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## LETTER

# RDR Application: An Accurate HTHP Rheological Modeling for The Sulphonated Water-Based Drilling Fluid

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### Abstract:

#### Introduction:

An accurate HTHP rheological model of drilling fluids is critical for the safe and economic drilling operation. However, general HTHP rheological modeling methods appear to be very limited in the predictive accuracy.

#### Materials and Method:

In this work, a particular relative dial readings(RDR) modeling experiment was conducted on a weighted sulphonated water-based drilling fluid within a certain temperature and pressure range(30-150°C, 0.1-100MPa), in combination to dial reading data of six specific shear rates 3, 6, 100, 200, 300, and 600rpm, to develop a highly accurate HTHP rheological model. The RDR modeling procedure was investigated in details, including relative dial reading, Arrhenius relation, polynomial of pressure coefficients, and polynomial of shear rate coefficients. An equation relating RDR to temperature, pressure, and shear rate was determined.

#### Results:

The predictive deviation was calculated to be lower than 11.7%, and large errors occurred under the conditions of high pressure and low shear rates; all of which meet the requirement of in-field predictive accuracy. These results not only provide an accurate HTHP rheological equation for the weighted sulphonated water-based drilling fluid, but also propose an effective HTHP rheological modeling strategy for drilling fluids.

**Keywords:** RDR, HTHP, Rheological model, The sulphonated water-based drilling fluids, Predictive deviation.

## 1. INTRODUCTION

The rheological properties of drilling fluids are always critical upon drilling. Reasonable control of rheology can direct some key operation designs such as hydraulic calculation, pressure loss calculation, hole cleaning efficiency, and equivalent circulating density(ECD) determination, which enable high rate of penetration(ROP) and low drilling cost. The determination of rheological data relies, to a large extent, on a rheological mathematic representation, which allows an accurate theoretical prediction. Therefore, the rheological modeling of drilling fluids usually behaves as the first step especially in the high temperature high pressure(HTHP) drilling operation.

However, it is well-known that in deep drilling operations, rheology of drilling fluid is relatively complicated and often influenced by temperature, pressure, shear history, and composition of the drilling fluids [1 - 5]. Otherwise,

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effects of temperature and pressure on rheology of drilling fluids appear to be reverse in the down-hole conditions. Not surprisingly, developing a correlation that will relate shear stress to temperature, pressure, and shear rate should be difficult for drilling fluids. In the last 20-30 years, two important HTHP rheological modeling strategies, i.e., multiplicative factor(MF) and relative dial reading(RDR) approach, have been developed. But only limited studies on these two modeling application have been referred. As for the MF modeling approach, it is necessary to firstly fit the actual dial reading data to a general rheological model; while for the RDR approach, the relation that relates dial reading(shear stress) of a particular fluid at different temperature, pressure, and shear rate conditions can be directly determined. Undoubtedly, the latter approach should be more accurate because of avoidance of general model assumption, when compared to the former one.

In this work, the weighted sulphonated water-based fluid was used to explore applicability of the RDR modeling approach in combination to operation environments in Southwest China Gas Fields. To shed more light on HTHP rheological modeling, development of HTHP rheological model of drilling fluids will be further illustrated below.

### 1.1. General HTHP Rheological Modeling Process

The general rheological modeling process involves two steps: one is to fit dial reading(or shear stress) and shear rate values to specific rheological equations(e.g., Yield Power Law and Bingham Plastic models); the other is to determine the effect of temperature and pressure on dial readings and define correction factors to correlate rheological parameters in down-hole conditions. The commonly reported correction factor is shown as follows:

$$f(P, T) = \exp\left(\frac{A + (BT + C)P}{T}\right) \quad (1)$$

where A, B, and C are characteristic constants. Following Eq.(1), McMordie *et al.* [6] modified the power-law model as,

$$\ln \tau = \ln K' + n \ln \dot{\gamma} + AP + B/T \quad (2)$$

where  $K'$  and  $n$  correspond to the consistency index and behavior index, respectively. This HTHP rheological model has been successfully used in the oil-based drilling fluid. Similarly, Houwen [7], Hiller [8], and Alderman [9] have applied the MF method to the two-parameter Casson and Bingham plastic models, as well as three-parameter Hirschel-Bulkley and Robertson-Stiff models. On the basis of modeling procedure and results, they concluded that the correlation of parameters in base equations can disturb the final predictive accuracy.

To diminish the correlation of parameters, Rommetveit *et al.* [10] proposed another way to construct base equation, which is written as,

$$f(P, T, \dot{\gamma}) = e^{g_1(P, T)} \dot{\gamma} + e^{g_2(P, T)} \quad (3)$$

where  $f(P, T, \dot{\gamma})$  is a factor that multiplies shear stress obtained at considered conditions. The constant functions  $g_1(P, T)$  and  $g_2(P, T)$  are determined by an optimistic fit to measured data. In this case, the intrinsic defects of the selected base models can be avoided, which makes prediction more accurate.

American Petroleum Institute(API) recommends the HTHP rheological model:

$$\tau(T, P, \dot{\gamma}) = \tau_o(\dot{\gamma}) e^{[\alpha(T - T_o) + \beta(P - P_o)]} \quad (4)$$

where  $\tau_o$  denotes the shear stress at a given rotational speed. This model is extended to viscosity expressions [11, 12].

