown in Equation (24). The coefficients α , β , r and q corresponding to X_1 , X_2 , X_3 and X_4 were obtained through least-squares regression or a linear programming algorithm:

$$\ln \frac{\tau_{yh}}{\tau_{yh0}} = \alpha(T - T_0) + \beta(P - P_0) + r(T - T_0)^2 + q(P - P_0)^2 \quad (24)$$

where $Y = \ln \frac{\tau_{yh}}{\tau_{yh0}}$ (dimensionless) is the natural logarithm of the yield stress under high-temperature and high-pressure conditions divided by the reference yield stress.

- (6) For prediction accuracy analysis, the measured temperature T and pressure P were substituted into the prediction model in Equation (23) to obtain the yield stress predicted by the model under different measured temperature and pressure conditions, denoted as $\tau_{yh-model}$. The mean relative error was then calculated by comparing $\tau_{yh-model}$ with the measured yield stress τ_{yh} using Equation (16).

According to the above method for developing the Herschel–Bulkley rheological parameter prediction model, multiple linear regression was performed for the Herschel–Bulkley yield stress, flow index, and consistency coefficient using the rheological parameters obtained through regression under different densities, temperatures, and pressures. The coefficients α , β , r and q in Equation (23), as well as the corresponding mean relative errors of prediction, were obtained, as shown in Table 5.

Table 5. Prediction model coefficients and MRE.

Index	Model Coefficients	1.8/(g/cm ³)	2.0/(g/cm ³)	2.2/(g/cm ³)	MRE/%
Yield stress	$\alpha/^\circ\text{C}^{-1}$	-3.1720×10^{-2}	-3.4949×10^{-2}	-2.2745×10^{-2}	18.60
	β/MPa^{-1}	7.3100×10^{-3}	1.7114×10^{-2}	2.2185×10^{-2}	
	$r/^\circ\text{C}^{-2}$	1.7707×10^{-4}	2.0807×10^{-4}	1.2867×10^{-4}	
	q/MPa^{-2}	-2.3117×10^{-5}	-3.0532×10^{-5}	-5.9471×10^{-5}	
Flow index	$\alpha/^\circ\text{C}^{-1}$	-4.6527×10^{-4}	1.1121×10^{-3}	1.3700×10^{-3}	2.10
	β/MPa^{-1}	2.0900×10^{-3}	3.4302×10^{-4}	1.6400×10^{-3}	
	$r/^\circ\text{C}^{-2}$	9.7492×10^{-6}	-7.0878×10^{-6}	-1.3776×10^{-5}	
	q/MPa^{-2}	-1.0434×10^{-5}	-1.5352×10^{-6}	-1.0705×10^{-5}	
Consistency coefficient	$\alpha/^\circ\text{C}^{-1}$	-8.4723×10^{-3}	-1.9020×10^{-2}	-2.0406×10^{-2}	12.95
	β/MPa^{-1}	-7.7310×10^{-4}	1.9100×10^{-3}	5.6107×10^{-5}	
	$r/^\circ\text{C}^{-2}$	-6.4405×10^{-5}	4.6870×10^{-5}	4.3399×10^{-5}	
	q/MPa^{-2}	2.1925×10^{-5}	3.8851×10^{-5}	6.1161×10^{-5}	

To evaluate its prediction performance, the proposed model was compared with the Minton–Bern model [30] and the Zhao model [15]. The Minton–Bern model contains only the first-order temperature and pressure terms, whereas the Zhao model additionally includes a temperature–pressure interaction term and a quadratic temperature term; both models were developed mainly for Bingham plastic rheological parameters. In contrast, the

present model directly predicts the three Herschel–Bulkley parameters and incorporates the quadratic pressure term $(P - P_0)^2$ to describe their nonlinear pressure dependence under high-pressure conditions. For a consistent comparison, all three models used the same reference temperature and pressure of 65 °C and 0.1 MPa, respectively. Based on the experimental data obtained in this study under the conditions of 60–160 °C and 60–140 MPa, the Herschel–Bulkley yield stress, consistency coefficient, and flow index were predicted using the three models. The comparison results are shown in Figure 11, corresponding to the average prediction accuracy bar charts of the three rheological parameters. The results show that the proposed model can predict the Herschel–Bulkley rheological parameters at any temperature and pressure within the tested ranges of 60–160 °C and 60–140 MPa using the corresponding parameters measured at the reference conditions of 65 °C and 0.1 MPa. The average prediction accuracies of the Herschel–Bulkley yield stress, flow index, and consistency coefficient are 81.40%, 97.90%, and 87.05%, respectively, which are significantly higher than those of the Minton–Bern model and the Zhao model. This also verifies that introducing the quadratic pressure term can significantly improve the fitting performance of the model and satisfy the requirements of engineering calculations. It should be noted that the proposed prediction model was established based on the experimental data obtained within the temperature range of 60–160 °C and pressure range of 60–140 MPa. Therefore, the model is mainly applicable within the tested temperature and pressure ranges. Further validation is required before applying the model to conditions beyond these ranges or to oil-based drilling fluids with substantially different formulations. The results can provide theoretical support for managed pressure drilling technology in deep and ultra-deep wells.

