

# Rheological Behaviour of Water-in-Light Crude Oil Emulsion

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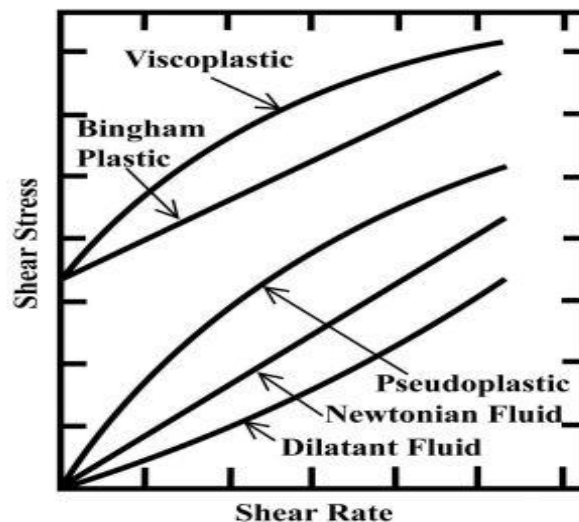
**Abstract.** Basically, emulsions consist of two immiscible liquids which have different density. In petroleum industry, emulsions are undesirable due to their various costly problems in term of transportation difficulties and production loss. A study of the rheological behaviour of light crude oil and its mixture from Terengganu were carried out using Antoon Paar MCR 301 rheometer operated at pressure of 2.5 bar at temperature 30°C. Water in oil emulsions were prepared by mixing light crude oil with different water volume fractions (20%, 30% and 40%). The objectives of present paper are to study the rheological behaviour of emulsion as a function of shear rate and model analysis that fitted with the experimental data. The rheological models of Ostwald-De-Waele and Herschel-Bulkley were fitted to the experimental results. All models represented well the rheological data, with high values for the correlation coefficients. The result indicated that variation of water content influenced shear rate-shear stress rheogram of the prepared emulsions. In the case of 100% light crude oil, the study demonstrated non-Newtonian shear thickening behavior. However, for emulsion with different volume water ratios, the rheological behaviour could be well described by Herschel-Bulkley models due to the present of yield stress parameter ( $R^2 = 0.99807$ ). As a conclusion, rheological studies showed that volume water ratio have a great impact on the shear stress and viscosity of water in oil emulsion and it is important to understand these factors to avoid various costly problems.

## 1. Introduction

Markets worldwide have shown an increasing demand for crude oil. Rheological behaviors of emulsion not only influence its visual and textural perception, but also affect its processing capabilities. For example, compared to Newtonian fluids, shear thinning fluids are more susceptible to applied stress. Thus, measuring shear thinning behavior is necessary as most fluids of interest come under this class of fluids. Crude oil is seldom produced alone and it generally is commingled with water. As the reservoir become older, the production of water can significantly increase. The water creates several problems and consequently, percentage of crude requiring treatment increases. The produced water must be separated from the oil and disposed properly. At the meantime, emulsions occur and might increase the cost of production. In order to correctly address the emulsion problem, it is vital to better understand the rheological properties of the emulsion. Rheological deals with the flow of fluid and deformation of matter under various kinds of strain and stress. The force can be applied in various ways: a compression, a tension, a shearing process, or some combination of three. Rheological properties of emulsion can be determined by measuring the relationship between stress, strain, temperature and time. Thorough knowledge of emulsion rheology is helpful in minimizing numerous difficulties during processes such as refining, transportation, separation and production. The rheological of emulsion commonly affected by temperature, volume fraction of dispersed phase, droplet size and interfacial tension. Emulsion can exhibits either Newtonian of non-Newtonian



behavior depending upon its composition[1],2]. Newtonian liquid can be defined as constant viscosity independent of shear rate. Newtonian liquid also exhibits uniform resistance to flow independent of flow conditions. Meanwhile, non-Newtonian liquid is defined as viscosity which changes with shear rate and type of deformation. It exhibits different resistance to flow, at different shear and extensional rates. Typically, viscosity of emulsion changes from a few hundred mPa.s to about 100 000 mPa.s [3]. Figure 1, shows some rheological behavior of fluid.



