International Journal of Advance Research in Science and Engineering
Volume No. 10, Issue No. 07, July 2021
www.ijarse.com
IJARSE
ISSN 2319 - 8354

A Comparative study on the Behaviour of Non-Newtonian Crude Oil with Different Rheological Models

Gaurav Himanta Khaklari[1], Prasenjit Talukdar[2]*, Rituraj Singh[3]

[1]*Department of Petroleum Technology, Dibrugarh University, Dibrugarh, Assam, India.786004*

[2,3]*Department of Petroleum Engineering, Dibrugarh University, Dibrugarh, Assam, India.786004*

**Corresponding author: Prasenjit Talukdar (prasenjit_duiet@dibru.ac.in)*

Abstract: Crude oil contains wax which shows non- Newtonian rheological behavior at low temperature due to wax precipitation. Such behavior can be seen during operating conditions, for instance, during transportation of crude oil. Therefore, reliable rheological model for crude oils which is applicable over the wide range of conditions is necessary for a large number of oil technology applications. In this study, a comparative study between four different rheological models which can facilitate to describe the behaviour of the non-Newtonian crude oils is carried out.

Keywords: *Crude Oil; Flow Curve; Rheological Model; Non-Newtonian Fluid; Pour Point Depressant; Wax Appearance Temperature.*

1. INTRODUCTION

Crude oil rheological properties depend on several factors including temperature, pressure, surface tension, diluent type and diluent composition, pH, shear stress and thermal history, memory and shear condition during the analysis. The investigation of crude oil flow is an important issue in the petroleum industry [1]. Typically, crude oils containing high content of asphaltenes, resins and paraffins show non-Newtonian properties during storage and transportation. A strong variation in temperature may induce non-Newtonian rheological responses for these waxy oils if temperature decreases below the "Wax Appearance Temperature" (WAT) [2]. One of the major flow assurance problems in the oil industry is the formation of wax during the transportation and production of crude oil [3]. During cold weather conditions these crude oil production encounters numerous operational problems due to obstruction in flow pipes or production lines which is caused due to paraffin formation and its blockage.Large amounts of paraffin wax in the crude oil impede the flow of crude oil due to wax precipitation [4]. As temperature decreases crude oil becomes more viscous and once it goes below the pour point temperature it can no longer flow or be pumped [5]. The temperature below which the liquid loses its flow characteristics is known as the pour point temperature. In such situations, some sort of experimental chemicals, namely Pour Point Depressants (PPDs)/ Flow improvers (FIs) are used which helps in lowering the pour point temperature and facilitate the flow of crude oil by lowering the wax appearance temperature (WAT) of the oil [6]. The successful extraction and transportation of crude oils through pipelines require detailed information about the rheological behavior. So, in order to develop the PPDs, we need to acquire these detailed information. Thus, to predict, design, or simulate flow behaviour with good accuracy oil technology applications need reliable rheological models over wide range of conditions [7]. In this experiment, a comparative study between four different rheological models was done to describe the behaviour of the non-Newtonian crude oil for the same crude oil sample.

2. MATERIALS AND METHODS

In this work, the crude oil sample was obtained from Oil India Limited, Assam and the Physio-chemical characteristics such as density, specific gravity, API, wax and water content, pour point and SARA distribution of crude oil was found out. Pycnometer was used to determined density which is a very precise method. API gravity is helpful in determining the quality of crude oil. Here the API gravity of the crude was determined using specific gravity value at 40^0C. The following formula is used.

$$API\ gravity = \frac{141.5}{RD} - 131.5$$

(Here, RD = Relative Density)

Water content determination was by centrifuge method (ASTM D 96-58 T).Pour point temperatures of the crude oil samples were measured using the standard test method for the pour point, ASTM D97-06.11. In this method standard ASTM pour point apparatus which includes test jar, bath, jacket and thermometer was used for the pour-point determination. Pour point was obtained by interval of every 30 C. When the flow stops on tipping the test jar horizontally, that temperature was noted as pour point.Viscosity was measured using MCR-72, Anton Paar Rheometer

Table1: Physio-Chemical characteristics of crude oil

Sl. No.	Parameter	Method	Crude oil
1.	Density	IP 160/64	0.879
2.	API Gravity	ASTM Table	26.8
3.	Pour point	ASTM D-97	36
4.	Water Content (%; V/V)	IP 74/64	2
5.	Wax Content (%; w/w)	Modified UOP 46-64	15.5
6.	SARA analysis: (%; w/w) Saturates: Aromatics: Asphaltenes: Resin: Resin Asphaltenes		 52 14 0.5 8 11.5

The Rheological models were measured using MCR-72, Anton Paar Rheometer and temperature was set at 40^0C.

