Chapter 8

Temperature Effect on Shear Thinning Behavior of Low-Viscous Oilfield Emulsion

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Additional information is available at the end of the chapter

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Abstract

Crude oil emulsion is causing a lot of problems, especially during crude oil production. There are many ways to mitigate the emulsion problems but this leads to an increment in operating expenses of oil production. In order to comply with the standard sales oil quality, crude oil emulsion must be treated properly. Hence, better understanding of emulsion is essential since emulsion can be available in almost all phases of oil production and processing. This chapter describes how temperature parameters would affect the rheological property of a low-viscous emulsion and how it would become a significant point associated with stability of crude oil emulsion in oilfield production. Experimental results indicated that the water-in-crude oil emulsion formed from low-viscous crude oil exhibits a non-Newtonian shear thinning behavior, which was best presented by the Herschel-Bulkley rheological model. Temperature ranges from 20 to 90°C were examined to study the effect of temperature toward shear stress and viscosity of oilfield emulsion. Measurement of shear stress at shear rates higher than 600 s^{-1} is a new direction in rheology study that not much is known about its effect on shear stress.

Keywords: oilfield emulsion, water in crude oil, low viscous, non-Newtonian, shear thinning, temperature

1. Introduction

Flow assurance in oil industries describes the concerns caused by corrosion, scale, wax, asphaltene, hydrate and oilfield emulsion, which occur in the upstream, midstream and downstream operational activities. Among the mentioned concerns, oilfield emulsion is the most complicated yet unavoidable. It is because the oilfield emulsion is formed in all the three stages of the operational activities. For example, during the upstream operation, oilfield emulsion is formed when producing oil and formation of water (water trapped in the oilfield reservoir) flow together in the porous media under turbulence state. Oilfield emulsion build up which occurs in the near-wellbore area can cause formation damage that restricts the flow of producing oil. Hence, this results in decreased production and increased lifting cost. Also, oilfield emulsion formation occurs in the enhanced oil recovery (EOR) process [1]. When seawater is used in EOR process, water-in-oil (W/O) emulsion in crude oil will be easily formed. Ionic salts such as magnesium chloride, MgCl and sodium chloride and NaCl in the seawater act as a natural emulsifying agent. Subsequently during the midstream operation, formation of oilfield emulsion happens at the exit of the wellbore when crude oil flows through a mechanical wellhead which is known as "Christmas tree" (an assembly of valves, spools, pressure gauges, chokes and fittings connected to a completed well). Turbulence flow and agitation in fittings, chokes and valves of the "Christmas tree" will disperse the produced water (formation water produced during oil production) as water droplets in crude oil phase (also known as water-in-oil (W/O) emulsion). Having similar effect as the ionic salts in seawater, asphaltene and resin compounds (natural polar surfactants in the crude oil) can act as an interfacial barrier between the dispersed water droplets and crude oil, thus preventing coalescence [2] and thus the W/O emulsion will inherently reach a stable condition. Meanwhile at the downstream activities, the carryover of water in the incoming crude oil can also form W/O emulsion in the pipelines when it flows between operating equipment. The carryover of water in the incoming crude oil can cause damage in a crude oil distillation tower where the carryover water will surge the tower pressure when it is vaporized to steam. A sudden increment in tower pressure will disrupt the tower internals or auxiliary equipment.

In conclusion, oilfield emulsion in oil industries is unfavorable as it can create corrosion problems to operating equipment and transportation systems or cause facilities' deterioration, which will lead to a non-economical production [3]. Unfortunately, it is very costly as well as difficult to treat a stable oilfield emulsion. In some cases, oil producers even had to reduce the selling price of their oil for not meeting the required oil quality (i.e., sales oil quality). In Malaysia, the parameter used to determine the oil quality is known as basic sediment and water (BS&W) where the oil must not contain more than 0.5 wt.% BS&W [4–6]. Hence, a good knowledge of crude oil emulsions is essential for enhancing the recovery processes at all oil production stages.