**Figure 1.** Rheological behavior of non-Newtonian fluid. [4]

The main objective of this investigation is to study the rheological properties of light crude oil and the characteristic of its emulsions. This investigation provide different rheological model to establish the viscosity rheogram as a function of volume water fraction ( i.e., 20%, 30%, and 40%) at a temperature of 30 °C.

## 2. Materials and methods

Light crude oil from Terengganu was used in this study for the preparation of emulsion. The emulsions were prepared with different volume fraction of water (i.e. 20%, 30%, and 40%). In order to prepare water in oil emulsions, water was added gradually to the oil in 250 ml beaker. Emulsions were homogenized with 10 000 rpm in 15 minutes. Emulsions were left in order to settle for a period of 24 hours in vials after homogenized. Rheological behaviors of the emulsions were analyzed by Antoon Paar MCR 301 rheometer which operates at pressure of 2.5 bar. The rheological test were conducted at temperature 30°C and shear rate varied from 0.1 – 1000 s<sup>-1</sup>. Light crude oil used in the experiment has physical properties as given in Table 1[5]

**Table 1.** Properties of light crude oil[5].

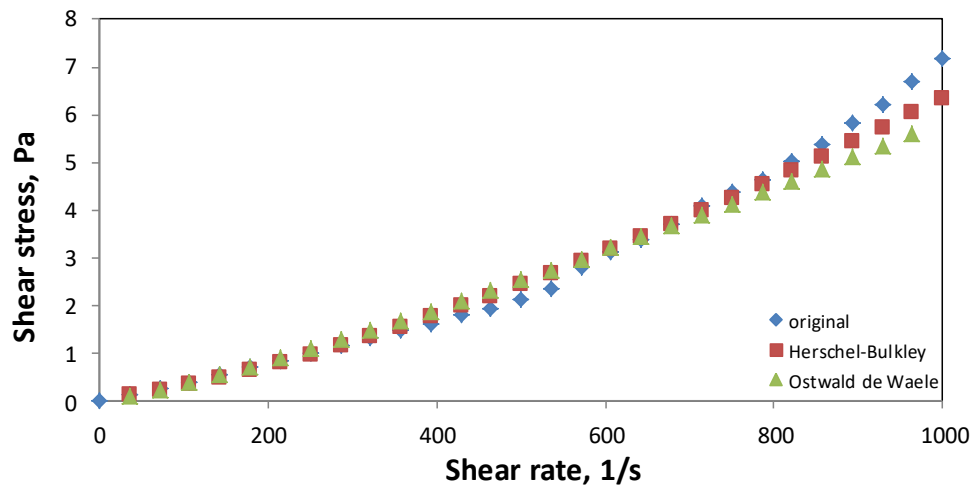
Analysis	Light crude oil
Physical State	liquid
Specific Gravity	0.85
API gravity	34.87 °API
Pour Point °C	- 20

## 3. Results and discussions

### 3.1. Rheological behavior of light crude oil

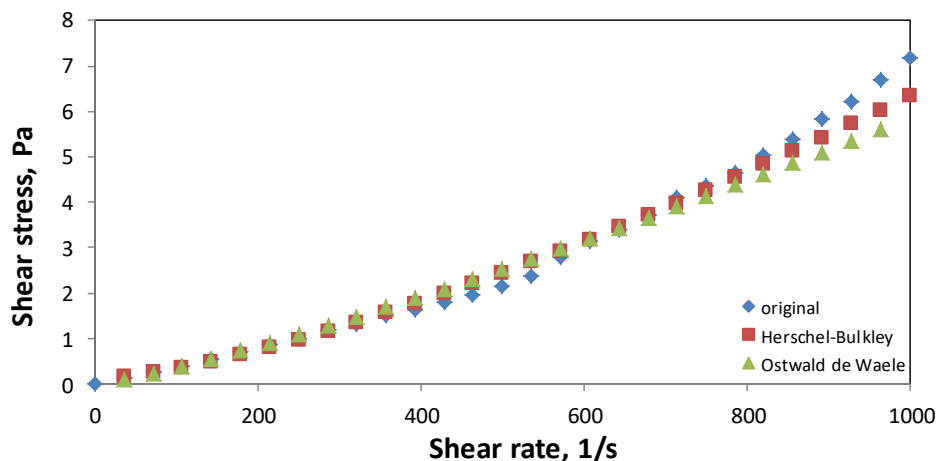
Figure 2 shows the flow behavior of the light crude oil in terms of shear stress and shear rate. It was investigated over a wide range of shear rate at 30°C. The measurement test was conducted under the