2.1 Rheological Analysis

In this work, the viscosity of crude oil was measured at different shear rates using differentrheological models. These rheological flow models are mathematical formulae which allow us to calculate the shear stress at any shear rate by applying a function "f":

$$\tau = f(\gamma)$$

where, τ= shear stress, f=function, γ= (du/dy) shear rate.

Table 2: The parameters of this function depend on the selected fluid model

For Newtonian fluid model 'f' is	μ
For Bingham plastic fluid model 'f' is	PV, YP
For Power Law fluid model 'f' is	n and K
For Herschel-Buckley fluid model 'f' is	τ_0 , n and K
For Ostwald fluid model 'f' is	n and K

2.1.1 Flow Model - Bingham Plastic

This model has an excess yield stress, intercepting with the shear stress axis. And the parameters are calculated by a simple regression analysis [8]. Laminar flow is described using the following equation [9].

$$\tau = YP + PV(\gamma)$$

where,

- τ = measured shear stress in lb/100ft^2
- YP = yield point in lb/100ft^2
- PV = plastic viscosity in cP
- γ= shear rate in sec^{-1}

For simplicity, we have taken YP=a, PV=b and γ=x in this experiment. (using MCR-72, Anton Paar Rheometer)
So, Bingham: y = a + b·x
Here,

Coefficient a:	57.409
Coefficient b:	0.17682
Correlation coefficient R:	0.95048
Correlation coefficient R²:	0.90341

2.1.2 Flow Model – Power Law

All fluids in this model are assumed to be pseudoplastic. Thetwo-parameter model does not consideran excess yield stress [8].The following equation describes the nature of such fluids [10].

$$\tau = K (\gamma)^n$$

where,

- τ = shear stress (Dynes/cm^2)
- K = Consistency Index
- γ = Shear Rate (sec^{-1})
- n = Power Law Index

For simplicity: τ=y, K=a, γ=x and n=p for this experiment, (using MCR-72, Anton Paar Rheometer)

So, Power Law: y = a·x^p

Coefficient a:	32.916
Coefficient p:	0.24856
Correlation coefficient R:	0.91191
Correlation coefficient R²:	0.83158

2.1.3 Flow Model – Herschel Bulkley

It is a three-parameter model and requires an initial calculation of yield stress or other parameters calculations [8]. The Yield-Power Law model describes rheological behaviour of drilling muds accurately then either of the other two models [11].

$$\tau = \tau_0 + K (\gamma)^n$$

where,

- τ = measured shear stress in lb/100ft^2
- τ_0= fluid yield stress (shear stress at zero shear rate) in lb/100ft^2
- K= Consistency Index
- n= Flow Index
- γ= Shear rate in sec^{-1}

For Simplicity: τ=y, τ_0=a, K=b, γ=x and n=p for this experiment.(using MCR-72, Anton Paar Rheometer)

So, Herschel-Bulkley: y = a + b·x^p

Coefficient a: -533.26
Coefficient b: 577.19
Coefficient p: 0.01
Correlation coefficient R: 0.99359
Correlation coefficient R²: 0.98724

2.1.4 Flow Model - Ostwald Model

The following equation describes the nature of such fluids.

$$\tau = K\,(\gamma)^n$$

where,

- τ = shear stress (Dynes/cm^2)
- K = Consistency Index
- γ = Shear Rate (sec^{-1})
- n = Power Law Index

For simplicity: τ=y, K=a, γ=x and n=p for this experiment, (using MCR-72, Anton Paar Rheometer)

Ostwald: y = a·x^p

Coefficient a: 32.916
Coefficient p: 0.24856
Correlation coefficient R: 0.91191
Correlation coefficient R²: 0.83158

The crude oil sample was analysedand the shear stress parameters were obtained at different shear rates using Bingham Plastic, Power Law, Herschel-Bulkley and Ostwald Models (Tables 3). After studying the models, it was observed that as the shear rate is increased, shear stress values isincreased correspondingly (Figures1, 2, 3 and 4). The Herschel-Bulkley model gave a good fit of experimental data with a lower mean absolute percentage deviation compared to other two models. In general, the correlation coefficients (R^2) obtained for crude oils for the four models were in the range of 0.83158-0.97024.

