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Improved Rheological Model of Oil-Based Drilling Fluid for South-western Iranian Oilfields

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ABSTRACT

In this study, predictive capabilities of apparent viscosity of oil-based drilling fluids which is used in National Iranian South Oilfields Company (NISOC) were evaluated using Newtonian and non-Newtonian models to drive a new suitable equation. The non-Newtonian models include Bingham plastic, Power law, Herschel-Bulkley, Casson, and Robertson-Stiff. To validate the results, the calculated viscosity from rheology models was compared to the fann 35 data of viscometer. The results showed that Robertson-Stiff model has the best prediction of shear stress and viscosity with an absolute average percent error of 3.58. This was followed by Herschel-Bulkley, Casson, Power law, Bingham plastic, and Newtonian with the absolute average percent error of 3.68, 3.77, 9.04, 20.09, and 44.02 respectively. Therefore, the new equation was proposed to predict the shear stress for oil-based drilling fluids which is used in Southwestern Iranian Oilfields. In comparison to the results of the experimental data of this study, it was revealed that the proposed equation has a good agreement with the real shear stress and apparent viscosities.

Keywords: Oil-Based Drilling Fluids, Rheological Models, Fann 35 Viscometer, Shear Stress.

INTRODUCTION

Drilling fluids perform several functions in drilling operations including controlling formation pressures, maintaining hole integrity and stability, cooling and lubricating the drill bit, and the drill string, cleaning the bottom hole, and suspending cuttings in the annulus when circulation is stopped or carrying them to the surface during drilling [1,2]. The rheological behavior of a drilling fluid directly affects all these activities; moreover, its knowledge enables better estimation of flow regimes, frictional pressure losses, equivalent circulating density under down hole conditions, hole-cleaning efficiency, swab/surge pressures; in addition, all of which are of extreme importance for improved drilling efficiency [3]. The determination of drilling fluid rheological properties is important in the calculation of circulating hydraulics and hole cleaning efficiency. Estimation of the rheological properties for the drilling fluids is an essential task for the safety and the economics of drilling a well. Various rheological models have been

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proposed to describe the rheological behavior of drilling fluid, particularly for drilling applications. The two parameters Bingham plastic model or the power law model is used most often because of its simplicity and the fair agreement of predictions with the rheograms. Although the power law model is useful as a first correction to Newtonian behavior, it may lead to substantial errors if the fluid exhibits yield stress. Other two parameter models like the Casson model have not found wide acceptance [4]. Three constant parameter models have been proposed by Herschel and Bulkley [4,5] and by Robertson and Stiff [4,6].

The proposed model and other models such as Bingham, power law, Herschel-Bulkley, Casson, and Robertson-Stiff have been investigated by Gucuyener [7]; moreover, they were tested with the measured data with a total number of seventy one drilling fluids; in addition, cement slurries of which twenty of them are presented in this study. A continuous regularization for the viscosity function which has been widely used in the numerical simulations of viscoplastic fluid flows, owing to its easy computational implementatio was introduced by Papanastasiou [8]. Shear stress/shear rate data were analyzed by Alderman et al [9]; in addition, the Herschel-Bulkley, Power, and Casson models were considered. The behavior of each rheological parameter in these models with respect to changes in temperature and pressure was investigated. The effectiveness of four different rheological models (Bingham plastic, Power Law, Robertson-Stiff, and Herschel-Bulkley) in prediction of the rheological behavior and the onset of turbulence of various muds flowing in pipes were analyzed by Khataniar et al [10]. They concluded that the Robertson-Stiff model provided the best fit of rheological data. It was shown by Davison et al [11] that Bingham plastic and Herschel-Bulkley models fit the data of low toxicity oil-based mud. Herschel-Bulkley and Casson models accurately fit the mud over a wide range of temperature, pressure, and shear rates. A new rheological model, called the Rational Polynomial model that could represent virtually any time-independent non-Newtonian fluid, was presented by Pilehvari et al [12]. A new unified rheological model was detailed in the papers which have been written by Zamora and Power [13]. The rheological parameters for this model are the plastic viscosity, yield point, and yield stress. The effect of two polymers on the rheological properties of KCl/polymer type drilling fluids was investigated by Versan and Tolga [14]. Moreover, Bingham Plastic, Power Law, Casson, Herschel Bulkley, and Robertson Stiff models for modeling rheology properties have been used by Versan and Tolga [14]. It was found by Kelessidis et al [4] that the Hershel-Bulkley model can effectively correlate the rheological data of several drilling fluids and proposed an improved method for the determination of the Herschel-Bulkley model parameters. In addition, the Golden Section search methodology was used by Kelessidis et al [4] to estimate the best value of the yield stress while the fluid consistency and fluid behavior indices are determined using linear regression on the transformed rheometric data. The effects of temperature on the rheological properties of two types of high-density water-based drilling fluids under high temperature and high pressure with a fann 50 SL rheometer were examined using Wang et al [15]. Four rheological models, the Bingham plastic, Power Law, Casson, and Herschel-Bulkley models were employed to fit the rheological parameters. The cubic splines were used by Bui and Tutuncu [16] to fit the experimental data obtained from field viscometers. The results showed that a very good fit to experimental data in comparison to Bingham, power law, and Herschel-Bulkley models was provided by the proposed model. The effect of black myrobalan rheological properties of flocculated bentonite mud was investigated by Neshat and Shadizadeh [17]. Moreover, Bingham Plastic, Herschel Bulkley, and Robertson Stiff models for modeling rheological properties were used by Neshat and Shadizadeh [17]. The results showed that Herschel- Bulkely and Robertson-Stiff models were more accurate than Bingham plastic in describing bentonite dispersion including black myrobalan. A rigorous predictive model for estimating drilling fluid density at wellbore conditions was suggested by Ahmadi et al [18]. Also, a couple of particle swarm optimization (PSO) and artificial neural network (ANN) were utilized to suggest a high-performance model for prediction of the drilling fluid density.

In this study, the Newtonian model and five major non-Newtonian rheological models were investigated to determine more alternatives for selecting the best model which represents accurately the shear stress-shear rate relationship for drilling fluids. These models are the Bingham, Power law, Herschel-Bulkley, Casson, and Robertson-Stiff. To determine the best rheological model fitting the behavior of the drilling fluids, the graph of the shear stress versus shear rate data of the drilling fluid was plotted. In this study, it was assumed that the model which gives the lowest mean absolute average percent error (EMAP) between the measured and calculated shear stresses is the best model for the drilling fluids. Finally, the new equation was proposed to predict the shear stress for six oil-based drilling fluids used in National Iranian South Oilfields Company.

