CHEMICAL ENGINEERING TRANSACTIONS

VOL. 45, 2015

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

Guest Editors: Petar Sabev Varbanov, Jiří Jaromír Klemeš, Sharifah Rafidah Wan Alwi, Jun Yow Yong, Xia Liu

ISBN 978-88-95608-36-5; **ISSN** 2283-9216 DOI:10.3303/CET1545236

Rheology Study of Water-in-Crude Oil Emulsions

Siew Fan Wong*[a], Ming Chiat Law[a], Yudi Samyudia[b], Sharul Sham Dol[a]

[a] Department of Petroleum Engineering, School of Engineering and Science, Curtin University, Miri Campus, CDT 250, 98009 Miri, Sarawak Malaysia
[b] Department of Chemical Engineering, School of Engineering and Science, Curtin University, Miri Campus, CDT 250, 98009 Miri, Sarawak Malaysia
wong.siew.fan@postgrad.curtin.edu.my

An emulsion is a mixture of two immiscible liquids, whereby droplets of one phase (dispersed phase) are encapsulated in another phase (continuous phase). Emulsions formation in pipelines is one of the most critical problems faced by the oil and gas industries. To solve this unfavourable emulsification problem, the rheological properties of emulsions have to be determined first because they have different effects on the transportation of fluid. In this paper, the rheological properties of water-in-crude oil (W/O) emulsions will be presented for discussion or reference. Bintulu light crude oil was used as the continuous phase and water was used as the dispersed phase to form the W/O emulsions. The experimental results have demonstrated that W/O emulsions with volume fraction of water greater than or equal to 0.1 displays a Newtonian fluid property for shear rates below 500 s^{-1}. For shear rates above 500 s^{-1}, they display a non-Newtonian fluid property. Different volumes of water phase result in different viscosities as well. The viscosity of W/O emulsion increases with the volume of water from 10 % up to 35 %. Then, it decreases with further increase in the volumes of water up to 100 %. For 10 % to 35 % of water volumes, increasing in viscosity is due to the increase in the amount of dispersed phase droplets which leads to higher friction among droplets. Meanwhile, for 40 % to 100 % of water volumes, the droplets start to coalesce and form larger droplets causing a specific area to decrease. Hence, the friction among the droplets is reduced. This leads to a decrease in viscosity. In general, the W/O emulsions for the volume fractions of water which are less than 0.8 will behave as a Newtonian fluid in turbulent flow.

1. Introduction

The oil and gas industries play a very important role in all the countries around the world because these industries not only contribute to the countries' economies but they also support the needs of community in the demand for crude oil. Over the past 20 y, the demand for crude oil has increased from 60 Mbbl/d to 84 Mbbl/d (Hasan et al., 2010). In Malaysia, the production of crude oil averaged 637.51 kbbl/d from year 1994 to 2014 (Trading Economics, 2015). According to The Malaysian Investment Development Authority (2013), the amount of Malaysia's oil and gas industries contribution to the gross national income (GNI) in the year 2009 was RM 110 billion and it is expected to increase up to RM 1.7 trillion by the year 2020.
Crude oil has been in global demand because it can be processed and refined into highly useable products such as asphalt, diesel, fuel oil, gasoline, kerosene, liquefied petroleum gas, lubricating oil, paraffin wax, bitumen and petrochemicals (Beltramini and Lu, 2002). The process is very complicated which requires both physical separations and chemical reactions. It has to pass through different units such as heater, desalter, separator, distillation column and others before it is refined into those useful products. While transporting the mixture of crude oil and water through all these oil production units, the turbulence, mixing and agitation through valves, pumps, surface chokes and pipes will lead to the formation of W/O emulsions in crude oil flow (Lim et al., 2015). As such, the formation of emulsions is undesirable for the oil and gas industries. This is because it will bring many unfavourable effects on the industries' activities, which include a decrease in the quality of crude oil product, an increase in the operational cost, a decrease in the crude oil production as well as a cause of corrosion to the transportation system. Figure 1 shows the crude oil processing stages where emulsions are formed.