In terms of rheology, oilfield emulsion exhibits a non-Newtonian behavior (refer **Figure 1**). This means that the viscosity of oilfield emulsion is a function of shear rate [7, 8]. Substantially, the oilfield emulsion viscosity is higher than that of the oil or the water as a result of the droplet crowding or amplified structural viscosity. A phenomenon when the viscosity increases at high shear rate is known as a shear thickening effect. Alternately, a shear thinning effect is used to reflect a decreasing viscosity condition. The reduction in viscosity at high shear rate is caused by the broken structure of the interfacial film at the emulsion droplet interface. The scenario of "high shear rate" represents the condition of near-wellbore area or near the operating mechanical equipment [9]. It is important to note that having to handle an oilfield emulsion with a shear thinning behavior under these conditions is preferable as it will not require expensive and complicated treatment. Therefore, it is the aim of this study to study the oilfield emulsion rheology by which the findings from this study reinforce the knowledge of emulsion rheological behavior. Also, this study focuses on the role of temperature factors controlling the rheological behavior of the emulsion.

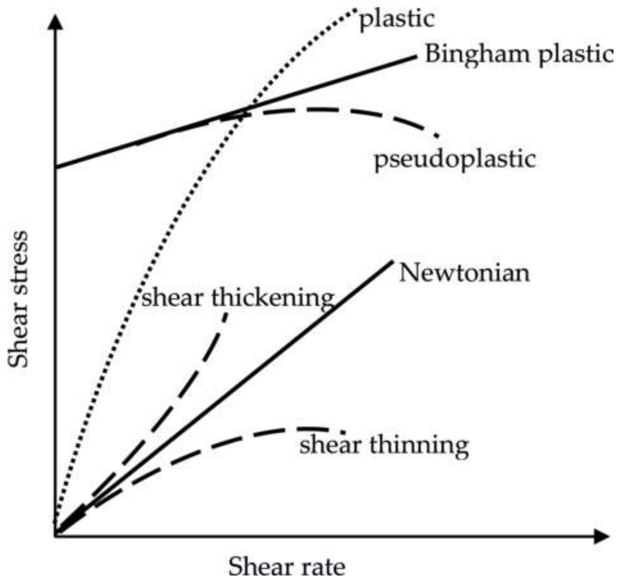

Figure 1. Types of rheological behavior.

Surprisingly, there have been inconsistent findings on rheological behavior of oilfield emulsion. According to Abivin et al. [10], the researchers manifested a Newtonian behavior at low shear rates, below 100 s^{-1}, when they measured the viscosity of live fluid emulsions for water cut of ≤30 w/w%. On the other hand, the emulsions showed a shear thinning tendency at high shear rates, above 100 s^{-1}. On the contrary, Issa and Hunt [11] revealed a non-Newtonian shear thickening behavior for emulsion samples with water cut ranges from 5 to 60%. Surprisingly, other researchers [12, 13] manifested a Newtonian behavior when they conducted a rheological study on emulsified stock tank oil samples and Cold Lake crude oil, respectively. Although many studies have been carried out for trying to understand the complex behavior of W/O emulsion, there are still many outstanding questions about, for example, the effect of temperature on the W/O emulsion behavior.

In the present chapter, rheological measurements of W/O emulsions prepared in an in-house equipment were carried out. For this purpose, emulsified Malaysia crude oil at 2.5 bars was used. The rheology was studied in a rheometer at 20–90°C, at 20 and 30% water cuts and at different shear rates.

2. Experimental procedures

Low viscosity type of crude oil from Bintulu, Sarawak, Malaysia, was received from PETRONAS Carigali Sdn. Bhd. and used in the preparation of 20 and 30 w/w% water-in-crude oil emulsion. Milli-Q water was used throughout the experiment. The properties of crude oil are tabulated in **Table 1**. The sample was homogenized using DIAX 900 homogenizer at 10,000 rpm for 30 min. Then, the produced emulsion was left for 24 h in a vial for

Properties	Sample
Physical state	Liquid
Specific gravity	0.84
API gravity	37.99°API
Pour point	−20°C

Table 1. Properties of Malaysia crude oil.