Theory

The rheological behavior of drilling fluids is very complex. Yield point, apparent viscosity, plastic viscosity, and gel points are the common rheological properties of the drilling fluid. Rheological models intend to provide assistance in characterizing the flow of fluid. Rheological models are mathematical equations used to predict the fluid behavior across a wide range of shear rates [19]. Commonly used model completely describes the rheological characteristics of drilling fluids over its entire shear-rate range. The combination of knowledge of rheological models and practical experience is necessary to fully understand the fluid performance. A plot of shear stress versus shear rate (rheogram) is often used to graphically depict a rheological model.

Newtonian Model

Newtonian fluids follow a simple relationship between shear stress and shear rate (Equation 1). Their viscosities are constant as described by the slope of the line on a linear plot of shear stress versus shear rate (Figure 1). An equation describing a Newtonian fluid is given as:

$$\tau = \mu \dot{\gamma} \quad (1)$$

When the shear stress (τ) of a Newtonian fluid is plotted against the shear rate (γ) in linear coordinates, a straight line through the origin is resulted. The Newtonian viscosity (μ) is the slope of this line [20].

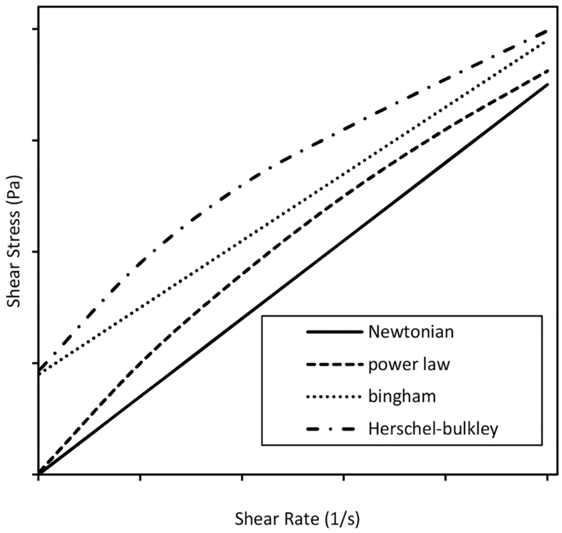


Figure 1: Rheograms of Newtonian, Bingham, Power Law, and Herschel-Bulkley model.

Bingham Plastic Model

This model describes fluids in which the shear stress/shear rate ratio are linear as the specific shear stress has being exceeded. Two parameters: plastic viscosity and yield point are used to describe this model. A rheogram of the Bingham plastic model on rectilinear coordinates is a straight line that intersects the zero shear-rate axes at a shear stress greater than zero (yield point) (Figure 1). The basic Bingham plastic equation is given as:

$$\tau = \tau_B + \mu_B \dot{\gamma} \qquad |\tau| \succ |\tau_B|$$
$$\dot{\gamma} = 0 \qquad |\tau| \prec |\tau_B| \tag{2}$$

where τ_B and μ_B are defined as the yield stress and plastic viscosity respectively [14,21].

Power Law Model

The Power Law is used to describe the flow of shear thinning or pseudoplastic drilling fluids. This model describes fluids in which the rheogram is a straight line when plotted on a log-log graph (Figure 2). Such a line has no intercept, so a true power law fluid does not exhibit a yield stress.

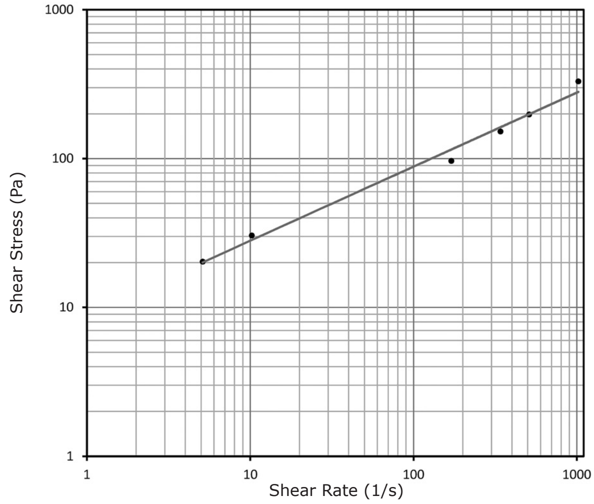


Figure 2: log-log graph of Power Law model.

The mathematical relationship of Power Law model is expressed as:

$$\tau = m \dot{\gamma}^n \tag{3}$$

where m and n are known as the consistency coefficient and flow index respectively [13].

$$log\,\tau = \log m + n \log \dot{\gamma} \tag{4}$$

$$n = \frac{N \sum\left(\log \dot{\gamma} . \log \tau\right) - \sum\left(\log \dot{\gamma}\right) \times \sum\left(\log \tau\right)}{N \sum\left(\log \dot{\gamma}\right)^2 - \left(\sum \ \log \dot{\gamma}\right)^2} \tag{5}$$

$$m = \exp[\frac{\sum\left(\log \tau\right) - n \sum\left(\log \dot{\gamma}\right)}{N}] \tag{6}$$

where N is data number. This procedure is employed for the parameter calculations of the power law model.

m is a measure of the consistency of the fluid, the higher the value of m the more viscous the fluid; moreover, *n* is a measure of the degree of non-Newtonian behavior of the fluid.

Herschel-bulkley Model

This model is used to describe the flow of pseudoplastic drilling fluids which require a yield stress to initiate flow. A rheogram of shear stress minus yield stress versus shear rate is a straight line on log-log coordinates (Figure 3). This model is widely used because it describes the flow behavior of most drilling fluids, and it includes a yield stress value and the Bingham plastic model and power law as special cases [14,22,23].

$$\tau = \tau_H + \mu_H \dot{\gamma}^n \qquad |\tau| \succ |\tau_H|$$
$$\dot{\gamma} = 0 \qquad |\tau| \prec |\tau_H| \tag{7}$$

where τ is the magnitude of the stress tensor, τ_H is the yield stress, $\dot{\gamma}$ is the magnitude of the rate of strain, μ_H is a consistency index, and n is the flow index.

Since this is a three-parameter model, an initial calculation of τ_H is required for other parameter calculations. τ_H is calculated as [14]:

$$\tau_H = \frac{\tau^{*2} - \tau_{min} \times \tau_{max}}{2\tau^* - \tau_{min} - \tau_{max}} \tag{8}$$

where τ* is the shear stress value corresponding to the geometric mean of the shear rate, γ* [14].

$$\gamma^* = \sqrt{\gamma_{min} \times \gamma_{max}} \tag{9}$$

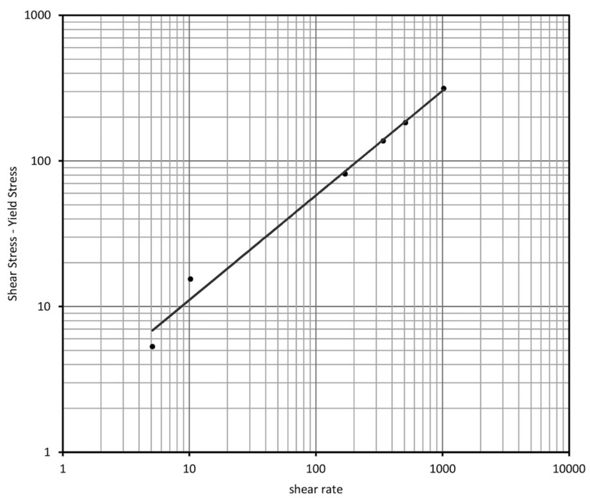


Figure 3: log-log graph of Herschel-Bulkley model.