It should be noted that upon modeling, general HTHP rheological models depend on the initial base equation and Arrhenius empirical relations, which can cause a large predictive deviation.

### 1.2. Specific HTHP Rheological Modeling Process

To avoid designation of initial rheological model, a specific HTHP rheological modeling process based on the RDR approach was developed by Hemphill [13]. Rather than using a designated rheological model, it directly correlated the changes in dial readings with temperature, pressure, and shear rate by the non-linear regression method. All the results

were related to a relative parameter measured at  $T_o$  and  $P_o$ . The RDR are defined as:

$$RDR = \frac{\theta_{T,P}}{\theta_{T_o,P_o}} \quad (5)$$

where  $\theta$  is the dial reading and  $T_o$  and  $P_o$  are the relative temperature and pressure, respectively. Combining with Arrhenius Relation, the RDR model is rewritten as:

$$RDR(T, P, \gamma) = C_1(P, \gamma) \exp\left[\frac{C_2(P, \gamma)}{T}\right] \quad (6)$$

where  $C_1$  and  $C_2$  are model coefficients that are dependent on the pressure and shear rate.

Using the RDR approach, an accurate HTHP rheological model was developed at eight specific shear rates under HTHP conditions(50-240°F, 0-8000psig) for an ester-based drilling fluid. Similarly, Demirdal [14] applied the RDR approach to establish an accurate HTHP rheological model for ester-based mud under HTHP conditions(40-280°F, 500-12000psig). As for the RDR modeling strategy, it is not necessary to use a rheological model as the base equation and, thus, the assumption of base rheological model can be avoided.

Previous RDR modeling studies focused mainly on ester- and synthetic-based drilling fluids and, consequently, the implication of RDR approach on the model applicability and the predictive accuracy in non-aqueous drilling fluids, is increasingly coming to light. In contrast, the RDR approach involved in HTHP rheological modeling for water-based drilling fluid has not been reported so far. Herein, the RDR approach was utilized to reveal its applicability of developing a highly accurate HTHP rheological equation in a weighted sulphonated water-based drilling fluid. This work on the RDR application in the water-based drilling fluid is complementary with respect to non-aqueous drilling fluids, which can not only determine a relation that relates RDRs with temperature, pressure, and shear rate, but also verify the validity of RDR approach as a novel HTHP rheological modeling tool for particular drilling fluids.

## 2. METHODOLOGY

### 2.1. Experimental Materials

The sulphonated water-based drilling fluid, as a common kind of HTHP drilling fluid, was typically employed in the oil and gas industry. Such fluid has a high density of 1.5g/ml, and consists of at least 7 functional additives such as hydrophilic solid phase, pH control agent, loss control agent, viscosifier, inhibitor, antioxidant, and weighting material was employed here, as shown in Table 1. The drilling fluid was heat-aged at 180°C for 16 hours before testing.

**Table 1. Components of the sulphonated water-based fluid referred here.**

Additives	Components	Content (wt.%)
--	Water	--
--	Clay	4~5
pH-adjusting agent	Sodium hydroxide	0.5
viscosifier	PAMS copolymer	1.0
viscosifier	Amphoteric sulfonated polymer	0.5
Filtrate loss reducer	Sulfonated phenolic resin	4
Filtrate loss reducer	Lignosulfonate	4
Weighting material	Barite	--

### 2.2. Examination on Rheological Data

Pressures applied in the tests were 0.1, 15, 25, 55, 85, and 100MPa. Temperatures used during the tests were 30, 60, 90, 120, and 150°C. At each combination of pressure and temperature, the rheological data(dial readings) of the weighted sulphonated drilling fluid were measured at six specific shear rates 600, 300, 200, 100, 6, and 3rpm, using a Fann IX77 HTHP Rheometer.

To establish an accurate equation, both statistics and detailed sample selection are essential. In principle, the more the testing data, the more accurate the final formula. Although the statistic data seem to be not enough, the RDR

approach was previously demonstrated to be accurate in defining a HTHP rheological model even with limited parameters [13, 14].

### 2.3. Modeling Procedure

The RDR approach was employed to determine a single relation that relates dial readings with shear rate, temperature, and pressure. The standard procedure of RDR modeling contains relative dial reading, Arrhenius relation, polynomial of pressure coefficients, and polynomial of shear rate coefficients, as shown in Fig. (1). To determine such an equation, non-linear and linear regression analysis has been used by a commercial software STATISTIC. Note that, on account of the requirements of accuracy, different expressions like logarithmic, exponential, and polynomial model can be obtained upon fitting.

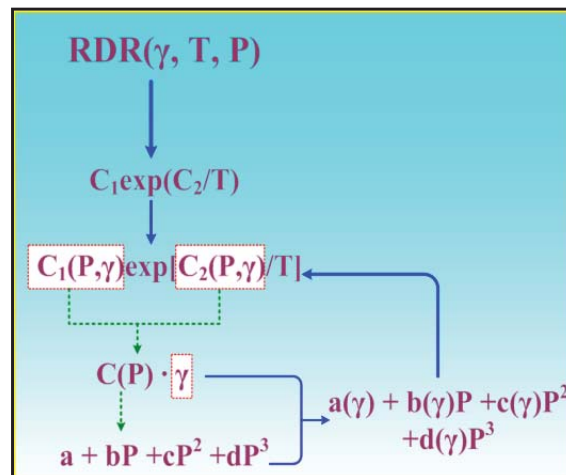


Fig. (1). HTHP rheological Modeling procedure of the RDR approach.

