Solid State Technology
Vol.63 No.2

NON-NEWTONIAN RHEOLOGY MEASUREMENT BY USING DIFFERENT TYPE OF RHEOLOGY INSTRUMENTS

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Abstract

A non-Newtonian fluid is a fluid whose flow properties cannot be defined by a single constant named viscosity. Many drilling fluids, polymer solutions and molten polymers are non-Newtonian Fluids in a Newtonian fluid, the relation between the shear stress and the shear rate is linear and the constant of proportionality being the coefficient of viscosity.

Analysis of fluid flow operations requires material-specific information such as the relation between density, pressure, and temperature which is collectively known as constitutive relations. Rheology is the science explained the suitable constitutive equations for description of the behavior of Non-Newtonian fluids.

Although the non-Newtonian behavior of many fluids has been known for a long time, the science of Rheology is, in many concepts, still in its beginning, and new phenomena are constantly being discovered and new theories proposed.

In this work we apply many of non-Newtonian models (Bingham, Power Law, Herschel – Bulkily model and Ellis model) to measure the Non-Newtonian properties such as consistency index (k), Power law parameter (n), plastic viscosity (μp), yield stress (τo) and other properties. Two fluid samples of Non-Newtonian fluids (fracturing fluid and drilling fluid) were used. Comparing between the results obtained from different models and the evaluation which model are suitable for each of the fluid sample used in this experimental work are also done. The results showed that Power law model is good to analyze the fracturing fluid data and getting good results. Also, the Bingham model was gave acceptable results and easier ways to get the important results for analyzing drilling fluid data.

Key word: Rheology, Non Newtonian, drilling mud, hydraulic fracturing fluid

Received: 20April; Accepted: 29September

introduction

Brief Description of the instruments used:

Bohlin Rheometer

Bohlin Rheometer (as shown in figure (1)) is the only Rheology instrument manufacturer to offer a full range of rotational and Capillary Rheometer - laboratory to process characterization. The range includes Viscometer, Rotational Rheometer, Asphalt Analyzer and Capillary Rheometer.

This instrument (Bohlin Rheometer) have wide ranges of measuring systems, like co-axial cylinder, parallel plate, cone plate, double gap, serrated plate, vane tools, high pressure cell, tapered plugs small sample cell, cup and bob etc. Also can be used for the range but not limited to Polymer, Food, Pharma, Paints, Inks & Industrial coating, cosmetics, plastics, petrochemicals, medical, adhesive, sealants, Surfacent, drilling fluids etc.

Figure(1)Bohlin Rheometer

FANN Model 35 [2]

The FANN® Model 35 viscometer is representing a direct reading viscometer, content variation of speeds.

These instruments have been designed so that viscosity in cp for the Newtonian - fluid and is measured at speed 300 rpm, while the viscosity can be measured at any speed when using multipliers of the dial readings.

Fluid formulation and Preparation:

Received: 20April; Accepted: 29September

Fracturing Fluid Preparation (Bohlin Rheometer):

The guar powder was mixed in water with the help of blender mixer with a concentration of 50 ppg (pounds per gallon). Mixing was done in the morning and was allowed to hydrate for 30 minutes. The experiment with the guar was done. Initial pH of the fluid was 6.84 which were raised to 7.84 before the experiment was done. Temperature reading before experiment was reported as 21.9 ^{o}C.

Drilling Mud Preparation (Fann Viscometer):

1000 ml of the drilling mud fluid was prepared by mixing 500 ml of 10 lbs/bbl Bentonite, and 500 ml of 1.5 lbs. /bbl. Xanthan. Fluid was measured for pH and temperature before the experiment and a pH of 9.82 and temperature of 23.6 ^{o}C was measured.

Experiment Procedure as Followed:

Fracturing Fluid (Bohlin Rheometer):

At the beginning of the test, temperature and pH of the fluid was recorded. Rheology tests were conducted using the C25 bob and cup measuring system of the Bohlin Rheometr. 13 cc of the fluid sample was measured by a syringe and was placed in the cup geometry. Since the test was reach to the specific temperature, temperature control unit was not turned on. The pressure at gauge was read at 40 psi and the computer was then turned on. Bohlin software was then started and Viscometry option was selected. The fluid temperature was noted at 22.7 ^{o}C and the same temperature was input in the software so that Rheology test is done at ambient temperature. Shear rate values consisted of 25 data points in the range from 0.0526 to 1580 sec^{-1}. All data obtained were recorded electronically and saved on a data file for further analysis.

Drilling Mud preparation:

The Temperature and pH of the sample was recorded before the test was started. Spring Number of Fann Viscometer was also waited down for each of the six speed and 12 speed Fann viscometers. The cup was filled up to that line (line at the proper test fluid level) with newly moved drilling fluid. Two types of Fann Viscometers were used in two separate tests. One was 6 speed type and the other one was 12 speed type with different spring number. Six speed viscometer can be run at 3, 6, 100, 200, 300 and 600 RPM, table (1). Twelve speeds viscometer can be run at 0.9, 1.8, 3, 6, 30, 60, 90, 100, 180, 200, 300 and 600 RPM, table (2).