Please cite this article as: Wong S.F., Law M.C., Samyadia Y., Dol S.S., 2015, Rheology study of water-in-crude oil emulsions, Chemical Engineering Transactions, 45, 1411-1416 DOI:10.3303/CET1545236

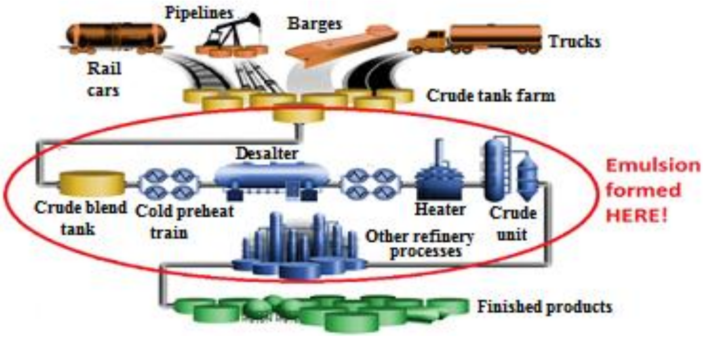

Figure 1: Crude Oil Process Flow Diagram (Baker Hughes Incorporated, 2014)

There are a few methods which will lead to the formation of emulsions. It includes mechanical systems like the colloid mill (CM) (Hebishy et al. 2013), high pressure, membrane systems as well as ultrasound (Schultz et al. 2004). At this point, there is no in-depth study on how the presence of turbulence energy will lead to the formation of emulsion. Since turbulence is characterized by four main features: irregularity, diffusivity, rotational and dissipative actions (Pijush and Ira, 2004), it is suspected these characteristics, which involve transfer and conversion of energy in turbulent flow will cause the emulsions to be formed. Indeed, energy is required to form an emulsion. In the pipelines, the fluid flow will certainly needs a certain amount of energy. From the kinetic energy budget equation, the turbulence kinetic energy in the turbulent flow will eventually get dissipated. It is postulated that some of the dissipated energy is used for the formation of emulsions.

Emulsions are also known as “chocolate mousse” or “mousse” among oil spill workers. Emulsions can be classified into three main groups, which are W/O emulsions, oil-in-water (O/W) emulsions and multiple emulsions. Multiple emulsions can be sub-classified into water-in-oil-in-water (W/O/W) emulsions and oil-in-water-in-oil (O/W/O) emulsions. Figure 2 shows three different types of emulsions.

The knowledge of emulsions behaviour is very important as it helps to determine the property of emulsions whether they behave as Newtonian or Non-Newtonian fluid. Gaining this knowledge is useful in the future study of emulsions formation and its evolution in a continuous pipeline flow. This is because the flow rate or the production of the crude oil with emulsions is related to the viscosity of the crude oil. This relationship can be explained by Hagen-Poiseuille equation in Eq(1) (Munson et al., 2010). However, this equation is only applicable for the laminar flow. For turbulent flow, Eq(2) can be used (Munson et al., 2010).

$$Q = \frac{\pi D^4 \Delta p}{128 \mu l} \quad (1)$$

$$\Delta p = \frac{4 l \tau_w}{D} \quad (2)$$

Newtonian fluid is the fluid which the shearing stress is linearly related to the rate of shearing strain. Non-Newtonian can be grouped into shear thinning and shear thickening. For shear thinning fluids, the apparent viscosity decreases with the increase in shear rate. For shear thickening fluids, the apparent viscosity increases with the increase in shear rate. Figure 3 displays the relationships in between shear stress and shear rate for liquid.

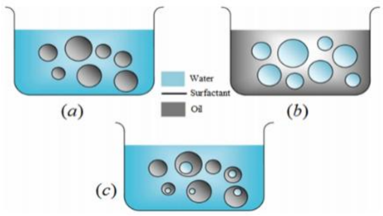

Figure 2: Types of emulsions: (a) W/O; (b) O/W; (c) W/O/W. (Hoshyargar, 2011)

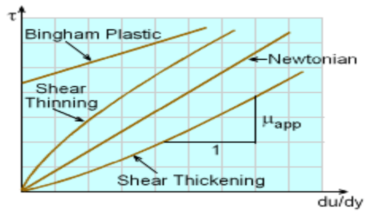

Figure 3: Shear stress and shear rate relationships in liquids (Ngo and Gramoll, n.d.)