## 3. RESULTS AND DISCUSSION

### 3.1. Relative Procedure of Dial Readings

To reduce the effect of T and P, a relative treatment was performed on dial reading data. Herein, RDR is defined as the ratio of the dial reading determined at any temperature and pressure to the dial reading determined at 0.1MPa and 30°C, shown as follows:

$$RDR = \frac{\tau}{\tau_{0.1MPa, 30^{\circ}C}} \tag{7}$$

Table 2 collects the dial readings and RDRs under the considered conditions. As might be anticipated, the water-based fluid is rarely pressure-dependent and highly temperature-dependent. Meanwhile, pressure effects on rheology can slightly rise at high temperature and low shear rates.

Table 2. Dial readings measured under the considered HPHT conditions <sup>a, b</sup>.

P (MPa)	T (°C)	Shear Rates (rpm)					
		600	300	200	100	6	3
100	60	116(0.5577)	87(0.5241)	77(0.5238)	66(0.5410)	53(0.5761)	53(0.6023)
100	90	68(0.3269)	47(0.2831)	39(0.2653)	32(0.2623)	25(0.2717)	24(0.2727)
100	120	49(0.2356)	31(0.1867)	25(0.1701)	18(0.1475)	13(0.1413)	13(0.1477)
100	150	38(0.1827)	21(0.1265)	16(0.1088)	11(0.0902)	7(0.0761)	7(0.0795)
85	60	117(0.5625)	88(0.5301)	78(0.5306)	67(0.5492)	54(0.5870)	53(0.6023)
85	90	68(0.3269)	47(0.2831)	39(0.2653)	32(0.2623)	25(0.2717)	24(0.2727)
85	120	49(0.2356)	31(0.1867)	25(0.1701)	18(0.1475)	13(0.1413)	13(0.1477)
85	150	38(0.1827)	21(0.1265)	16(0.1088)	11(0.0902)	8(0.0870)	7(0.0795)

(Table 4) contd....

P (MPa)	T (°C)	Shear Rates (rpm)					
		600	300	200	100	6	3
55	60	117(0.5625)	87(0.5241)	77(0.5238)	66(0.5410)	53(0.5761)	52(0.5909)
55	90	68(0.3269)	47(0.2831)	40(0.2721)	33(0.2705)	25(0.2717)	24(0.2727)
55	120	49(0.2356)	31(0.1867)	26(0.1769)	19(0.1557)	14(0.1522)	13(0.1477)
55	150	38(0.1827)	22(0.1325)	17(0.1156)	12(0.0984)	8(0.0870)	7(0.0795)
25	60	117(0.5625)	87(0.5241)	77(0.5238)	66(0.5410)	53(0.5761)	52(0.5909)
25	90	68(0.3269)	47(0.2831)	40(0.2721)	33(0.2705)	25(0.2717)	24(0.2727)
25	120	49(0.2356)	31(0.1867)	26(0.1769)	19(0.1557)	14(0.1522)	13(0.1477)
25	150	38(0.1827)	22(0.1325)	17(0.1156)	12(0.0984)	7(0.0761)	7(0.0795)
15	60	115(0.5529)	86(0.5181)	76(0.5170)	65(0.5328)	53(0.5761)	52(0.5909)
15	90	68(0.3269)	47(0.2831)	40(0.2721)	33(0.2705)	25(0.2717)	24(0.2727)
15	120	49(0.2356)	31(0.1867)	25(0.1701)	18(0.1475)	14(0.1522)	13(0.1477)
15	150	38(0.1827)	22(0.1325)	17(0.1156)	12(0.0984)	8(0.0870)	8(0.0909)
0.1	30	208(1)	166(1)	147(1)	122(1)	92(1)	88(1)

<sup>a</sup> T and P separately correspond to 30°C and 0.1MPa.

<sup>b</sup> Data in parenthesis correspond to RDRs.

### 3.2. Arrhenius Relation Between RDRs and Temperature

Arrhenius relation is considered to be appropriate to relate RDR to temperature.  $RDR(T)$  in terms of the investigated parameters can be shown as follows:

$$RDR(T) = C_1 \exp C_2(T)/T \tag{8}$$

wherein  $C_1$  and  $C_2$  are coefficients of Arrhenius relation.

Table 3 presents the coefficient analysis of  $RDR$  vs.  $T$  for Arrhenius relation. It is clear that all of the correlations ( $R^2$ ) are larger than 0.98, and the average value is  $0.9886 \pm 0.0035$ , suggesting a high predictive accuracy for Arrhenius relation.

Table 3. Coefficient analysis of  $RDR$  vs.  $T$  for Arrhenius relation.