Drilling Mud Preparation:

Received: 20April; Accepted: 29September

1000 ml of the drilling mud fluid was prepared by mixing 500 ml of 10 lbs./bbl. Bentonite and 500 ml of 1.5 lbs./bbl. Xanthan. Fluid was measured for pH and temperature before the experiment and a pH of 9.82 and temperature of 23.6 ^{o}C was measured.

Experimental data gathering

The first experimental was testing the fracturing fluid. The data that were gathered from the Bohlin viscometer at Ph 7.48 and 21.9 C^{o} were recorded electronically and saved on a data file for further analysis as shown in table (3).

Experiment work

The Model 35A and 35SA viscometer are used to test the viscosity of the drilling fluid instruments. In the first test we used the viscometer with six different speeds, by changing the speed of the instrument, recording the value of the dial reading of the viscometer. The speeds of the viscometer ia range from 3 to 600 RPM. The spring number which is used to test the drilling fluid is 1. Data gathered from this viscometer are listed in table (2).

In the second test we used the viscometer with 12 different speeds, by changing the speed of the instrument, recording the value of the dial reading of the viscometer. Their range of this viscometer is from 0.9 rpm up to 600 rpm. Select the specific speed, when setting the speed shift to the high sign or low speed sign. After that start the viscometer on and move the viscometer gear shift knob that position in the center. Data gathered from this viscometer are listed in table (3).

Data Analysis:

Fracturing Fluid (Bohlin Rheometer):

Power Law model

Figures (1) and (2) represent the relationship of Apparent Viscosity vs. Shear Rate and Shear Stress vs. Shear Rate respectively for power law model.

Received: 20April; Accepted: 29September

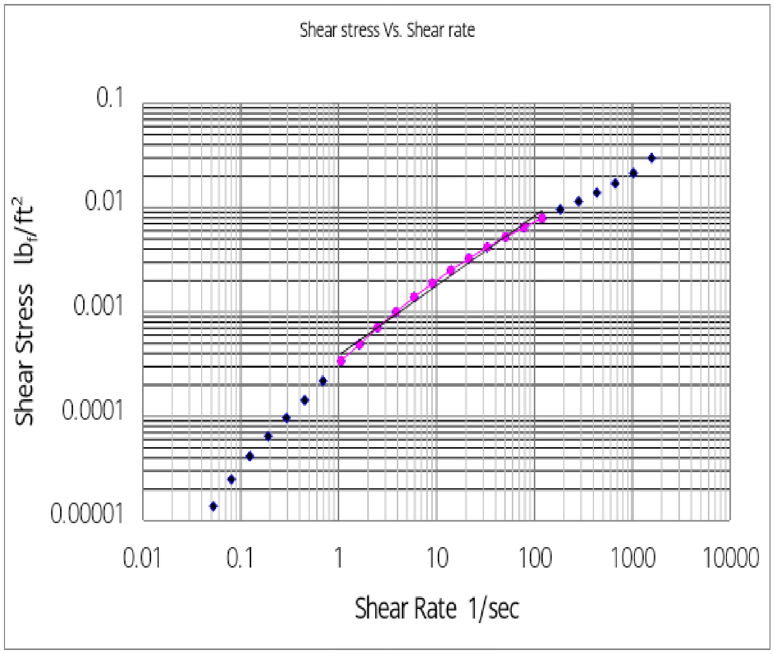


Fig. (1) Relation Between Shear Stress Vs. Shear Rate (Power Law Model)

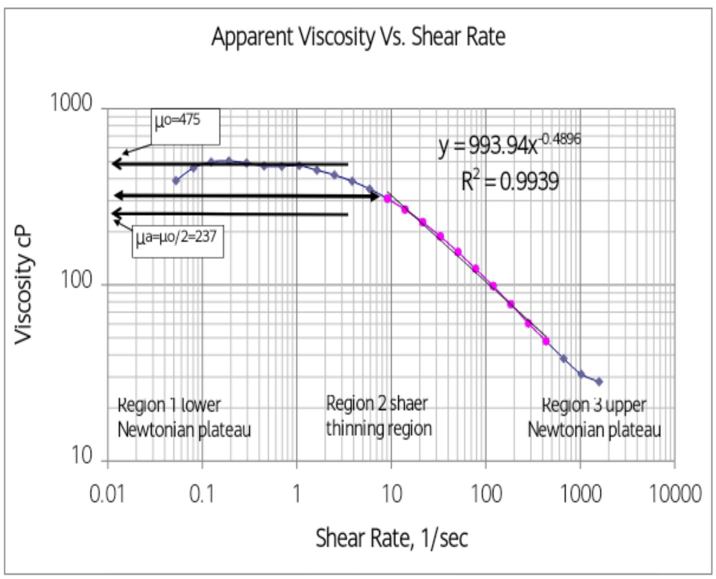


Fig. (2) Relation between Shear stress vs. apparent viscosity

From figure (1) we can get the value of intercept consistency index K lb.sec^n /ft^2 and from the slope we can get slope of the straight line =n.