Many researchers have carried out research on W/O emulsions using different types of oils under different experimental conditions. For example, Johnsen and Ronningsen have done experimental work to examine W/O emulsions with seven types of live North Sea crude oils with water volumetric concentration of 0 % to

90 %, temperature of 323 K to 343 K, pressure of 1,200 kPa to 10,000 kPa and flow velocity of 0.7 m/s to 3 m/s (Johnsen and Rønningsen, 2003). Farah et al. have carried out W/O emulsions rheological study using six different crude oils with 10 % up to 40 % water volumetric concentration at temperature of 281 K to 323 K and shear rate of 10 s^{-1} to 80 s^{-1} (Farah et al., 2005). Broboana and Balan have performed rheology study of W/O emulsions using Romanian crude oil with 30 % and 6 % water volumetric concentration at temperature of 278 K (Broboana and Balan, 2007) Ronningsen has reported that it is extremely important to predict phase inversion for a specific crude oil because it decides the maximum viscosity of the well stream. Maximum viscosity which then determines the transport capacity for a given design (Ronningsen, 2012). Despite all of these studies, there is no comprehensive rheological study to confirm the behaviour of W/O by using Bintulu Crude Oil. Therefore, this study focuses on using Bintulu Crude Oil with water volumetric concentration of 0 % to 100 %, at a temperature of 313 K, atmospheric pressure and flow velocity of 0.04 m/s to 1.05 m/s (within laminar region for all volume fractions of water less than 0.8).
Thus, the main objective of this study is to investigate the rheological properties of W/O emulsions for different water fractions. Then, the knowledge can be applied in a later stage of study which will be carried out using a continuous closed flow loop setup (as shown in Figure 4 and Figure 5).

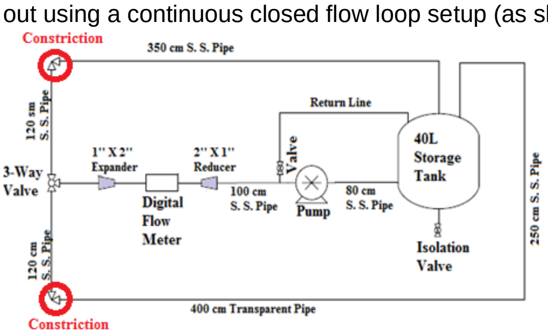

Figure 4: Layout of the continuous flow loop

Figure 5: Actual photo of the continuous flow loop

2. Materials and methods

2.1 Materials

2.1.1 Crude Oil

Bintulu crude oil was used as the continuous phase. Bintulu crude oil is one of the Sarawak low viscosity crude oils from east Malaysia. It has a kinematic viscosity of 1.979×10^{-6} m^2/s at 311 K. This crude oil is classified as light crude oil because it has an API gravity of 39.5 degrees at 289 K. According to the U.S. Geological Survey (URGS) definition, crude oils which have API gravity higher than 22 degrees are classified in light oil group (Meyer and Attanasi, 2003). Table 1 shows the properties of Bintulu crude oil.

Table 1: Properties of Bintulu Crude oil

Test parameters	Unit	Test results	Test method
Appearance	-	Opaque colour	Visual exam
Salt content	lbs/1,000bbls	10.9	N/A
Water and sediment	%vol	0.05	ASTM D4007-81
Total sulphur	%mass	0.047	ASTM D4294-03
Wax content	%mass	0.7	UOP 46
Asphaltenes	%mass	0.15	ASTM D6560

2.1.2 Water

Tap water was used as the dispersed phase. The tap water was used instead of distilled water because its condition is closer to the natural conditions.

2.2 Apparatus

2.2.1 Stirrer

An overhead stirrer model OST 20 digital supplied by Yellow Line was used to stir water in the crude oil phase to form W/O emulsions. Figure 6 shows the overhead stirrer used during the experiment. This type of stirrer automatically adjusts the speed through microprocessor controlled technology within the speed range of 30 – 2,000 rpm. The overhead stirrer gives a constant speed because a continuous comparison of shaft speed to desired speed is maintained and variations are adjusted automatically.