controlled rate (CR) mode, and the values of shear stress and shear rate were obtained. From Figure 2, light crude oil exhibits non-Newtonian behavior, as shown by the non-linearity between the shear rate and shear stress plotted rheogram. Additionally, shear stress increases gradually with shear rate, evidence of the increase in viscosity with increase in shear rate, confirming the non-Newtonian dilatant behavior of light crude oil. On the other hand, in the majority of studies, light crude oil has been modeled under non-Newtonian Pseudoplastic behaviour [6][2][7]. This is due to the complex mixture and origin of the crude oil



**Figure 2.** Relationship between shear stress and shear rate for light crude oil at 30 °C

Figure 3 shows the relation between viscosity and shear rate. It is observed that viscosity values decrease with increasing shear rates at low region up to  $100 \text{ s}^{-1}$  and hence called as shear- thinning. However, when the shear rate is above  $100 \text{ s}^{-1}$ , viscosity of crude oil exhibits a strong non-Newtonian shear thinning behavior. Variation viscosity was influenced by several factors such as concentration and nature of oil and particle size[8]. As viscosity increased significantly with shear rate, the molecules are starting to expand and filled the void space. Hence, lead to much larger of shear stress that caused viscosity rapidly increasing[4].



**Figure 3.** Relationship between viscosity and shear rate for light crude oil at 30 °C.

### 3.2. Modeling the rheology of emulsion

The light crude oil was used in the study, shear stresses and shear rates were calculated using equations derived from (Ostwald de Waele and Herschel –Bulkley), Equations (1) and (2) respectively. These models were applied to transform emulsion to information on fluid rheological behavior. The Ostwald de Waele model (Eq 1), also known as the Power Law model. The equation has two parameters ( $k$  and  $n$ ). Where  $n$  is the flow behaviour index and  $K$  gives the consistency index or viscosity ( $\text{Pa.s}$ )[9].

$$\tau = k(\dot{\gamma})^n \quad (1)$$

On the other hand, Herschel –Bulkley model consists of three adjustable parameters ( $\tau_0$ ,  $k$ ,  $n$ ) and it's considered as a precise model[10]. The Herschel –Bulkley model is expressed in equation 2, where  $k$  and  $n$  are consistency index and flow behaviour index respectively and  $\tau_0$  denotes the yield stress (Pa.s). The  $n$ -value in Equation (1) and (2) give fluid behavior information according to [11].