Casson Model

Casson model is a two-parameter model which is widely used in various industries. This model was represented by Casson to predict the behavior of oil suspensions. The mathematical relationship of Casson model is expressed as [24]:

$$\tau^{1/2} = \tau_C^{\ 1/2} + \left(\mu_C \dot{\gamma}\right)^{1/2} \qquad |\tau| \succ |\tau_C|$$
$$\dot{\gamma} = 0 \qquad |\tau| \prec |\tau_C| \tag{10}$$

Robertson-Stiff Model

Robertson and Stiff [6] developed a general model to describe the rheological behavior of drilling fluids and cement slurries. The basic equation is given as [6]:

$$\tau = m\left(\dot{\gamma}_y + \dot{\gamma}\right)^n \tag{11}$$

where m, n, and $\dot{\gamma}_y$ are the model parameters. Also, m and n can be considered similar to the parameters m and n of the Power-law model. The third parameter $\dot{\gamma}_y$ is a correction factor for the shear rate. Robertson – Stiff model is a three-parameter model and an initial calculation of $\dot{\gamma}_y$ is required for other parameter calculations. $\dot{\gamma}_y$ is calculated as [6]:

$$\dot{\gamma}_y = \frac{\dot{\gamma}_{min} \times \dot{\gamma}_{max} - \dot{\gamma}^{*2}}{2\dot{\gamma}^* - \dot{\gamma}_{min} - \dot{\gamma}_{max}} \tag{12}$$

where $\dot{\gamma}^*$ is the shear rate value corresponding to the geometric mean of the shear stress, τ*. The geometric mean of the shear stress (τ*) is then calculated from [6]:

$$\tau^* = \sqrt{\tau_{min} \times \tau_{max}} \tag{13}$$

Proposed Equation

The determination of drilling fluid rheological properties is important in the calculation of circulating hydraulics, and hole cleaning efficiency. Therefore, if we are able to determine accurate relationship between shear rate and shear stress; it will be a direct impact over the economics of exploitation projects for wellbore hydraulic management. For the proposed equation, a non-linear regression is used. We attempted to fulfill the following requirements in the development of the proposed equation:

1. The equation should fit closely to the experimental data;
2. The equation should exhibit the yield pseudo plastic character and if possible, should be a general case of the former ones;
3. The equation should contain minimum number of parameters; moreover,
4. The appropriate parameters should be easily determined.

It is evident that most available rheological models are originally developed as empirical correlations. Therefore, we attempted proposed new equation with minimum number of parameters using experimental data. After investigated various equations (such as sinus, exponential, power, liner, logarithmic, polynomial), the follow equation has good results.

$$\begin{cases} \tau^n = \tau_p{}^n + \left(\mu_p \dot{\gamma}\right)^n & \left|\tau\right| \succ \left|\tau_p\right| \\ \dot{\gamma} = 0 & \left|\tau\right| \prec \left|\tau_p\right| \end{cases} \quad (14)$$

where τ_p, μ_p, and n are the rheological coefficient characteristics of the fluid. To minimize the number of parameters and particularly for drilling applications, 20 values (0.05, 0.1, 0.15 . . . 1) investigated for n, and the most appropriate n was selected. It was assumed that the value of 'n' which gives the lowest mean absolute average percent error between the measured and calculated shear stresses is the best value of 'n' for the proposed equation.

EXPERIMENTAL PROCEDURES

Different drilling fluids are available and they are classified according to the base fluid in the mud. The drilling mud can be broadly classified as water based mud (WBM), oil based mud (OBM), synthetic based mud (SBM), emulsions, invert emulsions, air, foam fluids, and etc [25,26]. The type of drilling fluid to be used is selected based on the properties of the formation being drilled, environmental considerations, and cost.

Table 1: Component of oil based for 100 bbl drilling mud.

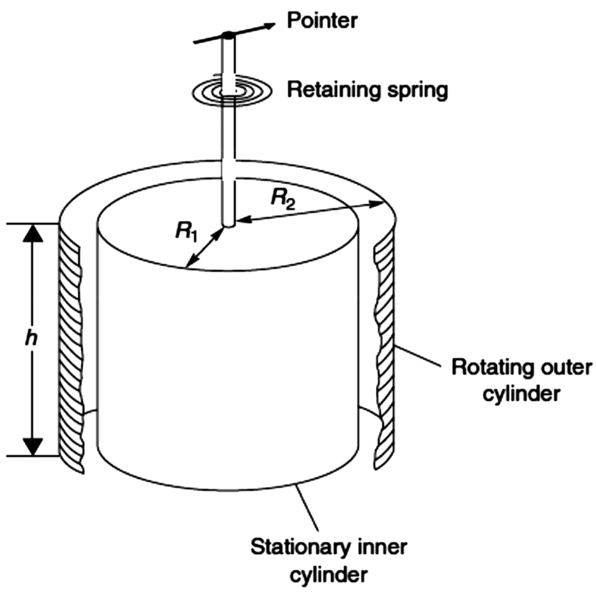
Material	Fluid A	Fluid B	Fluid C	Fluid D	Fluid E	Fluid F
Density (pcf)	77.5	64	78	70	75	81
Gasoil (bbl)	60	68	60	65	62	58
F.L-C (SX)	20	18	20	18	20	20
Primary Emulsion (DR)	2	1	2	1	2	2
Lime (SX)	20	18	20	18	20	20
Water $CaCl_2$ (bbl)	21	24	21	23	21	20
secondary Emulsion (DR)	0.8	0.8	0.8	0.8	0.8	0.8
Viscosities (SX)	2	1	2	1-2	1-2	2
L.S.P (TN)	4-5	2	4-5	3	4	5

Oil-based drilling fluids have excellent properties such as stability, lubricity, and temperature stability. Though, the excessive use of oil-based drilling fluids harms the environment [17]. Oil base mud is composed primarily of diesel oil or mineral oil and additives [27]. Oil-based drilling fluids (drilling muds) are used to meet demanding applications, including those requiring the highest degree of thermal stability [28]. In the present study, six oil-based muds drilling used in Southwestern Iranian oilfields were investigated. The chemical composition and weight of oil-based mud is given in Table 1.