From figure (2) which is shown the relation between share rate and apparent viscosity, we can get μ_o in the lower Newtonian plateau.

Received: 20April; Accepted: 29September

Ellis model:

$$\tau = \left[\frac{\mu_0}{1 + \left(\tau / \tau_{1/2} \right)^{\alpha - 1}} \right] * \gamma$$

Where:

$\tau_{1/2}$ is the value of τ at which $\mu_a = \mu_o/2$

α-1=is the slope of line obtain when $\left(\frac{\mu o}{\mu a} - 1\right)$ $VS.\left(\frac{\tau}{\tau\, 1/2}\right)$ plotted on log - log scale as shown below:

From **Ellis model**, figure (3) we can get the slope of the line α-1, $\tau_{1/2}$ and applies it in the Ellis model.

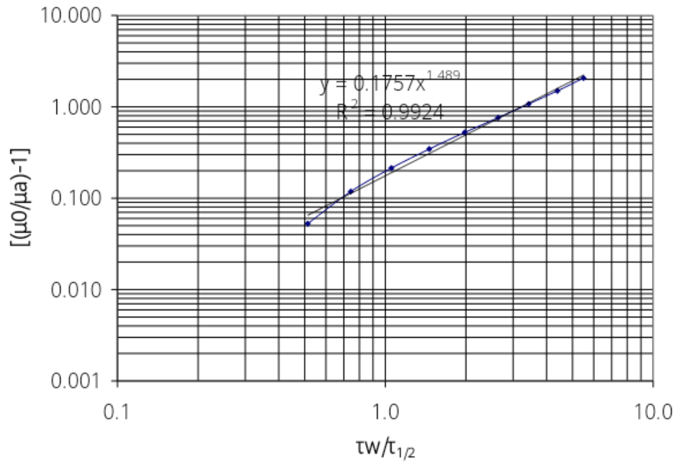


Fig. (3) Ellis Model

Bingham Plastic model

$\tau = \tau_o + \mu_p * \gamma$

Where:

τ_o is the intercept of the line between Shear Stress and Shear Rate on Cartesian scale figure (4) and also the slope of the straight line

Received: 20April; Accepted: 29September

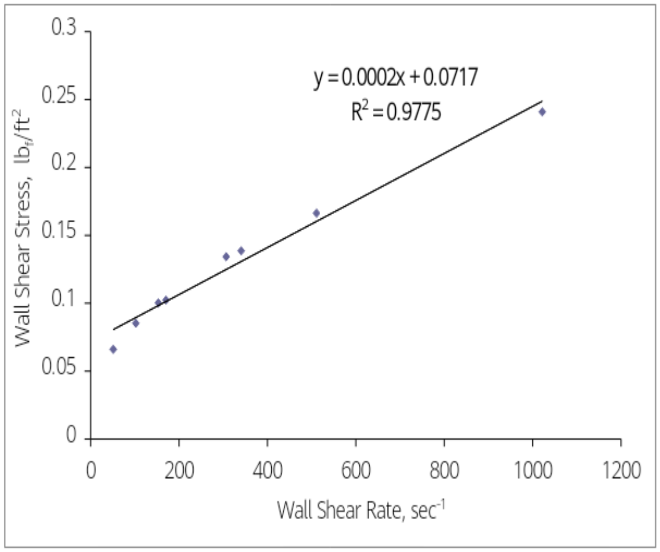


Fig. (4) Bingham model relation between shear stress vs. shear rate

From Bingham plastic model we can get the intercept τ_o and the slope = plastic viscosity μ_p.

<u>Herschel-Bulkley fluid</u>

The fluid in this model can be described by a three-parameter rheological model. A Herschel-Bulkley fluid can be described mathematically as follows

$$\tau = \tau_O + k(\gamma)^{1/m}$$

Where τ =Shear Stress

τ_o=Yield Stress lb/ft^2

K=Consistency Index lb_f. sec^n/ft^2

γ=Shear Rate sec^{-1}

The Herschel-Bulkley equation is preferred to power law or Bingham relationships because it results is more accurate to show the rheological behavior especially when adequate experimental data are available. The yield stress is normally taken as the 3 rpm reading, while the n and K values can be calculated from the 600 or 300 rpm values or graphically figure(5).