3. EXPERIMENTAL WORKS

Rotary viscometer tests of crude oil from Oil India Limited, Assam with high wax paraffin content wascarried out in the lab. The instrument used for this work was the MCR-72, Anton Paar Rheometer. The temperature was set at 40^{0}C and the max rpm was set to 70 at max. The corresponding shear stressesfor different shear rates was found out using this instrument for four different rheological models i.e. The Bingham model, Power Law model, Herschel Bulkley model and Ostwald model.Here, Table 3 shows some of the shear stress values at different shear rates intervals for all the four models.

Table3: Shear Rate (1/sec) vs. Shear Stress (in Pa) Values of Crude Oil At varying intervals for Different Models

Shear rate (1/s)	Bingham Plastic	Power Law	Herschel & Bulkley	Ostwald
7	58.47	54.092	55.272	51.97
14	59.885	63.544	59.366	59.251
21	61.122	70.638	61.773	62.719
28	62.36	75.534	63.488	63.412
35	63.598	79.015	64.647	64.452
42	64.836	83.3	65.912	66.186
49	65.897	86.881	66.837	66.879
56	67.311	89.776	67.53	67.001
63	68.549	92.384	68.347	67.227
70	69.787	94.925	68.981	68.613

4. RESULTS AND DISCUSSION

The shear stress vs shear rate vales are plotted in x and y axis to observe the behaviour of different models.The curves are indicated by different colour lines to indicate different models:

Table 4: Colour lines to indicate different models

Normal Curve	Binghum	Herschel Bulkley	Power Law	Ostwald
τ	τ	τ	τ	τ

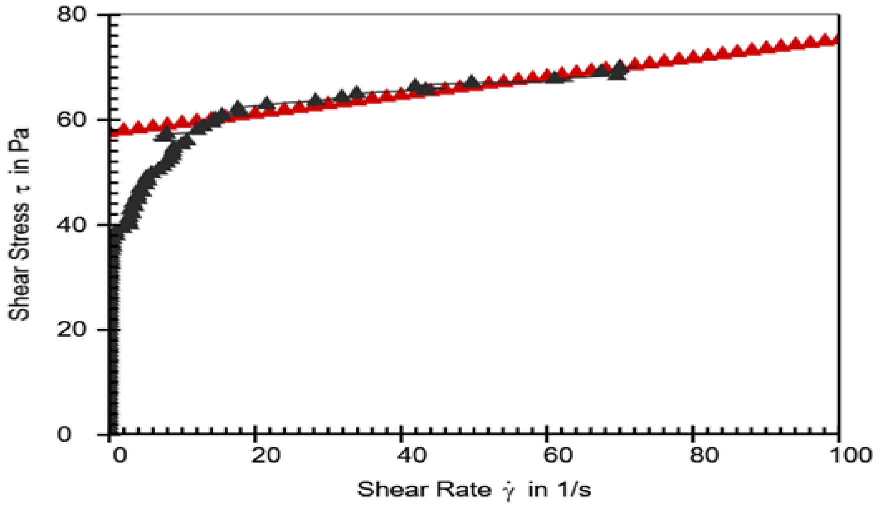

Fig.1: Bingham Plastic model curve for crude oil

Here, Fig. 1 shows the Bingham Plastic model of Shear stress vs shear rate. As the fluid starts to flow there is a linear relationship between shear stress and shear rate. The correlation coefficient R^2 was found to be 0.90341.