Furthermore, Fann 35 Viscometer was used for the rheological analysis of drilling fluids (Figure 4). The rotor of this rheometer is driven by an electric motor with six standard rotational speeds (that is, 3, 6, 100, 200, 300, and 600 rpm). Corresponding to the rotor rotation, the dial readings of Fann Viscometer were measured in degrees. The standard dimensions of Fann35 Viscometer are: bob radius (r_1) 0.017245m, rotor radius (r_2) 0.018415m, bob height (h) 0.038 m, and spring constant (k) 3.87×10^5 N/m. For consistent Fann35 Viscometer readings, the experiments were repeated three times daily. Dial reading (that is, bob deflection) measures the torque, which is accurately converted using Equation 15 to the shear stress [1].

The test fluid is contained in the annular space or shear gap between the cylinders. Rotation of the outer cylinder at known velocities is accomplished through precision gearing. The viscous drag exerted by the fluid creates a torque on the inner cylinder or bob. This torque is transmitted to a precision spring where its deflection is measured and then related to the test conditions and instrument constants.

(a)



(b)

Figure 4: (a) Fann viscometer Model 35SA, (b) Schematic diagram of viscometer.

To determine the rate of shear between two vertical coaxial cylinders, the outer (cup) one of which is rotating with constant angular velocity and the inner cylinder (bob) is stationary, following assumptions are made: (i) Flow in the annular region between two coaxial cylinders is purely steady, laminar and tangential, isothermal, incompressible. (ii) There is no flow in the radial and axial direction. (iii) There is no pressure gradient in θ-direction. (iv) The fluid is time-independent. (v) There is no slip at the wall. With these assumption the shear stress at the inner cylinder wall is given as [1]:

$$\tau = \frac{k\theta}{2\pi r_1 h} \qquad (15)$$

And the shear rate at the inner cylinder wall is given as [1]:

$$\dot{\gamma} = \frac{4\pi N_F}{60\left[1-\left(\frac{r_1}{r_2}\right)^2\right]} \qquad (16)$$

where k is spring constant (N/m), θ is dial reading (degree), r_1 is bob radius (m), h is bob height (m), N_F is rotor rotation speed (rpm), and r_2 is rotor radius (m).

To estimate the mean absolute percent error (E_{MAP}), a statistical method has been used [29]. This method is used based on the measured and calculated shear stresses:

$$E_{MAP} = \frac{100}{N}\sum\left|\frac{\tau_{measured}-\tau_{calculated}}{\tau_{measured}}\right| \qquad (17)$$

One set of data of drilling fluid has been used to illustrate the accuracy of this approach for selecting the best rheological model, one with the lowest E_{MAP} value.

The standard deviation is a measure which is used to quantify the amount of variation or dispersion of a set of data. For a finite set of numbers, the standard deviation is found by taking the square root of the average of the squared deviations of the values from their average value. The standard deviation is given as [29]:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i-\bar{x})^2} \qquad (18)$$

where $\bar{x} = \frac{1}{N}\sum_{i=1}^{N} x_i$

RESULTS AND DISCUSSIONS

Six drilling mud samples were used to evaluate the performance of the rheological models. The experimental data obtained from the viscometer were used to determine the values of shear stress and shear rate. The results of the viscometer data are shown in Table 2. The rheological data were obtained from various drilling holes.

Table 2: Rheological data from viscometer.

Drilling Fluids	θ_3	θ_6	θ_{100}	θ_{200}	θ_{300}	θ_{600}	PV* (cP)	YP** ($lb_f/100ft^2$)
Fluid A	4	6	19	30	39	65	26	12
Fluid B	2	3	9	16	21	37	16	6
Fluid C	17	19	40	56	62	91	30	21
Fluid D	5	6	19	28	38	62	19	8
Fluid E	3	4	16	27	34	56	24	12
Fluid F	6	7	23	38	50	84	36	17

*Plastic Viscosity

**Yield Point

Twenty values (0.05, 0.1, 0.15 . . . 1) for 'n' have been Investigated to evaluate value of 'n' for proposed equation (Equation 14). It was assumed that the value of 'n' which gives the lowest mean absolute average percent error between the measured and calculated shear stresses is the best value of 'n' for the proposed equation. The percent errors for different values of 'n', for each drilling fluid are shown in Figure 5. The results show that in the interval 0.35 to 0.5, the smallest amount of 'n' for the drilling fluids which were studied occurs. To summarize the error of 'n' parameter, an attempt is made to calculate the average percent error for each 'n' parameter. Average percent errors for each 'n' parameter are shown in Figure 6. The results show that n=0.4 (0.4=2/5) is the best value for n. Therefore, the proposed equation is as follows:

$$\tau^{2/5} = \tau_p^{2/5} + \left(\mu_p \dot{\gamma}\right)^{2/5} \qquad |\tau| \prec |\tau_p|$$
$$\dot{\gamma} = 0 \qquad |\tau| \prec |\tau_p| \tag{19}$$

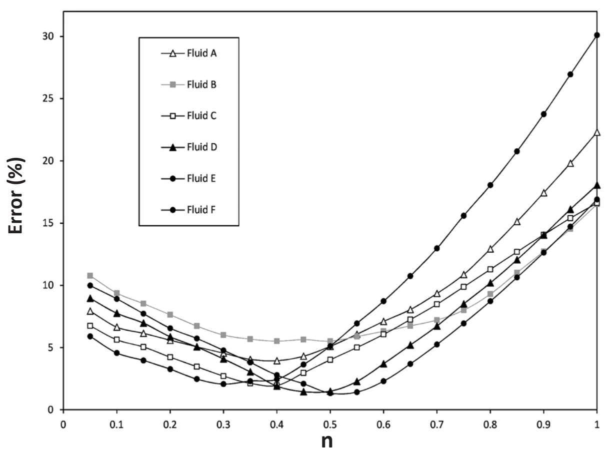


Figure 5: The percent errors for different values of 'n', for each drilling fluid.

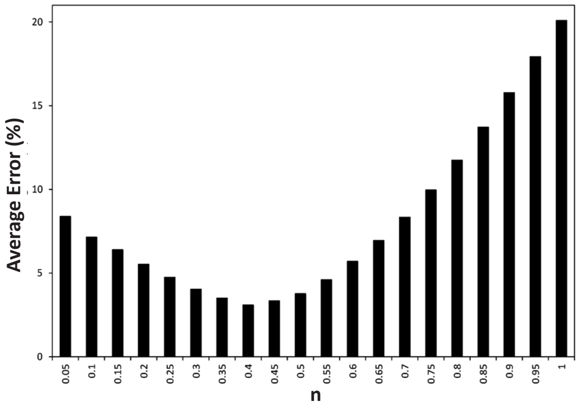


Figure 6: the average percent error for each 'n' parameter.