Received: 20April; Accepted: 29September

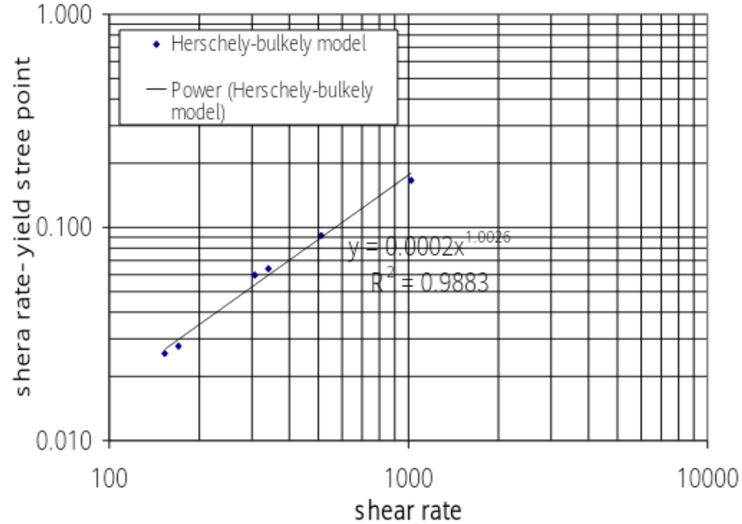


Fig. (5) Herschel–Bulkley model relation between shear stress vs. shear rate

Constitutive equation considers

In the experimental work there are two part, the first part is to test drilling fluid by using Fann 35 viscometer with spring number #1, and #2 The data obtain from the first run is tabled below in table (1)

Table (1) data form Fann 35 model, 6 speeds.

RPM	Dial Reading	Wall Shear Rate	Wall Shear Stress	App. Viscosity
		sec^{-1}	lb_f/ft^2	cp
600	22	1021.8	0.23452	25.92
300	15	510.9	0.1599	36.11
200	13	340.6	0.13858	43.84
100	10	170.3	0.1066	61.08
6	4	10.218	0.04264	234.67
3	2.5	5.109	0.02665	326.94

By Appling Bingham plastic model, plot Shear stress vs shear rate figure (6) on Cartesian scale. From this graph we can calculate the value of yield stress τ_o from intercept and the value of μ_p it is represent the slope.

$$\tau = \tau_o + \mu_p \gamma$$

Bingham plastic. Yield stress τ_o=0.0817 lbf/ft^2

Received: 20April; Accepted: 29September

Plastic viscosity μ_p=0.0002/2.068*10^{-5} =9.6 $lb_f.sec^n/ft^2$.

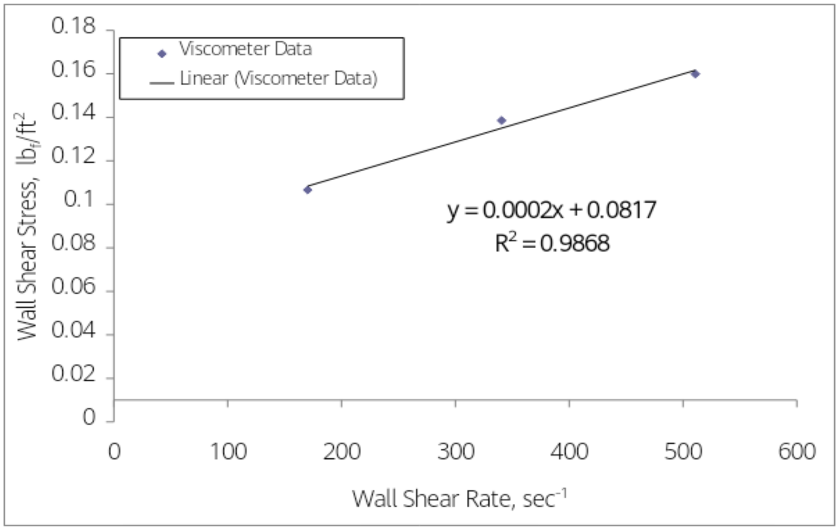


Fig. (6) Bingham Plastic model for first data set for drilling fluid

For the second data for the same drilling fluid tested by Fann 35 model spring number 1/5 (results in table (2)).

Table (2) Fann 35 model, drilling fluid, 12 speeds.

RPM	Dial Reading	Wall Shear Rate	Wall Shear Stress	App. Viscosity
		lb_f/ft^2	lb_f/ft^2	cp
600	113	1021.80	0.241	10.775
300	78	510.90	0.166	15.971
200	65	340.60	0.139	20.105
180	63	306.54	0.134	21.344
100	48	170.30	0.102	29.798
90	47	153.27	0.100	31.635
60	40	102.18	0.085	39.823
30	31	51.09	0.066	59.024
6	23	10.22	0.049	147.175
3	14	5.11	0.030	218.137
1.8	12	3.07	0.026	291.523
0.9	9	1.53	0.019	432.084

Received: 20April; Accepted: 29September

Applying Bingham plastic model to analyze the data

From figure (7) represent the relation between shear stress and shear rate we can get τ_o from intercept and the value of μ_p it is represent the slope.

$$\tau = \tau_O + \mu_p \gamma$$

Bingham plastic.