P(MPa)	$\dot{\gamma}$ (rpm)	$C_1$	$C_2$	$R^2$
100	3	0.0375	167.2237	0.9857
	6	0.0376	164.3890	0.9807
	100	0.0423	153.5008	0.9861
	200	0.0528	138.1225	0.9900
	300	0.0643	126.4127	0.9892
	600	0.0976	104.9750	0.9953
85	3	0.0375	167.2237	0.9857
	6	0.0385	164.0179	0.9865
	100	0.0416	155.4050	0.9873
	200	0.0521	139.7473	0.9909
	300	0.0635	127.8266	0.9901
	600	0.0967	106.0262	0.9958
55	3	0.0383	164.7892	0.9842
	6	0.0413	158.7604	0.9857
	100	0.0469	147.3398	0.9859
	200	0.0572	133.3671	0.9897
	300	0.0658	124.9897	0.9917
	600	0.0967	106.0262	0.9958
25	3	0.0383	164.7892	0.9842
	6	0.0395	161.4868	0.9808
	100	0.0469	147.3398	0.9859
	200	0.0572	133.3671	0.9897
	300	0.0658	124.9897	0.9917
	600	0.0967	106.0262	0.9958

(Table 5) contd....

P(MPa)	γ(rpm)	C <sub>1</sub>	C <sub>2</sub>	R <sup>2</sup>
15	3	0.0401	161.9553	0.9885
	6	0.0413	158.7615	0.9857
	100	0.0461	147.5490	0.9837
	200	0.0565	133.3969	0.9889
	300	0.0667	123.5629	0.9908
	600	0.985	103.9176	0.9947

**3.3. Modeling of Coefficient C<sub>1</sub> and C<sub>2</sub> vs. P**

Once the relation between RDR and T was determined, the next step was to determine whether coefficients of the model(C<sub>1</sub> and C<sub>2</sub>) are dependent on P and γ. Table 4 shows that both C<sub>1</sub> and C<sub>2</sub> are functions of P and γ. If these coefficients are defined as the functions of P and γ, RDR(T, P, γ) can be written as (5).

In order to get a general expression, the regression analysis was carried out to determine the effect of P and γ on these constants(C<sub>1</sub> and C<sub>2</sub>). Herein, the effect of P on C<sub>1</sub> and C<sub>2</sub> under constant γ was analysed . Third degree polynomial defines the relation of C<sub>1</sub> and C<sub>2</sub> vs. P as:

$$C_1(P) = a_1 + b_1P + c_1P^2 + d_1P^3 \tag{9}$$

$$C_2(P) = a_2 + b_2P + c_2P^2 + d_2P^3 \tag{10}$$

wherein a, b, c, and d are the model coefficients.

**Table 4. Coefficient analysis of C<sub>1</sub> and C<sub>2</sub> vs. P for third degree polynomial relation.**

Coefficients	C <sub>1</sub> (P)					
	3	6	100	200	300	600
a <sub>1</sub>	0.73	0.72	0.31	0.20	0.13	0.18
b <sub>1</sub>	-4.0×10 <sup>-4</sup>	-4.0×10 <sup>-4</sup>	-5.0×10 <sup>-5</sup>	-8.6E-6	4.0×10 <sup>-5</sup>	2.0×10 <sup>-5</sup>
c <sub>1</sub>	-6.5×10 <sup>-8</sup>	-6.4×10 <sup>-8</sup>	-1.2×10 <sup>-8</sup>	-2.9×10 <sup>-9</sup>	6.0×10 <sup>-9</sup>	3.9×10 <sup>-10</sup>
d <sub>1</sub>	-3.2×10 <sup>-12</sup>	-3.2×10 <sup>-12</sup>	-7.8×10 <sup>-13</sup>	-1.5×10 <sup>-13</sup>	2.8×10 <sup>-13</sup>	-1.5×10 <sup>-14</sup>
R <sup>2</sup>	0.998	0.997	0.999	0.995	0.997	0.998
Coefficients	C <sub>2</sub> (P)					
	3	6	100	200	300	600
a <sub>2</sub>	-251.34	41.66	11.75	50.18	75.78	74.46
b <sub>2</sub>	-0.17	0.04	-1.5×10 <sup>-2</sup>	-2.7×10 <sup>-3</sup>	0.01	5.5×10 <sup>-3</sup>
c <sub>2</sub>	-3.0×10 <sup>-5</sup>	4.1×10 <sup>-6</sup>	-2.0×10 <sup>-6</sup>	-9.7×10 <sup>-8</sup>	2.1×10 <sup>-6</sup>	9.8×10 <sup>-7</sup>
d <sub>2</sub>	-1.5×10 <sup>-9</sup>	3.0×10 <sup>-11</sup>	-9.9×10 <sup>-11</sup>	-7.0×10 <sup>-12</sup>	9.7×10 <sup>-11</sup>	3.7×10 <sup>-11</sup>
R <sup>2</sup>	0.996	0.995	0.995	0.996	0.994	0.996

It can be readily found that coefficients of multiple determination(R<sup>2</sup>) for C<sub>1</sub>(P) and C<sub>2</sub>(P) are all close to 1.0, which reveals significant correlation between the actual and predictive values. Apparently, the proposed third degree polynomial is quite suitable to fit C(P). Next, C<sub>1</sub>(P) and C<sub>2</sub>(P) were further used to establish C<sub>1</sub>(P, γ) and C<sub>2</sub>(P, γ).

**3.4. Relation Between Coefficients of C<sub>1</sub>(P) and C<sub>2</sub>(P) and γ**

In order to determine C<sub>1</sub>(P, γ) and C<sub>2</sub>(P, γ), the effect of γ on coefficients(a, b, c, and d) shown in C(P) should be determined. Non-linear regression analysis was carried out using either one-parameter or two-parameter curves. The relations between the coefficients of C<sub>1</sub>(P) and C<sub>2</sub>(P) and γ are presented in Table 5.