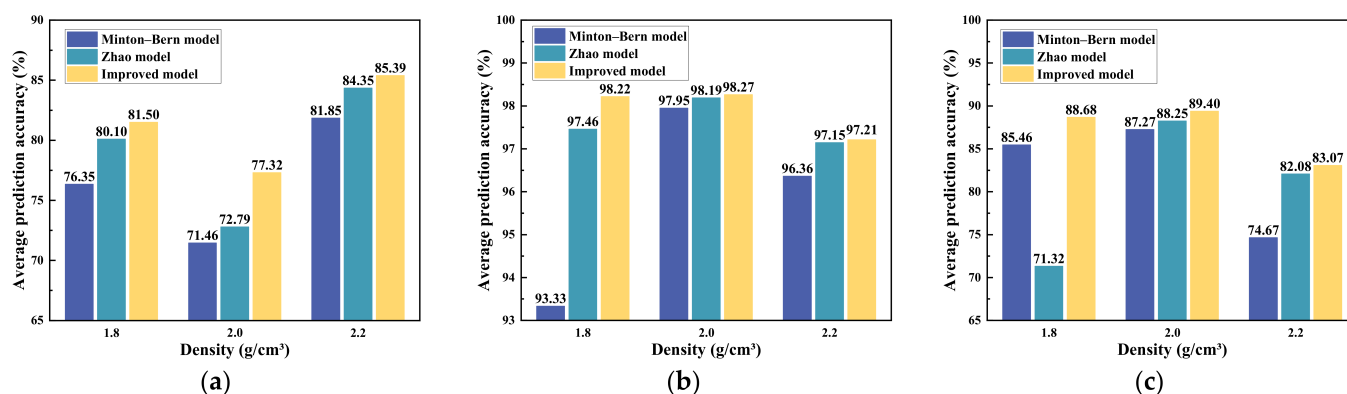


Figure 11. Comparison of prediction accuracy for Herschel–Bulkley rheological parameters of oil-based drilling fluids with different densities. (a) yield stress; (b) flow index; (c) consistency coefficient [15,30].

6. Conclusions

In this study, oil-based drilling fluids from deep high-temperature and high-pressure wells of the Tarim Basin were used to conduct rheological tests within the temperature and pressure ranges of 60–160 °C and 60–140 MPa. Based on the experimental data, regression algorithms were established for the Bingham plastic, power law, Casson, and Herschel–Bulkley rheological equations, and the optimal rheological characterization equation was selected. The accuracy of the regression model was verified through comparison with Landmark WellPlan software. Furthermore, the variation patterns of rheological parameters under different densities, temperatures, and pressures were analyzed. On the basis of previous rheological parameter prediction models, an improved prediction model was proposed. The main conclusions are as follows:

- (1) The high-temperature and high-pressure rheological properties of this oil-based drilling fluid formulation are more consistent with the three-parameter Herschel–Bulkley rhe-

ological equation. Under different temperature and pressure conditions, the mean relative error between the shear stress calculated by the Herschel–Bulkley model and the experimental values is only 2.64%. The established regression algorithm exhibits higher computational accuracy than Landmark WellPlan software in rheological parameter regression, with a mean relative error of only 2.049%.