The viscometer data were used to calculate the parameters of the Newtonian, Bingham, power law, Herschel-Bulkley, Casson, Robertson-Stiff, and proposed models. These seven models have been applied to the reported data set. For each rheogram, the best fit of the data was computed. For the Newtonian model and Bingham plastic fluid, a linear least square method is used, while for the Power Law, Herschel-Bulkley, Casson, Robertson–Stiff models, and proposed equation, a non-linear regression was used. The rheological parameters of each model are given in Table 3. The models were then applied to the original shear rate data to calculate shear stresses, which were compared to the experimental shear stresses.

The plot of experimental data and shear stress predicted by each models versus shear rate for fluid A (oil based mud 77.5 pcf) is shown in Figure 7. These observations are quantified in Table 4 in which the mean absolute percent error and the average standard deviation for each model are listed. However, the proposed equation had the smallest average percent error and the smallest standard deviation, thus indicating the best overall fit. The proposed equation was used to calculate the shear stresses in which an average percent error of 3.95 was obtained; in addition, compared to 5.10% which was obtained in using Casson model and 5.15% using the Herschel-Bulkley model, Newtonian model had the largest average percent error.

Table 3: Constant parameters for rheological models.

Rheological Models	Constant parameters	Fluid A	Fluid B	Fluid C	Fluid D	Fluid E	Fluid F
Newtonian model	μ (pois)	0.35	0.19	0.53	0.33	0.30	0.45
Bingham Plastic	τ_B (lb_f/100 ft^2)	7.306	3.296	24.415	7.663	5.892	8.889
	μ_B (pois)	0.30	0.17	0.36	0.28	0.26	0.39
Power Law	m ($lb_f.s^n$/100 ft^2)	1.863	0.890	10.161	2.254	1.220	2.521
	n	0.497	0.514	0.305	0.459	0.543	0.486
Herschel-Bulkley	τ_H (lb_f/100 ft^2)	3.122	1.692	15.998	4.442	2.368	5.497
	μ_H ($lb_f.s^n$/100 ft^2)	0.447	0.165	0.758	0.272	0.261	0.240
	n	0.717	0.775	0.681	0.783	0.783	0.849
Casson	τ_C (lb_f/100 ft^2)	3.076	1.360	15.539	3.580	2.084	3.893
	μ_C (pois)	0.20	0.12	0.17	0.18	0.19	0.26
Robertson-Stiff	m ($lb_f.s^n$/100 ft^2)	0.574	0.157	3.164	0.510	0.374	0.395
	γ_y (s^{-1})	17.13	27.02	31.68	25.29	15.13	31.45
	n	0.686	0.789	0.489	0.695	0.731	0.778
Proposed equation	τ_P (lb_f/100 ft^2)	2.172	0.952	12.947	2.634	1.387	2.797
	μ_P (pois)	0.15	0.09	0.10	0.13	0.15	0.20

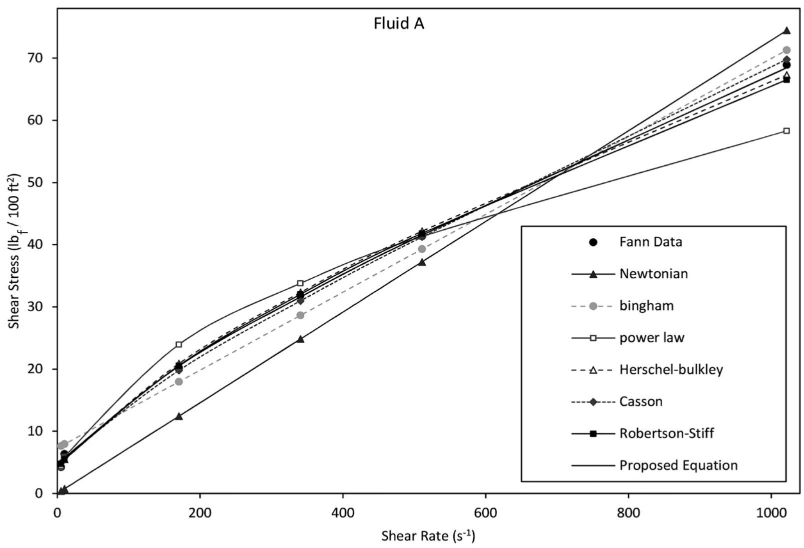


Figure 7: Comparison of rheological models for fluid A.

Table 4: Results of percent error for fluid A.

Shear Rate (s^{-1})	Newtonian model	Bingham Plastic	Power Law	Herschel-Bulkley	Casson	Robertson-Stiff	Proposed equation
5.1069	91.22	79.78	1.25	7.51	16.27	12.27	9.96
10.2138	88.30	24.88	7.09	13.78	8.40	13.75	10.29
170.23	38.41	10.80	18.77	3.67	1.75	1.98	1.63
340.46	21.99	9.98	6.16	1.61	2.63	0.63	0.73
510.69	9.99	4.96	0.11	1.98	0.27	1.11	0.41
1021.38	8.01	3.45	15.42	2.34	1.29	3.49	0.69
Ave. error. (%)	42.99	22.31	8.13	5.15	5.10	5.54	3.95
Standard deviation	34.53	26.62	6.87	4.34	5.64	5.37	4.38

The rheogram for fluid B (oil based mud 64 pcf) is shown in Figure 8. Table 5 shows the average percent error and the average standard deviation for each model. The Proposed equation and Casson model were used to calculate the shear stresses and an average percent error of 5.52 was obtained.

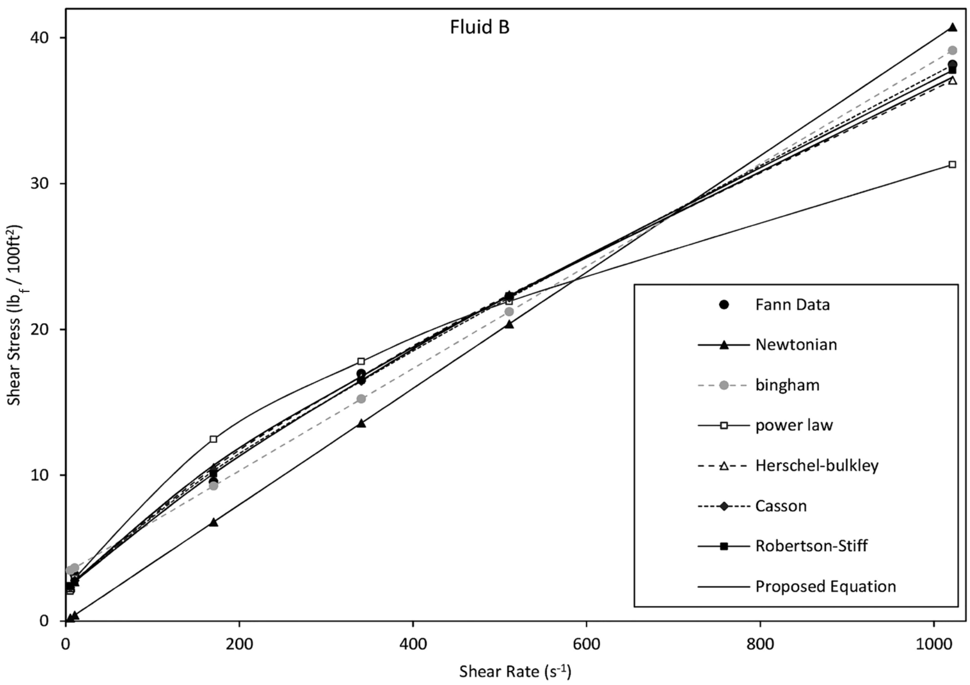


Figure 8: Comparison of rheological models for fluid B.