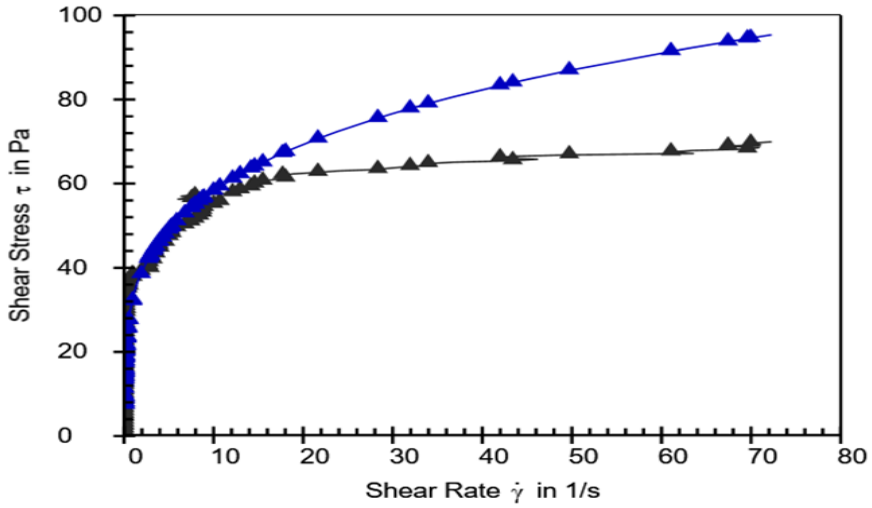

Fig.2: Power law model curve for crude oil

Here, Fig. 2 shows the Power law model of Shear stress vs shear rate. It provides an alternative to the Bingham plastic model for concentrated non-settling slurries [12]. The correlation coefficient R^2 was found to be 0.83158.

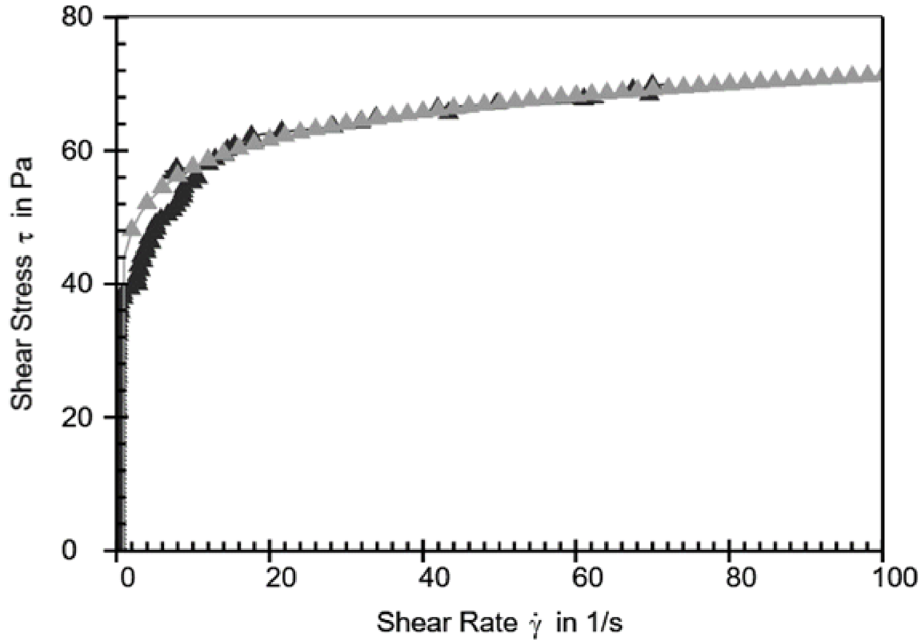

Fig.3: Herschel Bulkley model curve for crude oil

Here, Fig.3 shows the Herschel Bulkley model for Shear stress vs shear rate. This model is a combined behaviour of Bingham and power-law fluids in a single relation. The material behaves as a very viscous fluid with viscosity, for very low strain rates. After a minimum value of strain-rate corresponding to a threshold stress, the viscosity is represented by the power-law relation [11].The correlation coefficient $R^2$for this model was found to be 0.98724.