**Table 5. Relations between coefficients of C(P) and γ.**

C(P)	Equations of Coefficients of C(P) vs. γ	R <sup>2</sup>
C <sub>1</sub>	a = (1.32073 + 0.02104 γ) <sup>1/1.06571</sup>	0.998
	b = -0.00065 + 0.00012ln(γ + 5.37232)	0.986
	c = (-1.1431×10 <sup>-7</sup> ) - 2.1299×10 <sup>-8</sup> (γ + 6.18217)	0.992
	d = (-6.3934×10 <sup>-12</sup> ) - 2.1299×10 <sup>-8</sup> (γ + 11.02309)	0.996
C <sub>2</sub>	a = 6.80525 + 7.38181 ln(γ - 3)	0.983

(Table 7) contd....

C(P)	Equations of Coefficients of C(P) vs. $\gamma$	R <sup>2</sup>
	$b = 0.0133 + 0.004351 \ln(\gamma - 3)$	0.894
	$c = (-2.3171 \times 10^{-6}) + 7.6818 \times 10^{-7} \ln(\gamma - 3)$	0.942
	$d = (-1.5396 \times 10^{-10}) + 3.7431 \times 10^{-11} \ln(\gamma - 3)$	0.978

Listed in Table 5 are the relation that well relate coefficient of C(p) to shear rate. For all relation, R<sup>2</sup> values are almost equal to 0.9, and average value is as high as 0.971±0.027, suggesting a good relation between the predictive and actual values. Substituting relations listed in Table 5 to C<sub>1</sub>(P) and C<sub>2</sub>(P), the coefficients C can be shown as a function of P and  $\gamma$  as follows:

$$C_1(P, \gamma) = (1.32073 + 0.02104\gamma)^{\frac{1}{1.06571}} + [-0.00065 + 0.00012\ln(\gamma + 5.37232)]P + [1.1431 \times 10^{-7} + 2.1299 \times 10^{-8}(\gamma + 6.18217)]P^2 - [6.3934 \times 10^{-12} + 2.1299 \times 10^{-8}(\gamma + 11.02309)]P^3 \tag{11}$$

$$C_2(P, \gamma) = 6.80525 + 7.3818\ln(\gamma - 3) - [0.0133 + 0.004351\ln(\gamma - 3)]P + [-2.3171 \times 10^{-6} + 7.6818 \times 10^{-7} \ln(\gamma - 3)]P^2 + [1.5396 \times 10^{-10} - 3.7431 \times 10^{-11} \ln(\gamma - 3)]P^3 \tag{12}$$

These two Eq.11 and Eq.12 achieved above can be further substituted into RDR(T). As a consequence, a function relating RDR to T, P, and  $\gamma$  can be determined by using one equation (see Eq. 7).

### 3.5. Analysis on Deviation of RDR Rheological Model

Analysis on the predictive deviation of HTHP rheological model developed here was further carried out to evaluate its applicability. Table 6 lists main results, including the tested and calculated dial readings, residual, and absolute error. The absolute error percentages vary in the range of 0~12%, and the average error percentage is calculated as 3.3397±2.2006, which reflects high predictive accuracy for the developed HTHP rheological equation within certain temperature and pressure range.

**Table 6. Analysis on deviation of the HTHP rheological model developed for the weighted sulphonated water-based drilling fluid.**

No	Independent Variables			Dial Readings		Residual	Absolute Error (%)
	P(MPa)	T(°C)	$\gamma$ (rpm)	Factual	Calculated		
1	100	60	3	0.6023	0.6037	-1.39×10 <sup>-3</sup>	0.23
2	100	60	6	0.5761	0.5676	8.50×10 <sup>-3</sup>	1.48
3	100	60	100	0.5410	0.5279	1.31×10 <sup>-2</sup>	2.42
4	100	60	200	0.5238	0.5223	1.55×10 <sup>-3</sup>	0.30
5	100	60	300	0.5241	0.5281	-4.04×10 <sup>-3</sup>	0.77
6	100	60	600	0.5577	0.5581	-3.83×10 <sup>-4</sup>	0.07
7	100	90	3	0.2727	0.2734	-6.30×10 <sup>-4</sup>	0.23
8	100	90	6	0.2717	0.2583	1.34×10 <sup>-2</sup>	4.93
9	100	90	100	0.2623	0.2470	1.53×10 <sup>-2</sup>	5.82
10	100	90	200	0.2653	0.2647	5.90×10 <sup>-4</sup>	0.22
11	100	90	300	0.2831	0.2878	-4.69×10 <sup>-3</sup>	1.65
12	100	90	600	0.3269	0.3267	1.88×10 <sup>-4</sup>	0.06
13	100	120	3	0.1477	0.1469	8.73×10 <sup>-4</sup>	0.59
14	100	120	6	0.1413	0.1367	4.64×10 <sup>-3</sup>	3.29
15	100	120	100	0.1475	0.1372	1.03×10 <sup>-2</sup>	6.98
16	100	120	200	0.1701	0.1613	8.73×10 <sup>-3</sup>	5.14
17	100	120	300	0.1867	0.1881	-1.39×10 <sup>-3</sup>	0.75
18	100	120	600	0.2356	0.2336	1.94×10 <sup>-3</sup>	0.82