Table 5: Results of percent error for fluid B.

Shear Rate (s^{-1})	Newtonian model	Bingham Plastic	Power Law	Herschel-Bulkley	Casson	Robertson - Stiff	Proposed equation
5.1069	90.39	63.95	3.07	7.28	9.01	13.84	4.30
10.2138	87.19	14.93	7.73	15.44	12.62	14.74	13.47
170.23	28.85	2.86	30.61	10.25	8.07	5.91	11.89
340.46	19.95	10.15	4.91	0.97	2.91	2.66	1.14
510.69	8.52	4.72	1.54	0.51	0.44	0.14	0.03
1021.38	6.73	2.52	17.98	2.83	0.08	1.07	2.30
Ave. error. (%)	40.27	16.52	10.98	6.21	5.52	6.39	5.52
Standard deviation	35.10	21.66	10.27	5.39	4.68	5.87	5.24

Fluid C (oil based mud 78 pcf) was evaluated using Model 35 Fann viscometer, thus the results are shown in Figure 9 and Table 6. The results show that the Proposed equation provides a very good fit to experimental data. The Proposed equation was used to calculate the shear stresses, in which an average percent error of 1.96 was attained compared to 2.41 and 3.64% which were obtained in using the Robertson-Stiff model and Herschel-Bulkley model respectively.

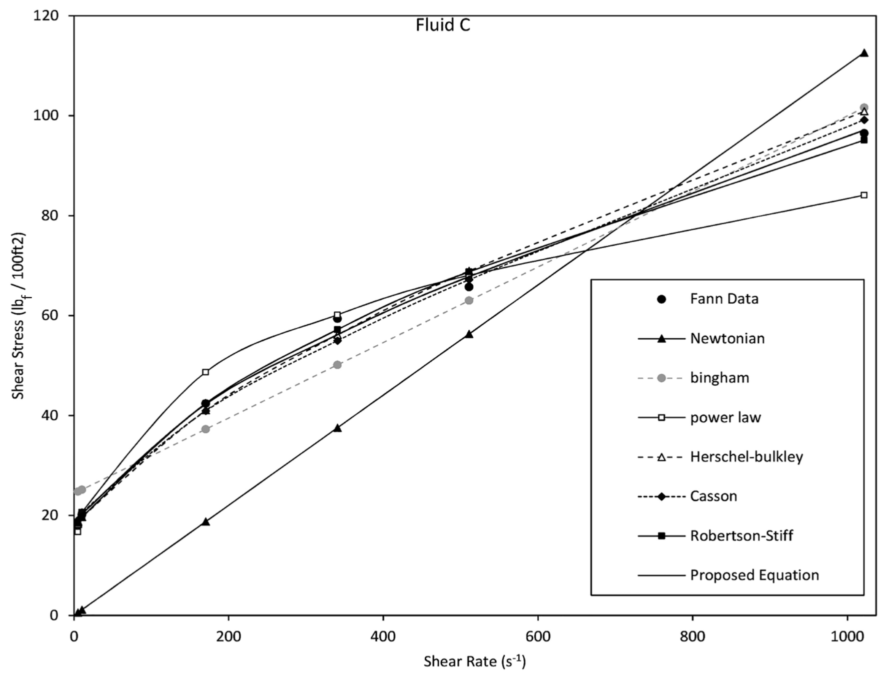


Figure 9: Comparison of rheological models for fluid C.

Table 6: Results of percent error for fluid C.

Shear Rate (s^{-1})	Newtonian model	Bingham Plastic	Power Law	Herschel-Bulkley	Casson	Robertson-Stiff	Proposed equation
5.1069	96.88	37.58	7.32	1.51	5.82	2.32	1.60
10.2138	94.41	25.01	2.45	2.29	2.48	2.44	0.60
170.23	55.74	12.10	14.78	3.20	3.47	0.01	0.36
340.46	36.78	15.54	1.29	5.40	7.38	3.69	5.43
510.69	14.34	4.14	3.53	4.88	2.20	4.58	3.11
1021.38	16.72	5.33	12.86	4.56	2.79	1.44	0.66
Ave. error. (%)	52.48	16.61	7.04	3.64	4.02	2.41	1.96
Standard deviation	33.47	11.65	5.17	1.42	1.92	1.48	1.80

A comparison of the rheological models for fluid D (oil based mud 70 pcf) is presented in Figure 10. The Results of percent error for each model is given in Table 7. This result shows that the Casson model is the best model to represent the rheological properties for this oil-base mud and this is closely followed by the proposed equation, Herschel-Bulkley and Robertson-stiff models, respectively.

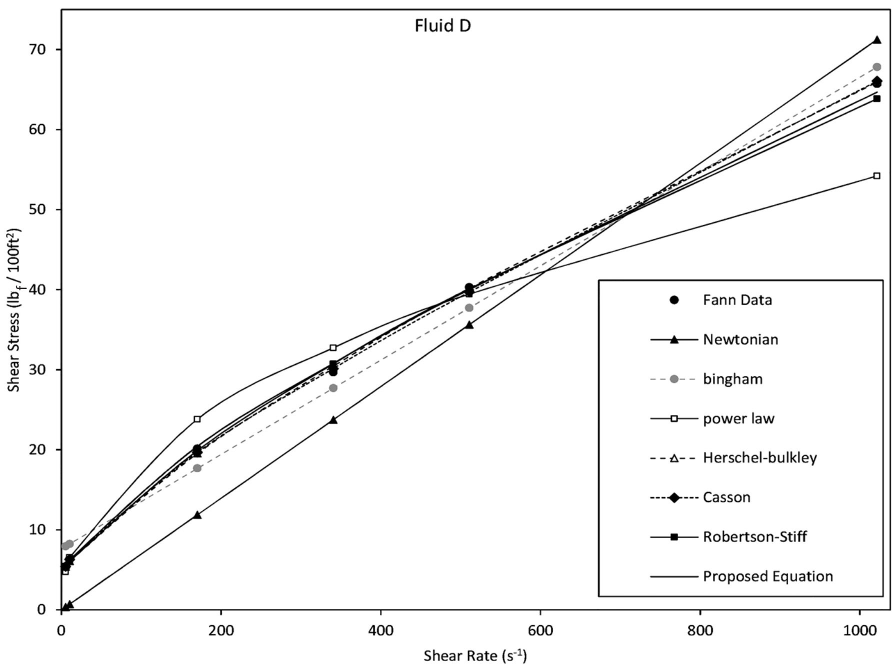


Figure 10: Comparison of rheological models for fluid D.