2.2.2 Viscometer

A rheometer model AR 1500 supplied by TA Instruments was used to study the rheology of W/O emulsions. It uses air-bearing technology, drag-cup motor for stress application and optical encoder for displacement/strain measurement. It is armed with a temperature controller to control the temperature in the range of 233 K to 473 K. The cone and plate geometry was used for the experiment. The diameter of the cone was 60 mm and the cone angle was 2 degrees. The gap in between the cone and plate for sample fluid was set to be 61 mm. Figure 7 shows the rheometer used for the experiments.

Figure 6: Stirrer

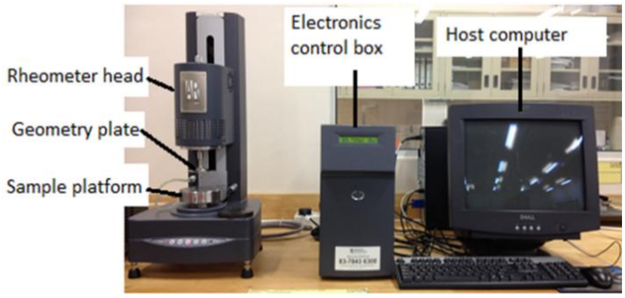

Figure 7: Rheometer model AR 1500

2.3 Experimental Methods

All emulsions samples were prepared in the beakers. Water was poured into the beaker filled with crude oil at desired volume fraction or water cut. Water cut in this study is referred to the ratio of water compared to the volume of total liquids. The volume of total liquids used in this study was 100 mL (taken as 100 %). Then, the solution was allowed to stir for 60 s using the overhead stirrer at a speed of 500 rpm. In the present study, the W/O ratio was varied from 0.1 to 1.0. Then, the mixed mixture was used for rheology measurements using viscometer. Table *2* presents the operating conditions used for the experiments in this study.

Table 2: Operating Conditions for the Experiments

Operating	Unit	Condition
Temperature	K	298
Shear rates	s^{-1}	0 – 1,000
Volume fractions of water or water cuts	- or %	0.1 – 1.0 or 10 – 100

3. Results and discussions

Figure 8 represents the results of viscosity versus shear rate for emulsions at nine different water cuts. As a whole, the figure shows that the viscosity of emulsions decreases with the increase in the shear rate for lower shear rates only. This condition indicates that these emulsions behave as shear thinning fluid at lower shear rates. For shear rates higher than 500 s^{-1}, the change in the viscosity of all the tested emulsions is insignificant. This condition implies that all the emulsions can be considered as Newtonian fluid at higher shear rates.

From this study, it is also known that at the same shear rate, the characteristic of the emulsions flow is different for different water cuts. The characteristic can either be laminar, transitional or turbulent flow. The characteristic of the emulsions flow is different because it is based on the Reynold's number, which is dependent on the density of fluid, the average velocity of fluid, the diameter of pipe and the viscosity of fluid (Munson et al., 2010). Since the density and the viscosity of the tested emulsions is different at different water cuts, hence different flow characteristic is determined at the same shear rate. For example, for water cuts below 80 %, the shear rates of 500 s^{-1} is corresponding to laminar and transitional flow. Meanwhile, for water cuts of 80 % and above, the shear rate of 500 s^{-1} is resembling for fully turbulent flow. Therefore, when applying these results into the study of fully developed turbulent flow using a lab-scale continuous pipeline in the next stage study, the shear thinning property can be excluded for emulsions at all water cuts which is below 80 %. This is because the change in the viscosity is insignificant for Reynold's number above 4,000 for water cuts below 80 %.