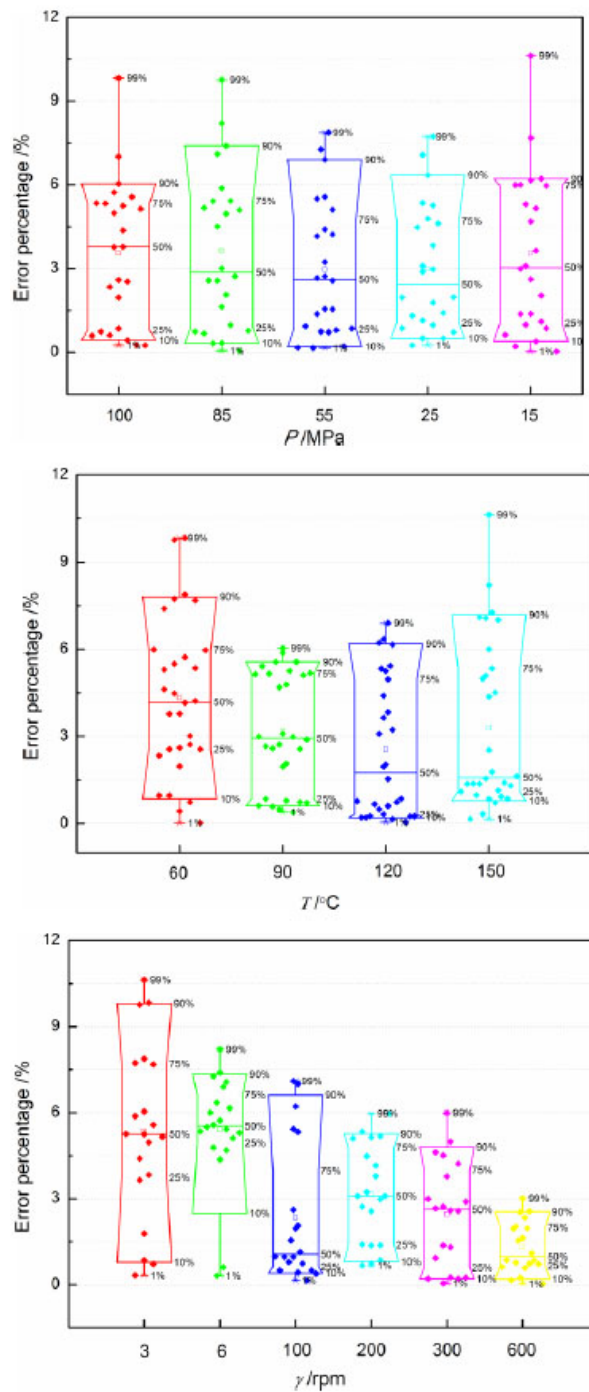
No	Independent Variables			Dial Readings		Residual	Absolute Error (%)
	P(MPa)	T(°C)	$\gamma$ (rpm)	Factual	Calculated		
19	100	150	3	0.0795	0.0823	$-2.74 \times 10^{-3}$	3.44
20	100	150	6	0.0761	0.0729	$3.17 \times 10^{-3}$	4.17
21	100	150	100	0.0902	0.0801	$1.01 \times 10^{-2}$	11.20
22	100	150	200	0.1088	0.1062	$2.67 \times 10^{-3}$	2.46
23	100	150	300	0.1265	0.1334	$-6.90 \times 10^{-3}$	5.45
24	100	150	600	0.1827	0.1839	$-1.16 \times 10^{-3}$	0.64
25	85	60	3	0.6023	0.6014	$8.35 \times 10^{-4}$	0.14
26	85	60	6	0.5870	0.5795	$7.41 \times 10^{-3}$	1.26
27	85	60	100	0.5492	0.5367	$1.25 \times 10^{-2}$	2.27
28	85	60	200	0.5306	0.5264	$4.22 \times 10^{-3}$	0.79
29	85	60	300	0.5301	0.5305	$-4.15 \times 10^{-4}$	0.08
30	85	60	600	0.5625	0.5604	$2.07 \times 10^{-3}$	0.37
31	85	90	3	0.2727	0.2733	$-5.90 \times 10^{-4}$	0.22
32	85	90	6	0.2717	0.2650	$6.76 \times 10^{-3}$	2.49
33	85	90	100	0.2623	0.2527	$9.57 \times 10^{-3}$	3.65
34	85	90	200	0.2653	0.2661	$-7.54 \times 10^{-4}$	0.28
35	85	90	300	0.2831	0.2875	$-4.35 \times 10^{-3}$	1.54
36	85	90	600	0.3269	0.3271	$-2.25 \times 10^{-4}$	0.07
37	85	120	3	0.1477	0.1475	$2.69 \times 10^{-4}$	0.18
38	85	120	6	0.1413	0.1434	$-2.06 \times 10^{-3}$	1.46
39	85	120	100	0.1475	0.1416	$5.89 \times 10^{-3}$	3.99
40	85	120	200	0.1701	0.1624	$7.71 \times 10^{-3}$	4.53
41	85	120	300	0.1867	0.1879	$-1.13 \times 10^{-3}$	0.60
42	85	120	600	0.2356	0.2337	$1.84 \times 10^{-3}$	0.78
43	85	150	3	0.0795	0.0831	$-3.57 \times 10^{-3}$	4.49
44	85	150	6	0.0870	0.0807	$6.25 \times 10^{-3}$	7.18
45	85	150	100	0.0902	0.0838	$6.38 \times 10^{-3}$	7.08
46	85	150	200	0.1088	0.1074	$1.44 \times 10^{-3}$	1.32
47	85	150	300	0.1265	0.1337	$-7.23 \times 10^{-3}$	5.72
48	85	150	600	0.1827	0.1840	$-1.30 \times 10^{-3}$	0.71
49	55	60	3	0.5909	0.5924	$-1.51 \times 10^{-3}$	0.26
50	55	60	6	0.5761	0.5785	$-2.41 \times 10^{-3}$	0.42
51	55	60	100	0.5410	0.5409	$4.56 \times 10^{-5}$	0.01
52	55	60	200	0.5238	0.5252	$-1.42 \times 10^{-3}$	0.27
53	55	60	300	0.5241	0.5282	$-4.13 \times 10^{-3}$	0.79
54	55	60	600	0.5625	0.5647	$-2.20 \times 10^{-3}$	0.39
55	55	90	3	0.2727	0.2721	$6.68 \times 10^{-4}$	0.24
56	55	90	6	0.2717	0.2721	$-3.40 \times 10^{-4}$	0.12
57	55	90	100	0.2705	0.2670	$3.48 \times 10^{-3}$	1.29
58	55	90	200	0.2721	0.2706	$1.50 \times 10^{-3}$	0.55
59	55	90	300	0.2831	0.2875	$-4.41 \times 10^{-3}$	1.56
60	55	90	600	0.3269	0.3274	$-4.77 \times 10^{-4}$	0.15
61	55	120	3	0.1477	0.1470	$6.84 \times 10^{-4}$	0.46
62	55	120	6	0.1522	0.1499	$2.31 \times 10^{-3}$	1.52
63	55	120	100	0.1557	0.1553	$4.66 \times 10^{-4}$	0.30
64	55	120	200	0.1769	0.1682	$8.65 \times 10^{-3}$	4.89
65	55	120	300	0.1867	0.1897	$-2.92 \times 10^{-3}$	1.57
66	55	120	600	0.2356	0.2335	$2.12 \times 10^{-3}$	0.90
67	55	150	3	0.0795	0.0821	$-2.51 \times 10^{-3}$	3.16
68	55	150	6	0.0870	0.0850	$1.92 \times 10^{-3}$	2.21