Yield stress τ_o= 0.0717 lb_f/ft^2

Plastic viscosity μ_p=0.0002/2.068*10^{-5} =9.6 $lb_f.sec^n/ft^2$.

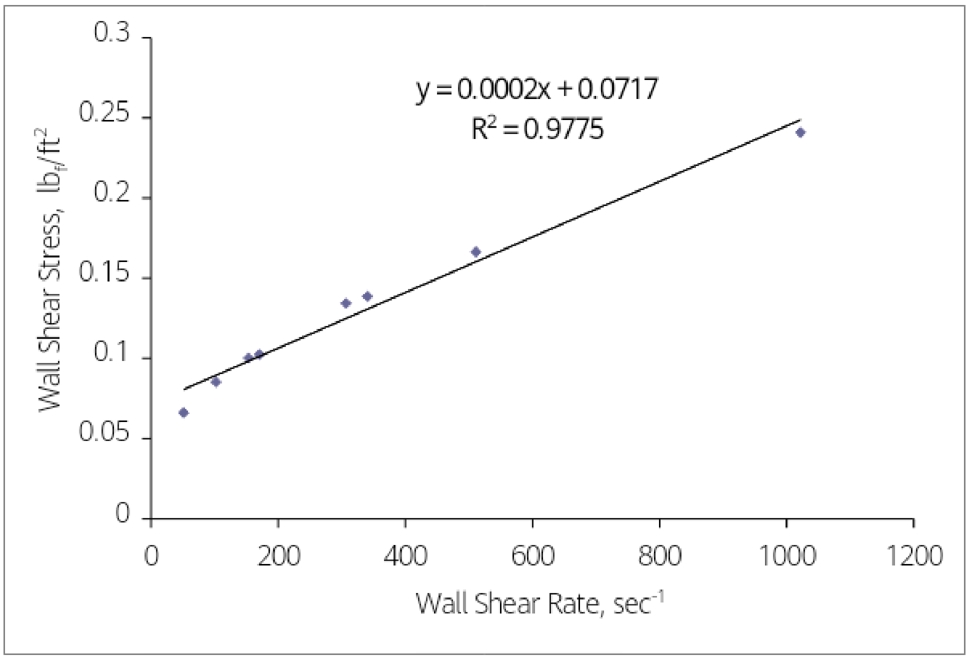


Fig. (7) Bingham Plastic model for second data set for drilling fluid S.N=1/5

Received: 20April; Accepted: 29September

Herschel–Bulkley model

The relation between shear stress and shear rate on log-log scale is:

$$\tau = \tau_o + \mu_p \gamma^{\frac{1}{m}}$$

The plot for Herschel–Bulkley model represents the relation between shear rate vs. (shear stress/ yield stress point) as shown in fig (8)(9) below:

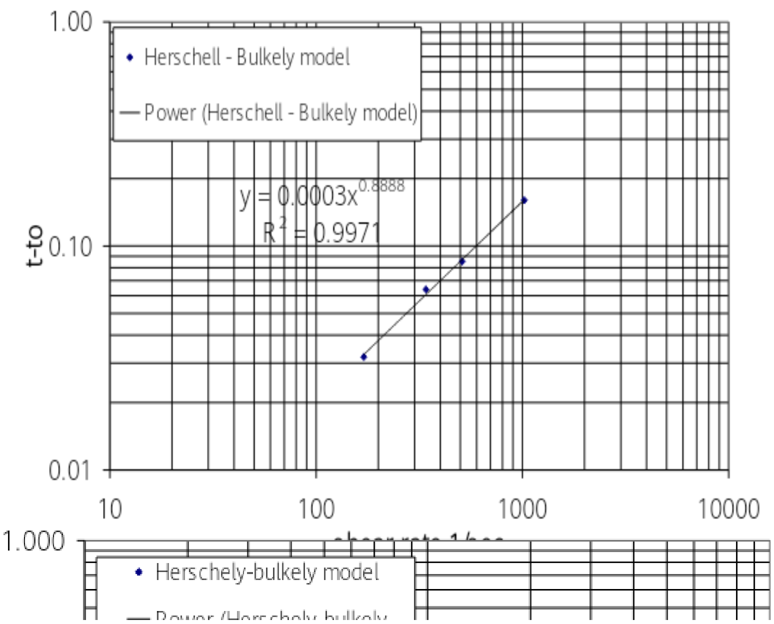
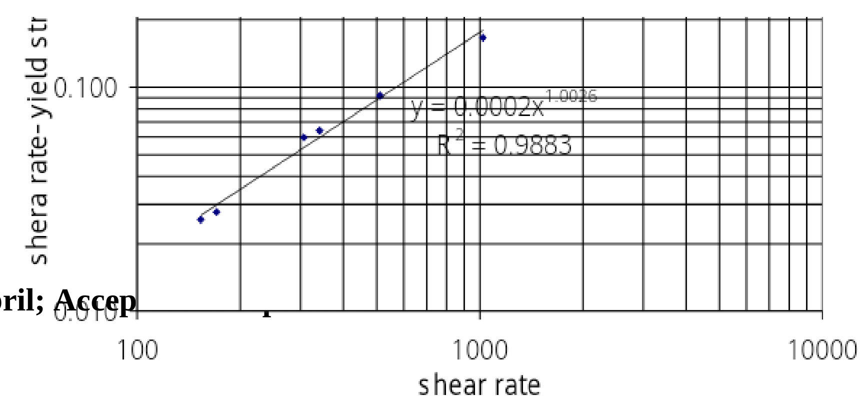