Table 7: Results of percent error for fluid D.

Shear Rate (s^{-1})	Newtonian model	Bingham Plastic	Power Law	Herschel-Bulkley	Casson	Robertson-Stiff	Proposed equation
5.1069	93.28	50.20	10.16	2.09	2.66	2.92	2.05
10.2138	88.80	29.89	2.91	3.93	0.53	4.46	1.97
170.23	41.06	12.20	18.22	2.89	2.24	1.25	1.35
340.46	20.01	6.66	10.27	2.61	1.61	3.55	3.73
510.69	11.59	6.34	2.13	0.26	1.44	0.49	0.73
1021.38	8.37	3.15	17.54	0.32	0.50	2.89	1.62
Ave. error (%)	43.85	18.07	10.21	2.02	1.5	2.59	1.91
Standard deviation	34.97	16.82	6.28	1.34	0.80	1.34	0.93

The plot of experimental data and shear stress predicted by each models versus the shear rate for fluid E (oil based mud 75 pcf) is shown in Figure 11. Table 8 shows the mean absolute percent error and the average standard deviation for each model. The proposed equation had the smallest average percent error indicating the best overall fit. In calculating the shear stresses using the proposed equation, an average percent error of 2.45 was attained compared to 3.23 and 3.37% observed in using the Robertson-Stiff and Herschel-Bulkley model respectively. Newtonian model and Bingham model have the largest average percent error.

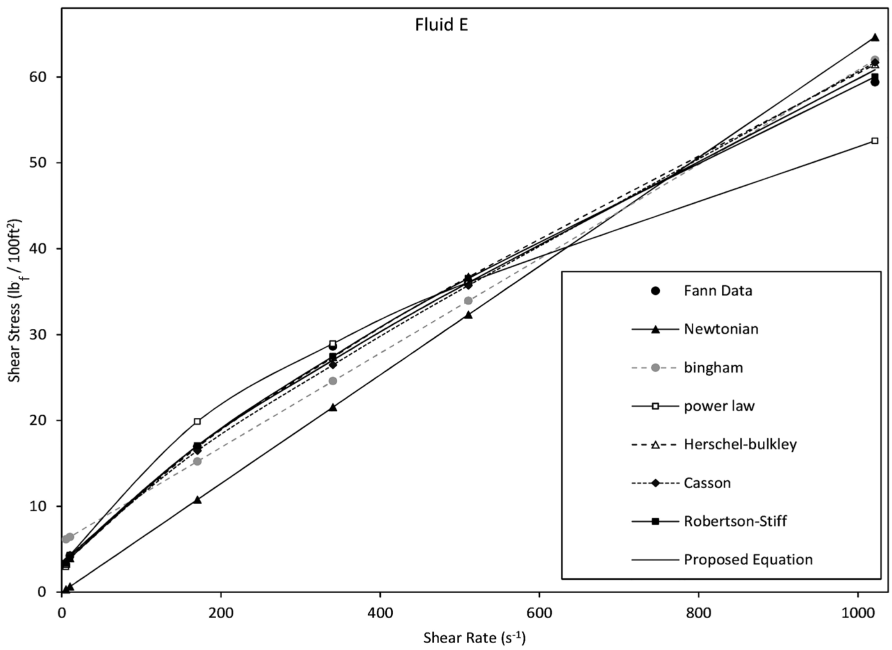


Figure 11: Comparison of rheological models for fluid E.

Table 8: Results of percent error for fluid E.

Shear Rate (s^{-1})	Newtonian model	Bingham Plastic	Power Law	Herschel-Bulkley	Casson	Robertson -Stiff	Proposed equation
5.1069	89.84	94.02	6.98	3.81	13.13	6.21	5.63
10.2138	84.76	52.13	1.64	6.29	2.48	6.10	0.54
170.23	36.51	10.16	17.08	0.39	2.78	0.52	0.43
340.46	24.75	14.10	1.09	4.39	7.52	4.10	5.65
510.69	10.36	5.85	0.05	1.83	0.90	1.37	0.00
1021.38	8.85	4.40	11.50	3.51	3.92	1.07	2.44
Average error (%)	42.51	30.11	6.39	3.37	5.12	3.23	2.45
Standard deviation	33.02	32.85	6.21	1.87	4.12	2.36	2.38

Figure 12 shows the rheological behavior of each model for fluid F (oil based mud 81 pcf). This figure also shows the comparison between the measured data and the calculated data for all models. Table 9 shows the mean absolute percent error and the average standard deviation for each model.

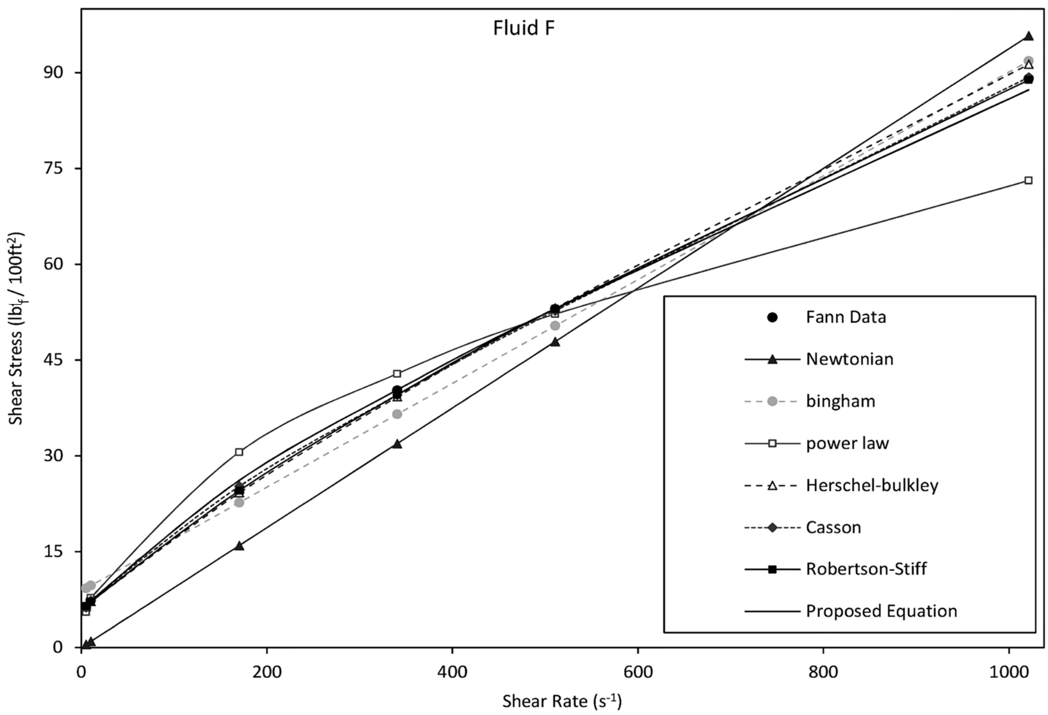


Figure 12: Comparison of rheological models for fluid F.