No	Independent Variables			Dial Readings		Residual	Absolute Error (%)
	P(MPa)	T(°C)	$\gamma$ (rpm)	Factual	Calculated		
69	55	150	100	0.0984	0.0948	$3.57 \times 10^{-3}$	3.63
70	55	150	200	0.1156	0.1135	$2.16 \times 10^{-3}$	1.86
71	55	150	300	0.1325	0.1368	$-4.32 \times 10^{-3}$	3.26
72	55	150	600	0.1827	0.1840	$-1.28 \times 10^{-3}$	0.70
73	25	60	3	0.5909	0.5886	$2.31 \times 10^{-3}$	0.39
74	25	60	6	0.5761	0.5748	$1.31 \times 10^{-3}$	0.23
75	25	60	100	0.5410	0.5371	$3.84 \times 10^{-3}$	0.71
76	25	60	200	0.5238	0.5197	$4.14 \times 10^{-3}$	0.79
77	25	60	300	0.5241	0.5221	$1.99 \times 10^{-3}$	0.38
78	25	60	600	0.5625	0.5599	$2.64 \times 10^{-3}$	0.47
79	25	90	3	0.2727	0.2719	$8.66 \times 10^{-4}$	0.32
80	25	90	6	0.2717	0.2736	$-1.90 \times 10^{-3}$	0.70
81	25	90	100	0.2705	0.2694	$1.06 \times 10^{-3}$	0.39
82	25	90	200	0.2721	0.2706	$1.48 \times 10^{-3}$	0.54
83	25	90	300	0.2831	0.2866	$-3.43 \times 10^{-3}$	1.21
84	25	90	600	0.3269	0.3270	$-3.82 \times 10^{-5}$	0.01
85	25	120	3	0.1477	0.1479	$-1.56 \times 10^{-4}$	0.11
86	25	120	6	0.1522	0.1511	$1.03 \times 10^{-3}$	0.68
87	25	120	100	0.1557	0.1599	$-4.12 \times 10^{-3}$	2.65
88	25	120	200	0.1769	0.1698	$7.03 \times 10^{-3}$	3.97
89	25	120	300	0.1867	0.1899	$-3.11 \times 10^{-3}$	1.66
90	25	120	600	0.2356	0.2337	$1.83 \times 10^{-3}$	0.78
91	25	150	3	0.0795	0.0833	$-3.71 \times 10^{-3}$	4.66
92	25	150	6	0.0761	0.0850	$-8.90 \times 10^{-3}$	11.70
93	25	150	100	0.0984	0.1004	$-2.01 \times 10^{-3}$	2.04
94	25	150	200	0.1156	0.1157	$-2.87 \times 10^{-5}$	0.02
95	25	150	300	0.1325	0.1372	$-4.68 \times 10^{-3}$	3.53
96	25	150	600	0.1827	0.1841	$-1.45 \times 10^{-3}$	0.79
97	15	60	3	0.5909	0.5908	$8.39 \times 10^{-5}$	0.01
98	15	60	6	0.5761	0.5793	$-3.21 \times 10^{-3}$	0.56
99	15	60	100	0.5328	0.5361	$-3.35 \times 10^{-3}$	0.63
100	15	60	200	0.5170	0.5185	$-1.54 \times 10^{-3}$	0.30
101	15	60	300	0.5181	0.5204	$-2.32 \times 10^{-3}$	0.45
102	15	60	600	0.5529	0.5545	$-1.57 \times 10^{-3}$	0.28
103	15	90	3	0.2727	0.2726	$1.51 \times 10^{-4}$	0.06
104	15	90	6	0.2717	0.2735	$-1.75 \times 10^{-3}$	0.64
105	15	90	100	0.2705	0.2643	$6.15 \times 10^{-3}$	2.27
106	15	90	200	0.2721	0.2682	$3.94 \times 10^{-3}$	1.45
107	15	90	300	0.2831	0.2856	$-2.45 \times 10^{-3}$	0.87
108	15	90	600	0.3269	0.3267	$2.47 \times 10^{-4}$	0.08
109	15	120	3	0.1477	0.1492	$-1.43 \times 10^{-3}$	0.96
110	15	120	6	0.1522	0.1512	$9.50 \times 10^{-4}$	0.62
111	15	120	100	0.1475	0.1562	$-8.63 \times 10^{-3}$	5.85
112	15	120	200	0.1701	0.1675	$2.55 \times 10^{-3}$	1.50
113	15	120	300	0.1867	0.1886	$-1.83 \times 10^{-3}$	0.98
114	15	120	600	0.2356	0.2342	$1.37 \times 10^{-3}$	0.58
115	15	150	3	0.0909	0.0854	$5.53 \times 10^{-3}$	6.09
116	15	150	6	0.0870	0.0862	$7.36 \times 10^{-4}$	0.85
117	15	150	100	0.0984	0.0989	$-5.46 \times 10^{-4}$	0.55
118	15	150	200	0.1156	0.1137	$1.92 \times 10^{-3}$	1.66