- (2) The density of the oil-based drilling fluid has a significant influence on the Herschel–Bulkley yield stress and consistency coefficient, whereas its influence on the Herschel–Bulkley flow index is relatively weak.
- (3) High temperature and high pressure have significant effects on the Herschel–Bulkley yield stress and consistency coefficient of oil-based drilling fluids with different densities, but have a relatively minor effect on the Herschel–Bulkley flow index. Moreover, the Herschel–Bulkley yield stress, flow index, and consistency coefficient of this oil-based drilling fluid formulation exhibit opposite variation patterns under low-density and high-density conditions.
- (4) The improved prediction model for Herschel–Bulkley rheological parameters can be used to calculate rheological parameters at any temperature and pressure within the ranges of 60–160 °C and 60–140 MPa based on the rheological parameters measured at the standard temperature of 65 °C and atmospheric pressure of 0.1 MPa. The average prediction accuracies of Herschel–Bulkley yield stress, flow index, and consistency coefficient are 81.40%, 97.90%, and 87.05%, respectively. Compared with the Minton–Bern model and the Zhao model, the proposed model shows significantly improved accuracy and satisfies the requirements of engineering calculations.

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References

1. Xu, S.; Yang, D.; Liu, B.; Jia, C.; Zhang, Y. Multi-field coupling controls the formation and evolution of deep reservoirs. *Adv. Geo-Energy Res.* **2025**, *17*, 176–178. [\[CrossRef\]](#)
2. Liu, Y.; Zhang, J.; Huang, H. Key technologies and development direction for deep and ultra-deep drilling and completion in China. *Acta Pet. Sin.* **2024**, *45*, 312–324. [\[CrossRef\]](#)
3. Zhao, W.; Dou, L. Potential, distribution and exploration strategy of petroleum resources remained onshore China. *Pet. Explor. Dev.* **2001**, *28*, 592. [\[CrossRef\]](#)
4. Wang, C.; Feng, S.; Zhang, Z.; Zhou, B.; Lyu, X.; Zhou, B. Key technologies for drilling design of well Shendi Take-1. *Pet. Drill. Tech.* **2024**, *52*, 78–86. [\[CrossRef\]](#)
5. Cai, M.; Luo, X.; Chen, L.; He, M.; Peng, H.; He, B. Ultra-large borehole drilling technologies of 10000-meter deep well SDCK1. *Pet. Drill. Tech.* **2024**, *52*, 87–92. [\[CrossRef\]](#)