Table 9: Results of percent error for fluid F.

Shear Rate (s^{-1})	Newtonian model	Bingham Plastic	Power Law	Herschel-Bulkley	Casson	Robertson-Stiff	Proposed equation
5.1069	92.47	46.23	12.48	1.43	1.60	2.26	5.94
10.2138	87.10	30.93	5.06	2.75	0.24	2.96	1.41
170.23	34.55	6.85	25.50	0.57	3.58	0.74	7.30
340.46	20.77	9.30	6.38	2.53	1.79	1.85	0.10
510.69	9.68	4.98	1.54	0.26	0.56	0.01	0.02
1021.38	7.53	3.14	17.91	2.55	0.29	0.23	1.95
Ave. error (%)	42.02	16.90	11.48	1.68	1.34	1.34	2.79
Standard deviation	34.93	16.06	8.21	1.00	1.17	1.09	2.83

The values for the mean absolute average percent error are given for each model in Figure 13. This figure shows that the Newtonian model is not perfect for modeling the behavior of oil-base mud. Also, the results show that the use of Power law and Bingham plastic resulted wrong prediction of shear stress for oil-base mud, while these two models have been used for drilling process in South-western Iranian Oilfields.

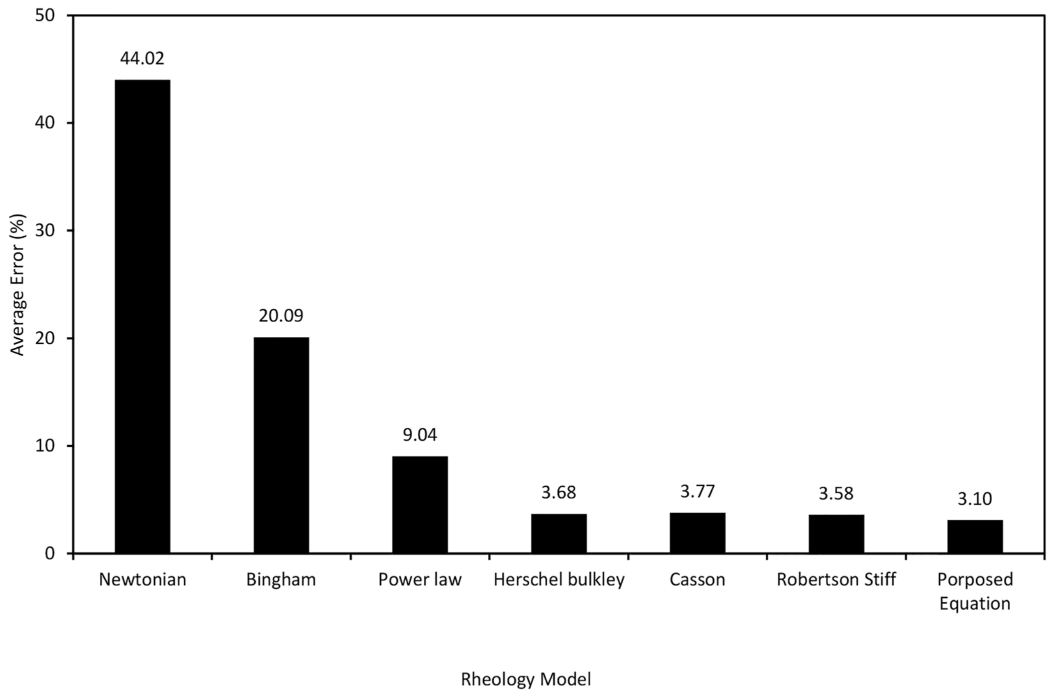


Figure 13: Comparison between mean absolute average percent errors for all models.

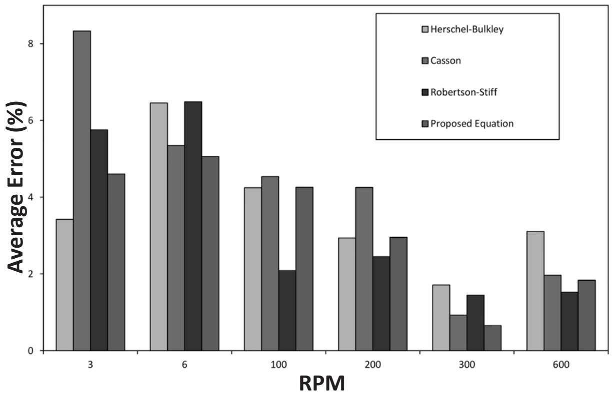


Figure 14: absolute percent errors for Herschel-Bulkley, Casson, Robertson-stiff and proposed equation with different velocity.

Figure 13 shows that the proposed equation is the best model for representation of the rheological properties of oil-base mud, and this is closely followed by Robertson-stiff, Herschel-Bulkley, and Casson models respectively.

Figure 14 shows the results of Herschel-Bulkley, Casson, Robertson-stiff models and the proposed equation with different velocity. It was observed that the percent errors of the rheological models were reduced as the shear rate increases.

CONCLUSIONS

Selection of the best rheological model is of great importance in obtaining correct results for drilling. A simple and direct approach has been presented for selection of the best rheological model for any non-Newtonian fluid according to the lowest EMAP criteria.

The experimental data obtained from the Fann 35 Viscometer were used to determine the values of the shear stress and shear rate. Six oil base mud samples were used to evaluate the performance of the rheological models.

In this study, the rheological models, Newtonian, Bingham plastic, Power law, Herschel-Bulkley, Casson, and Robertson-Stiff were evaluated for accurate representation of the wide range of shear stress/shear rate data. These models were confirmed to describe the rheology of most non-Newtonian fluids, accurately.

The results showed that Robertson-Stiff model had the best prediction of shear stress and viscosity with an absolute average percent error of 3.58. This was followed by Herschel-Bulkley, Casson, Power law, Bingham plastic and Newtonian with the absolute average percent error of 3.68, 3.77, 9.04, 20.09, and 44.02 respectively.

Conclusively, the new equation is proposed to predict the shear stress of six oil-based drilling fluids used in Southwestern Iranian oilfields. By comparing the results obtained with the experimental data, it is revealed that the proposed equation has a good agreement with real shear stress and apparent viscosities with an absolute average percent error of 3.10.

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NOMENCLATURES

ANN	: Artificial Neural Network
EMAP	: Mean Absolute Average Percent Error
NISOC	: National Iranian South Oilfields Company
PSO	: Particle Swarm Optimization

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