Fig (8) The Relation between shear stress/yield stress point vs shear rate



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From the above graphs for S.N 1

τ o=0.0853, k=0.0003/2.068*10^{-5} =14.5 $lb_f.sec^n/ft^2$. and 1/m=0.888.

for SN 2

τ o=0.0853, k=0.0002/2.068*10^{-5} =9.6 $lb_f.sec^n/ft^2$. and 1/m=1.0026.

The second part of the experimental work is to test the fracturing fluid by applying Power law model and **Ellis model**. to analyze the results of the sample, we used **Bohlin Rheometer**, measure the temperature and pH.

The data we get from the Bohlin Rheometer are listed in table (3).

Table 3 date obtained from Bohlin Rheometer

group 2				Temperature[1]	'22.4 °C	
TABLE 1 :	Test Run[1]	Temp Run[1]	Shear Rate '(1/s)	Percentage Deviation '(%)	Shear Stress '(Pa)	Viscosity '(Pas)
Time	Temperature	Target Shear Rate				
'(s)	'(°C)	'(1/s)				
30.147	22.4	0.053	0.053	-0.04	0.0205	0.390
60.442	22.4	0.081	0.081	0.22	0.0372	0.461
90.74	22.4	0.124	0.124	0.1	0.0617	0.497
121.051	22.4	0.191	0.191	-0.04	0.0963	0.504
151.328	22.4	0.293	0.294	-0.12	0.1443	0.491
181.632	22.4	0.451	0.451	-0.12	0.2131	0.472
211.927	22.4	0.693	0.692	0.14	0.3254	0.471
242.238	22.4	1.064	1.064	0.04	0.5057	0.475
272.522	22.4	1.635	1.630	0.29	0.7279	0.446
302.822	22.4	2.512	2.508	0.17	1.0541	0.420
333.122	22.4	3.860	3.856	0.12	1.4931	0.387
363.425	22.4	5.932	5.920	0.19	2.0683	0.349
393.708	22.4	9.114	9.100	0.16	2.8070	0.308
423.997	22.4	14.004	13.997	0.05	3.7388	0.267
454.307	22.4	21.518	21.483	0.16	4.8655	0.226
484.602	22.5	33.064	33.048	0.05	6.2234	0.188
514.908	22.4	50.803	50.792	0.02	7.7911	0.153
545.205	22.5	78.063	78.040	0.03	9.6279	0.123
575.499	22.5	119.950	119.890	0.05	11.7910	0.098
605.781	22.5	184.310	184.230	0.04	14.3020	0.078

Received: 20April; Accepted: 29September

636.08	22.5	283.190	283.210	-6.64E-03	17.0980	0.060
666.407	22.5	435.140	435.050	0.02	20.7960	0.048
696.687	22.5	668.620	668.580	5.64E-03	25.4480	0.038
727	22.5	1027.400	1026.700	0.07	31.9460	0.031
754.567	22.5	1578.600	1578.900	-0.02	44.5170	0.028

By applying Power law model on table 3 data:
Plotting Shear stress vs shear rate on log-log scale shows in figure (10).