No	Independent Variables			Dial Readings		Residual	Absolute Error (%)
	$P$ (MPa)	$T$ (°C)	$\gamma$ (rpm)	Factual	Calculated		
119	15	150	300	0.1325	0.1355	$-2.96 \times 10^{-3}$	2.23
120	15	150	600	0.1827	0.1844	$-1.67 \times 10^{-3}$	0.92

To gain a further insight into the relation between deviation and variables, deviation distributions with respect to  $T$ ,  $P$ , and  $\gamma$  is investigated. All of the results are presented in Fig. (2).



**Fig. (2).** Box plots of error percentage vs.  $P$ ,  $T$ , and  $\gamma$ , respectively, for the RDR models, where the 10th, 25th, 50th, 75th, and 90th percentile of deviation dataset are marked.

Fig. (2) compares distribution of deviation data related to  $P$  for the RDR models. Here, the key percentiles of deviation dataset are marked in box plots. It can be readily found that the extreme deviation is about 11%, and 99% deviation are less than 11%, reflecting excellent prediction for the RDR model. Besides, the median line at 100MPa is slightly higher than others, which suggests that the predictive accuracy at 100MPa is lower than others. The fact that the deviation area of 85MPa exhibits slightly larger means a larger error distribution.

In Fig. (2), the distribution of error percentage vs.  $T$  is offered. It is clear that the extreme deviation appears at 150°C, and the highest median line at 60°C. Meanwhile, the deviation area is longer at 60°C than others. These results show that the predictive accuracy is slightly lower at 60°C than any others.

In addition, Fig. (2) gives box plots of the distribution of error percentage vs.  $\gamma$ . One readily finds that the extreme deviation appears at 3rpm, and the high median lines appear at 3 and 6rpm. This finding reveals that the predictive accuracy should be worse at low shear rates than those at high shear rates. That is to say, the established model does not always accurately predict the measured shear stresses at low shear rates.

According to deviation analysis given above, the RDR model defined for water-based drilling fluid has a low predictive error less than 11.7%. Although large errors occur at high pressure and low shear rates, they meet requirement of predictive accuracy on-site. It can be reasonably concluded that an accurate HTHP rheological model is established for the sulphonated water-based drilling fluid considered here.

## CONCLUSION

Developing an accurate HTHP rheology model is complex for drilling fluids, due to the involvement of multiple variables. In the present work, the RDR experiment was conducted on the weighted sulphonated water-based drilling fluid applied in Southwest China Gas Fields, to establish an accurate HTHP rheology model at six specific shear rates(3-600rpm) under certain temperature(30-150°C) and pressure(0.1-150MPa) conditions. The predictive deviation was examined to evaluate applicability of RDR approach in HTHP rheological modeling for the sulphonated water-based drilling fluid.

The modeling procedure was discussed in detail for the purpose of validating RDR application. The determined HTHP rheological equation has a lower predictive deviation(<11.7%), illustrating that it can relate dial readings with shear rate, temperature, and pressure very well. The larger errors readily happen at high pressure and low shear rates. This work not only develops the highly accurate HTHP rheological equation for the weighted sulphonated water-based drilling fluid, but also validates RDR application in the field of HTHP rheological modeling of drilling fluids. As an excellent modeling tool, the RDR approach can be extended to other drilling fluids, which would have large application potential in the future.

## CONSENT FOR PUBLICATION

Not applicable.

## CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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