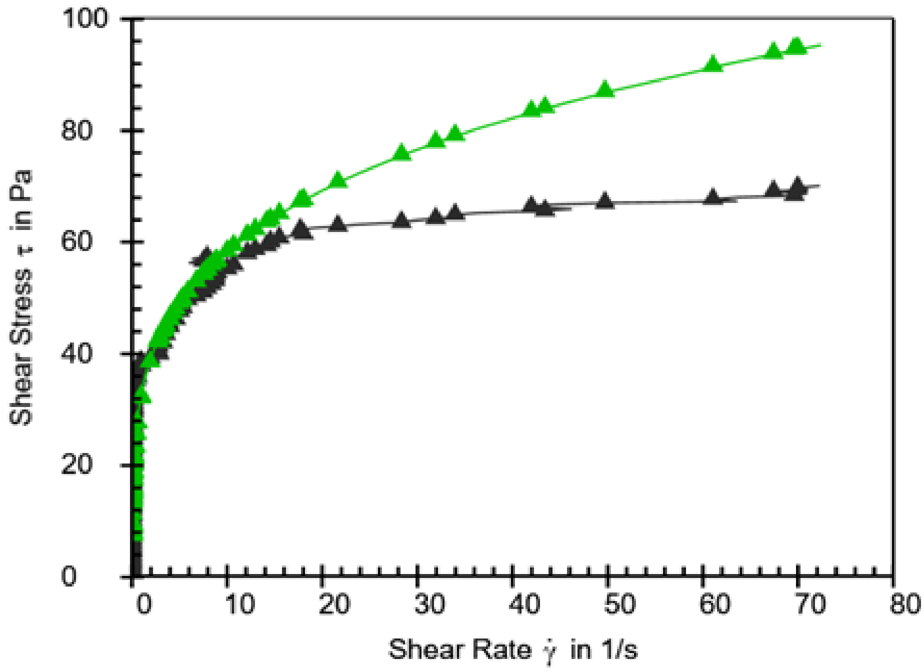

Fig.4: Ostwald model curve for crude oil

Here, Fig.4 shows the Ostwald model for Shear stress vs shear rate. The correlation coefficient R^2 was found to be 0.83158.

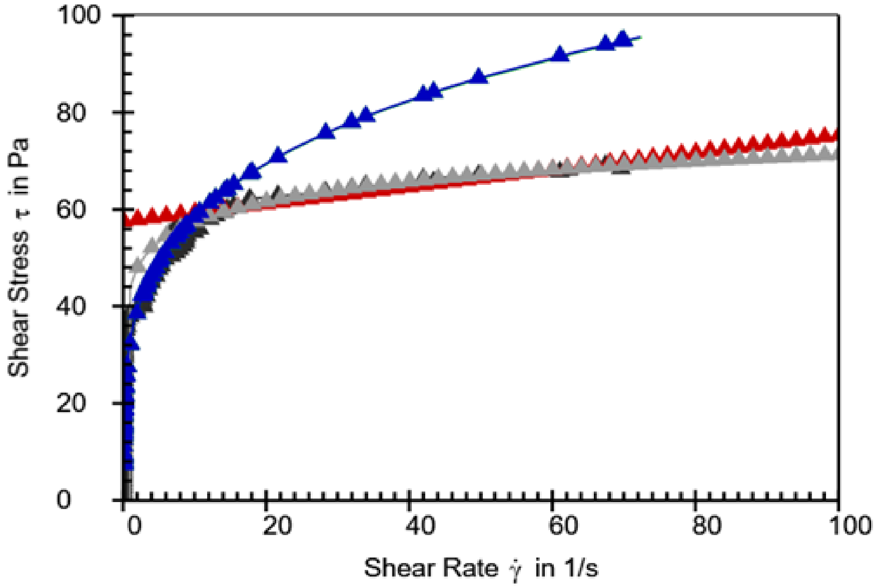

Fig.5: Cumulative Shear stress vs Shear rate curve for four models

Here, Fig. 5shows the combined shear stress vs shear rate values of all the four models. From thiswork, it can be seen that Herschel Bulkley model gives the best correlation coefficient value (i.e. R^2= 0.98724) for the crude oil out of the four and it is the best fitted model for this crude oil.

5. CONCLUSION

In this research, rheological experiments were carried out on crude oil and it was observed that the viscosity tends to increase at higher shear rates. Also, comparison among four models, namely, the Bingham model, the Power Law model, Herschel Bulkley model and Ostwald model were presented for the same crude oil sample. Among the four models, Herschel Bulkley model was the best fitted model for this crude oil with a correlation coefficient of 0.98724.The results implies that the crude oil used in this experiment exhibits non-Newtonian flow characteristics.In future, to further our research we intend to consider these experiments using PPDs to understand and improve the flow characteristics of crude oil.

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