$$\tau = \tau_0 + k(\dot{\gamma})^n \quad (2)$$

$n < 1 \Rightarrow$  non-Newtonian Pseudoplastic behaviour

$n = 1 \Rightarrow$  Newtonian behaviour

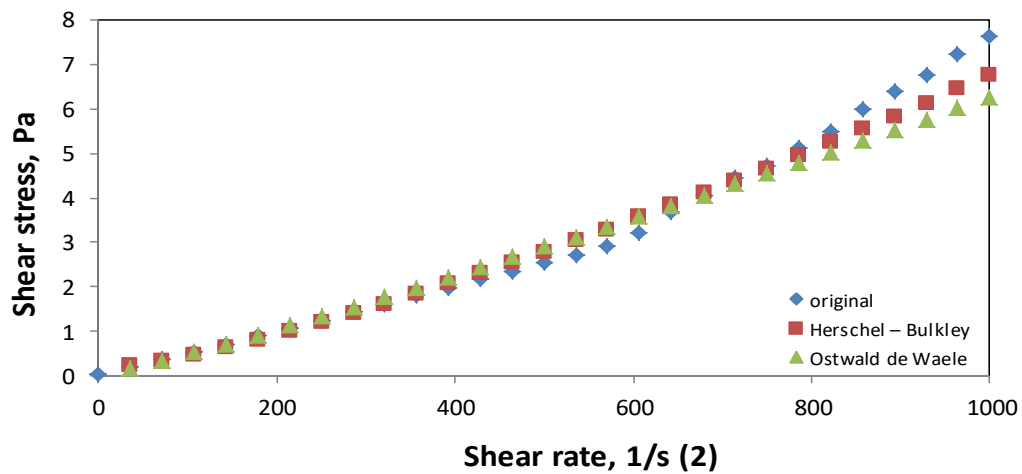
$n > 1 \Rightarrow$  non-Newtonian Dilatant behavior

These two models are the best in describing the colloidal suspension of emulsion [12][13][14]. The calculated values were compared to the measured values to determine which of the model could predict better shear stresses and shear rate over the range of study. To assess the rheological behavior of crude oil emulsion at different water contents, the experimental data were fitted to the two proposed rheological models mentioned previously. The results of the experiments are shown in Table 2 and in Figures 4,5 and 6. It can be seen that both models satisfactorily represent the rheological behavior of crude oil emulsion. However, Herschel – Bulkley model provided the best fit of the rheological data. Regression coefficients ( $R^2$ ) of Herschel – Bulkley model showed the highest value, which is 0.99807 for 40 % volume water fraction. This is because the present of parameter of yield stress. Meanwhile, Ostwald de Waele model consist only two parameters (does not consist parameter of yield stress). In industrial processes, yield stress is vital quality control parameter, particularly for comparing manufacturing products on different production lines[8]. The  $R^2$  value shown in Table 1 indicates how well the regression analysis fits the shear stresses- shear rate data (see Figure 2,3,4). The closer the  $R^2$  value is to 1.00, the better the linear regression; analysis has fit the data. Similar results have been reported by [12][7][5].

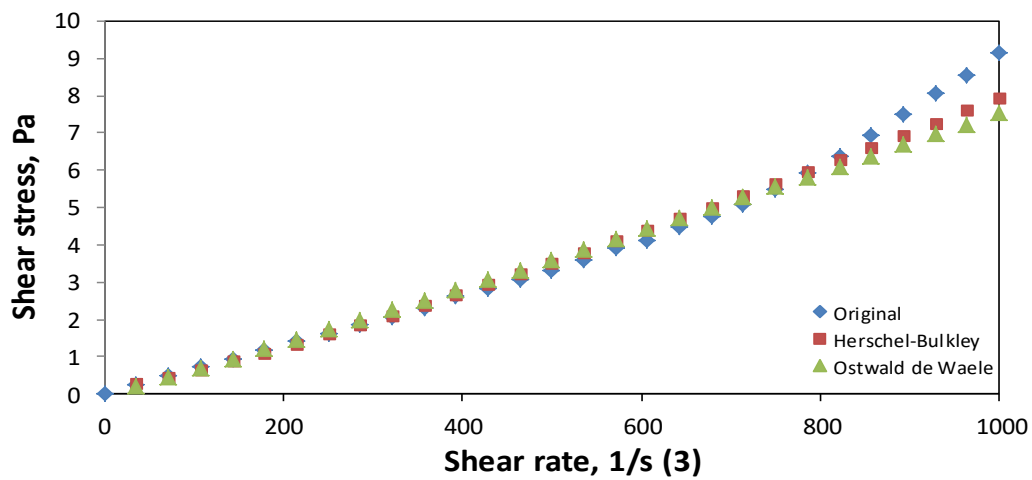
The decrease of water content in the three-different volume water fraction seemed to increase the consistency factor, ( $k$ ). However, decrease the value of behavior index, ( $n$ ). It shows that the values for the behavior index ( $n$ ) are higher than 1 (except for 40% volume water fraction) indicating a non-Newtonian Dilatant behavior of light crude oil emulsion. This rheological parameter varied from 1.1172 to 0.9948 for the Ostwald de Waele model and from 1.3192 to 1.0046 for the Herschel-Bulkley model. The Herschel-Bulkley and Ostwald de Waele models both indicated a Dilatant behavior of 20% volume water fraction of emulsion since the value  $\tau_0$  was  $> 0$  (0.13 Pa) and  $n > 1$  (Table 2). Herschel-Bulkley model indicated that 30% volume water fraction of emulsion performed as a Dilatant behavior, since the yield stress value was  $> 0$  (0.14 Pa) and a flow behavior index of 1.21 (Table 2). Results obtained by Ostwald de Waele confirmed a Dilatant behavior  $n > 1$  (1.0628) for 30% volume water fraction. However, 40% volume water fraction results obtained by the Ostwald de Waele models indicated a Pseudoplastic non-Newtonian behavior, since value  $n$  (0.99482) but Herschel - Bulkley model indicated a Newtonian behavior since  $n = 1$ .