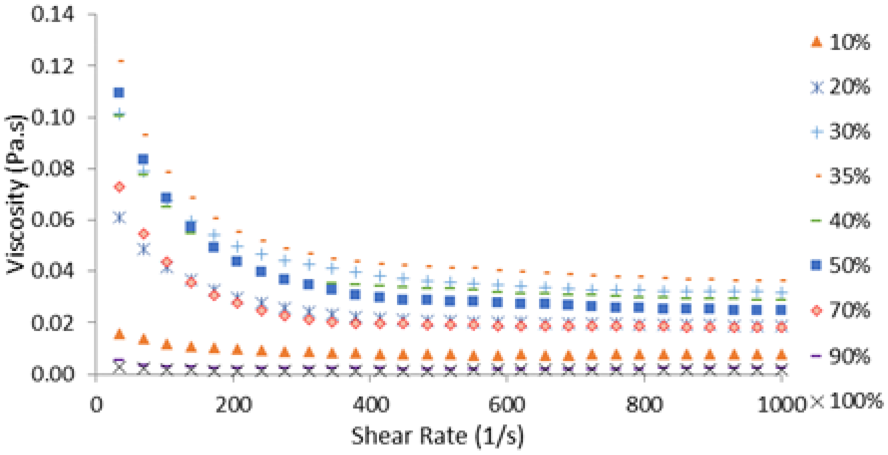

Figure 8: Measured viscosity of emulsions versus shear rate

Figure 9 shows the relative viscosity of all the nine tested mixtures obtained at rheometer velocity of 1.047 m/s. In this study, the relative viscosity is referred to the ratio of the viscosity of the emulsion to the viscosity of pure crude oil. The figure demonstrates that different volumes of water phase (also known as water cuts) results in different viscosity. The viscosity of emulsions increases with the water cut from 10 % up to 35 %, then decreases with a further increase in the water cut up to 100 % (pure water). From the figure, it is clearly shown that the increase in the relative viscosity for water cut from 0 % to 100 % is within a factor of 20. The highest increase in the relative viscosity is at water cut of 35 %. From 10 % to 35 % water cuts, the viscosity increase is most likely due to the increase in the amount of dispersed phase droplets. The dispersed phase droplets refer to the water droplets. Higher amount of dispersed phase droplets directly leads to higher friction among the droplets. Meanwhile for 40 % to 100 % water cuts, the dispersed phase droplets start to coalesce and form larger droplets causing specific area to be decreased. Once the amount of droplets is reduced, the friction among the droplets is reduced as well. This leads to a decrease in viscosity. Another reason for decreasing in viscosity at water cut starting from 40 % is probably due to the inversion from oil continuous system to water-continuous system. The water-continuous system has lower viscosity than the oil-continuous system because water viscosity is lower than that of oil.

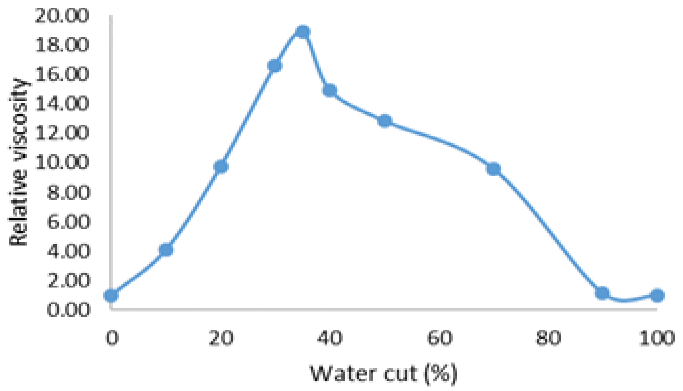

Figure 9: Measured relative viscosity of emulsions at a velocity of 1.047 m/s

4. Conclusions

The paper presented the experimental investigations of the rheological behaviour of W/O emulsions at shear rate from 0 to 1,000 s^{-1}. The crude oil used for the study was Bintulu crude oil provided by

PETRONAS Cari Gali Malaysia. In summary, W/O emulsions formed from Bintulu crude oil behave differently at different shear rates. W/O emulsion shows shear thinning behaviour when the shear rate is between 0 to 500 s^{-1} for water cut that is greater than 0.1. Meanwhile for shear rate in between 500 to 1,000 s^{-1}, W/O emulsions at all volume fraction behave as Newtonian fluid. In this study, the shear rate of 500 s^{-1} corresponds to the laminar and transitional flow for water volume fraction that is lesser than 0.8. Hence, it can be concluded that when working with W/O emulsions in turbulent flow, Newtonian fluid property is to be taken into account instead of non-Newtonian fluid property for water volume fraction lesser than 0.8.

The rheological results obtained are useful for further study. Further study refers to the study of W/O emulsions in fully developed turbulent flow using a lab-scale continuous pipeline. The present rheological results can be correlated with the flow regime of crude oil in the pipeline transportation in furtherance of the study into energy minimization for oil transportation in pipelines.

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