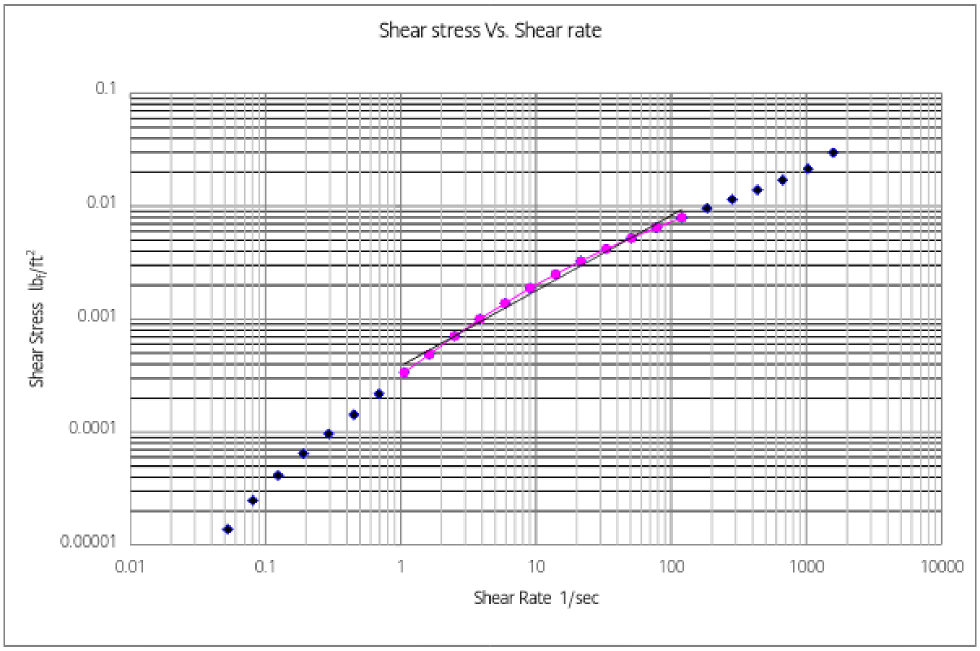


Fig. (10) Relation between Shear stress vs Shear rate

Received: 20April; Accepted: 29September

And plot shear rate vs apparent viscosity fig. (11)

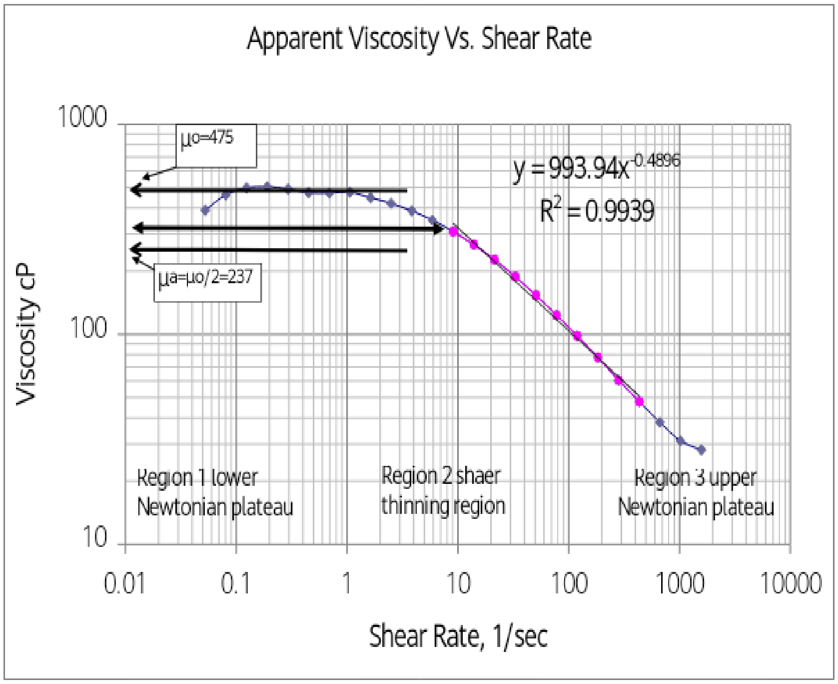


Fig (11) the relation between shear rate vs apparent viscosity

The test fluid behaved as a typical non-Newtonian pseudo plastic fluid over a large shear rate range. For a relatively large range of intermediate shear rates, the plots of wall shear stress and apparent viscosity versus wall shear rate on log-log coordinates are fairly straight lines. These straight lines can be conformed to the following power law rheological model.

$$\tau_W = k_V \gamma^n{}_W$$

Taking the logarithm of both sides of Equation 1:

$$\log(\tau_W) = \log(k_V) + n^* \log(\dot{\gamma}_W)$$

In order to fit the data to this equation, τ versus γ_w should be plotted on a log-log coordinate system. One must identify the points that fit a single straight line. Because of this some lower and upper shear rate data points were not used. Values of n and Kv are determined from the slope and intercept of the fitted straight lines, respectively.