6. Zhao, G.; Guo, Y.; Yang, C.; Chang, X.; Zhang, X. Evaluation of the cross-scale mechanical behavior and fracability of deep shales: How innovations benefit the exploitation of deep resources. *Adv. Geo-Energy Res.* **2025**, *17*, 91–94. [\[CrossRef\]](#)
7. Jia, C. Prospects and five future theoretical and technical challenges of the upstream petroleum industry in China. *Acta Pet. Sin.* **2024**, *45*, 1–14. [\[CrossRef\]](#)
8. Zhang, Y.; Li, M.; Zhao, Q.; Song, X.; Zhang, R.; Yang, L. Wellbore pressure model for drilling fluid in ultra-deep rock salt formations at high temperatures and pressures. *Phys. Fluids* **2024**, *36*, 023341. [\[CrossRef\]](#)
9. Shen, Z.; Zhang, H.; Yu, X.; Wang, M.; Gao, C.; Li, S.; Zhang, H. Experimental optimization of high-temperature-resistant and low oil-water ratio high-density oil-based drilling fluid. *Processes* **2023**, *11*, 1129. [\[CrossRef\]](#)
10. Sun, J.; Yang, J.; Bai, Y.; Lyu, K.; Liu, F. Research progress and development of deep and ultra-deep drilling fluid technology. *Pet. Explor. Dev.* **2024**, *51*, 1022–1034. [\[CrossRef\]](#)
11. Ma, Y.; Cai, X.; Yun, L.; Li, Z.; Li, H.; Deng, S.; Zhao, P. Practice and theoretical and technical progress in exploration and development of Shunbei ultra-deep carbonate oil and gas field, Tarim Basin, NW China. *Pet. Explor. Dev.* **2022**, *49*, 1–20. [\[CrossRef\]](#)
12. Yang, H.-W.; Li, J.; Jiang, J.-W.; Zhang, H.; Guo, B.-Y.; Zhang, G.; Chen, W. A dynamic managed pressure well-control method for rapid treatment of gas kick in deepwater managed pressure drilling. *Pet. Sci.* **2022**, *19*, 2297–2313. [\[CrossRef\]](#)
13. Zhang, Y.; Li, Y.-A.; Kong, X.-W.; Liu, H.; Sun, T.-F. Temperature prediction model in multiphase flow considering phase transition in the drilling operations. *Pet. Sci.* **2024**, *21*, 1969–1979. [\[CrossRef\]](#)
14. Yin, Q.; Yang, J.; Li, Z.; Huang, Y.; Luo, M.; Wang, B.; Tyagi, M.; Xu, G.; Zhao, X. A field case study of managed pressure drilling in offshore ultra high-pressure high-temperature exploration well in the South China Sea. *SPE Drill. Complet.* **2020**, *35*, 503–524. [\[CrossRef\]](#)
15. Zhao, S.; Yan, J.; Shu, Y.; Li, H.; Li, L.; Ding, T. Prediction model for rheological parameters of oil-based drilling fluids at high temperature and high pressure. *Acta Pet. Sin.* **2009**, *30*, 603–606. [\[CrossRef\]](#)
16. Leusheva, E.; Morenov, V. Effect of temperature conditions in Arctic offshore oil fields on the rheological properties of various based drilling muds. *Energies* **2022**, *15*, 5750. [\[CrossRef\]](#)
17. Lei, H.; Cai, C.; Zhang, B.; Luo, J.; Chen, P.; Xiao, D. Experimental study and rheological modeling of water-based and oil-based drilling fluids under extreme temperature-pressure condition. *Energies* **2025**, *18*, 4687. [\[CrossRef\]](#)
18. Politte, M.D. Invert oil mud rheology as a function of temperature and pressure. In Proceedings of the SPE/IADC Drilling Conference, New Orleans, LA, USA, 6–8 March 1985. [\[CrossRef\]](#)
19. Fisk, J.V.; Jamison, D.E. Physical properties of drilling fluids at high temperatures and pressures. *SPE Drill. Eng.* **1989**, *4*, 341–346. [\[CrossRef\]](#)
20. Wang, H.; Liu, X. Comparison and optimization of rheological modes of drilling fluids. *Drill. Prod. Technol.* **1996**, *19*, 63–67.
21. Sun, X.; Qiu, S.; Wang, J.; Wang, Z.; Sun, J.; Sun, B. Experiment and methodology for drilling fluid rheology determination under high-temperature and high-pressure conditions. *Phys. Fluids* **2025**, *37*, 043118. [\[CrossRef\]](#)
22. Zhang, H.; Luo, R.; Yang, H. Calibration modeling of drilling fluid rheological parameters in variable temperature environment based on support vector machine. *Rev. Sci. Instrum.* **2024**, *95*, 105107. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Yan, J.; Zhao, X. Rheological properties of oil-based drilling fluids at high temperature and high pressure. *Acta Pet. Sin.* **2003**, *24*, 104–109. [\[CrossRef\]](#)
24. Ye, Y.; Fan, H.; Liu, Y. A new approach for predicting the rheological properties of oil-based drilling fluids under high temperature and high pressure based on a parameter-free method. *Appl. Sci.* **2023**, *13*, 8592. [\[CrossRef\]](#)
25. Zhou, H. A method of predicting high-temperature high-pressure rheological property based on viscometer readings. *Drill. Fluid Complet. Fluid* **2019**, *36*, 325–332. [\[CrossRef\]](#)
26. Qiu, Z.; Zhao, C.; Zhang, X.; Zhang, J.; Zhao, Y.; Chen, A.; Yang, Z. Study and performance evaluation of ultra-high temperature high-density oil-based drilling fluids. *Drill. Fluid Complet. Fluid* **2021**, *38*, 663–670. [\[CrossRef\]](#)
27. Wang, L.; Li, C.; Liu, S.; Li, H.; Xu, M.; Wang, Q.; Ge, R.; Jia, C.; Wei, G. Geotemperature gradient distribution of Kuqa foreland basin, north of Tarim, China. *Chin. J. Geophys.* **2003**, *46*, 403–407. [\[CrossRef\]](#)
28. Agwu, O.E.; Akpabio, J.U.; Ekpenyong, M.E.; Inyang, U.G.; Asuquo, D.E.; Eyoh, I.J.; Adeoye, O.S. A critical review of drilling mud rheological models. *J. Pet. Sci. Eng.* **2021**, *203*, 108659. [\[CrossRef\]](#)
29. Mahmoud, A.; Gajbhiye, R.; Elkatatny, S. Evaluation of claystone-ER as a novel rheological additive for enhancing oil-based drilling fluid performance under high-pressure high-temperature conditions. *Clays Clay Miner.* **2025**, *73*, e3. [\[CrossRef\]](#)
30. Minton, R.C.; Bern, P.A. Field measurement and analysis of circulating system pressure drops with low-toxicity oil-based drilling fluids. In Proceedings of the IADC/SPE Drilling Conference, Dallas, TX, USA, 28 February–2 March 1988. [\[CrossRef\]](#)

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