**Table 2.** Modeling analysis of experimental data

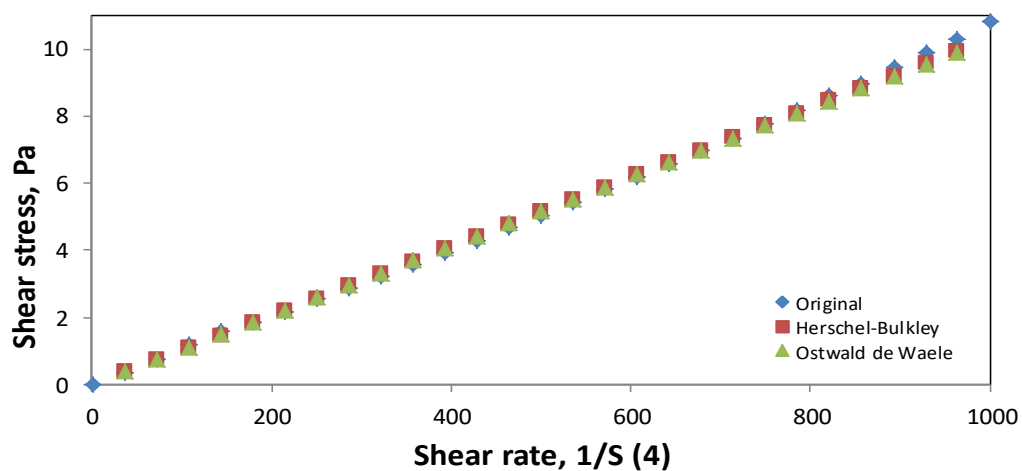
Composition of the water fraction	Ostwald de Waele			Herschel - Bulkley			
	$n$	$k$	$R^2$	$\tau_0$	$k$	$n$	$R^2$
0%	1.21000	0.00138	0.95497	0.09258	0.00037	1.4110	0.98340
20%	1.11720	0.00280	0.94889	0.13176	0.00073	1.3192	0.97819
30%	1.06280	0.00488	0.95931	0.14256	0.00182	1.2110	0.97870
40%	0.99482	0.01065	0.94740	0.01595	0.00997	1.0046	0.99807



**Figure. 4.** Shear stress versus shear rate experimental data and fitting plots for 20% water volume fraction.



**Figure. 5.** Shear stress versus shear rate experimental data and fitting plots for 30% water volume fraction.



**Figure 6.** Shear stress versus shear rate experimental data and fitting plots for 40% water volume fraction.

#### 4. Conclusion

Rheological behavior of light crude oil and its emulsion were investigated. Based on the results, the rheological behavior of light crude oil and its emulsion can be best presented by the Herschel-Bulkley model with highest regression correlation coefficient,  $R^2$  value is 0.99807. The value of flow behavior index,  $n$  decrease (from 1.4110 to 1.0046) as volume water fraction increase, and characterizing non-Newtonian Dilatant behavior for light crude oil emulsion. In addition, experimental results showed the rheological behavior of studied emulsion were significantly influenced by their water content and the nature of the crude oil.

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