n-1 = Slope = -0.682

Received: 20April; Accepted: 29September

Thus, n = 1 - 0.682 = 0.318

k = Intercept = 1022.9 $cp.sec^{1-n}*2.08*10^{-5}$

$k=0.021276\ lb_f.sec^n/ft^2$

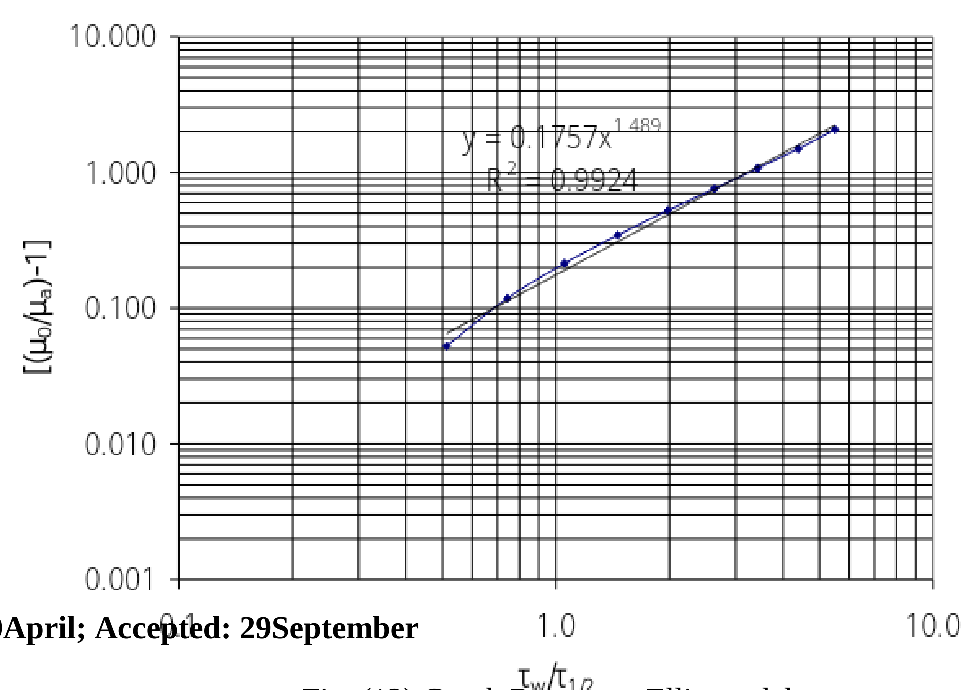
Ellis model:

The relation between shear stress and shear rate is:

$$\tau = \left[\frac{\mu_0}{1+\left(\tau/\tau_{1/2}\right)^{a-1}}\right] * \gamma$$

From the relation between shear rate and μa, can find the value of μ_0=375 and $\tau_{1/2}$=0.00095.

For fracturing fluid we can analyze it by using Ellis model by plot the relation between $\mu_0/\mu_a - 1$ vs $\tau/\tau_{1/2}$ on log-log scale and we get figure (12) below:



Received: 20April; Accepted: 29September

Fig. (12) Graph Represent Ellis model

From the graph we can get α-1 =1.4283

From the above results, the results can be summarized as follows:

Fracturing fluid

Guar powder +water (concentration 50 PPG), pH=6.84 and raised to 7.84, temperature 21.9 c^o.

The fluid tested by Bohlin Rheometer.

Applying two models to analyze the data obtained (Power Law and Ellis model).

Drilling mud

1000 ml of drilling mud:

500 ml 10 lbs/bbl bentonite

500 ml 1.5 lbs/bbl Xanthan

pH=9.82 temperature 23.6 c^o.

Fann 35 model used to obtain the data and two types of spring #1 and #2

Two models used to analyze the data:

Bingham model and Herschel–Bulkley model.

The results for both drilling mud and fracturing fluid are shown in table (4)

Table (4) illustrate the results when applying different models

	Model name	Parameter
Fracturing fluid Bohlin Rheometer	Power Law	$K=0.02127\ lb_f.sec^n/ft^2$ n=0.318
	Ellis model	μ_o=475 cp $\tau_{1/2}=0.0025\ lb_f/ft^2$ α-1=1.4283
Drilling fluid Fann 35 S#1	Bingham model	$\tau_o=0.0817\ lb_f/ft^2$ μ_p=9.6 cp

Received: 20April; Accepted: 29September

	Herschel–Bulkley model	μ_p=14.5 cp τ_o=0.0853 lb_f/ft^2 1/m=0.888
Drilling fluid Fann 35 S#2	Bingham model	μ_p=9.6 cp τ_0=0.0717 lb_f/ft^2
	Herschel–Bulkley model	μ_p=9.6 cp τ_0=0.853 lb_f/ft^2 1/m=1.00026

Received: 20April; Accepted: 29September

Conclusions:

The main aim of this paper is to use the Bohlin CS-50 and model 35 Fann viscometer, and to characterize two fluid samples of Non-Newtonian fluids (fracturing fluid and drilling fluid). After analyze the data obtained from the using the two instruments we can conclude that Power law model is good to analyze the fracturing fluid data and getting good results when we apply the power law on fracturing fluid. The parameters that gotten are useful to analyze this type of fluid and it can also evaluate the type of fluid by using n & k parameters.

From the above results it can conclude that Bingham model is give useful results and easy to get the important results for analyzed drilling fluid. And we can see for the same drilling fluid we got almost the same results when using same instrument with different spring number (1, 2), but when using Herschel model it can note that, the results was not the same results, in spite of using the same fluid and the same instrument.

Recommendations:

1- Test the two fluids after period of time to indicate the type of fluid depending on classification (time independent, time dependent).
2- Applying other models to analyze the data obtained from the using of two instruments (Bohlin and Fann).
3- Applying different test condition pressure and temperature, and also different material concentration.

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