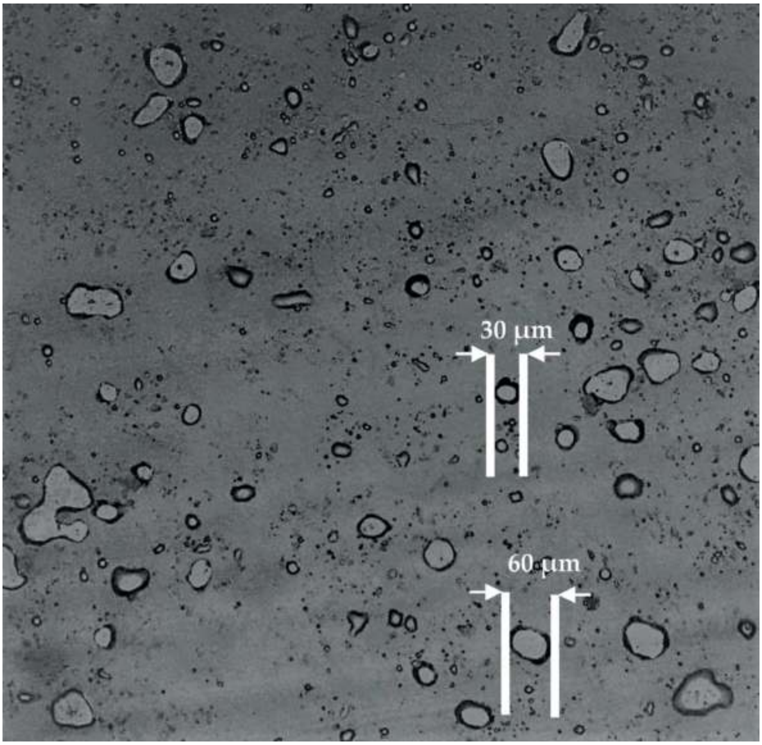

Figure 2. An image of water-in-crude oil emulsion which was captured using an optical microscope (OLYMPUS DP72).

creaming phase to complete. **Figure 2** shows the optical image of the prepared water-in-crude oil emulsion. Rheological behavior of the emulsion was analyzed by using a rheometer instrument (Antoon Paar MCR 301) at 2.5 bar. The rheological tests were conducted within a temperature range of 20–90°C and a shear rate varied from 0.1 to 1000 s^{-1}.

3. Results and discussion

3.1. Rheological model of light crude oil emulsion

A rheological model was developed for the prepared water-in-crude oil emulsion using the basic equation of the Herschel-Bulky model as in Eq. (1) [14] and the experimental data of this study.

$$\tau = \tau_0 + k\,(\gamma)^{n} \tag{1}$$

where τ is the applied shear stress (Pa), n is the flow behavior index (constant), γ is the shear rate (s^{-1}), τ_0 is the apparent yield stress (Pa) and k is the consistency index (Pa s^n). The developed rheological model is stated in Eq. (2) with a recorded regression correlation coefficient, R^2 of 0.99853, and a calculated $n > 1$.

$$\tau = 0.0938 + 0.00494\,\gamma^{1.2308} \tag{2}$$

In the present chapter, we concluded from the Herschel-Bulky model that the water-in-crude oil emulsion for light type of crude oil emulsion at temperature ranges from 20 to 90°C is a dilatant non-Newtonian type since the flow behavior index is greater than 1. On the contrary, it has been reported earlier by Alboudwarej et al. [12] that a heavy type of crude oil emulsion demonstrated both Newtonian and non-Newtonian behaviors at temperature ranges from 20 to 70°C. They highlighted that the oilfield emulsions have formed several different morphologies (water/oil emulsion (W/O), oil/water/oil emulsion (O/W/O), double water/oil/water emulsion (W/W/O/W) and others). The difference in morphology hence produced structural diversity and was postulated by Alboudwarej et al. [12] causing the scatter of the rheological properties of oilfield emulsion from Newtonian to non-Newtonian. To characterize quantitatively the scatter rheological properties, we determined the rheological behavior of the oilfield emulsion as a function of temperature.

3.2. Rheological behavior of light crude oil emulsion

Figures 3(a), **(b)** and **4(a)**, **(b)** summarize the rheogram behavior of shear stress, in Pa, on shear rate, in s^{-1}, for the Malaysian light crude oil emulsion at water cut 20 and at 30 w/w%, respectively. It is important to point out that in the present chapter (1) the water cut selected is reflecting the typical water cut levels of down-hole samples from oil reservoir and (2) the recorded shear rate measurements are from 0.1 to 1000 s^{-1}. As most of emulsion literatures presented the “high shear rate” only within a range of less than 600 s^{-1} [14–17], we determined that a new finding from the present chapter would contribute to the rheology knowledge of oilfield emulsion.

In this case, we found that the shear stress was a strong function of shear rate and temperature [see **Figures 3(a)**, **(b)** and **4(a)**, **(b)**]. Obviously, the water cut, 20 and 30%, has no significant effect on the shear stress. Since the correlation between the shear stress and the

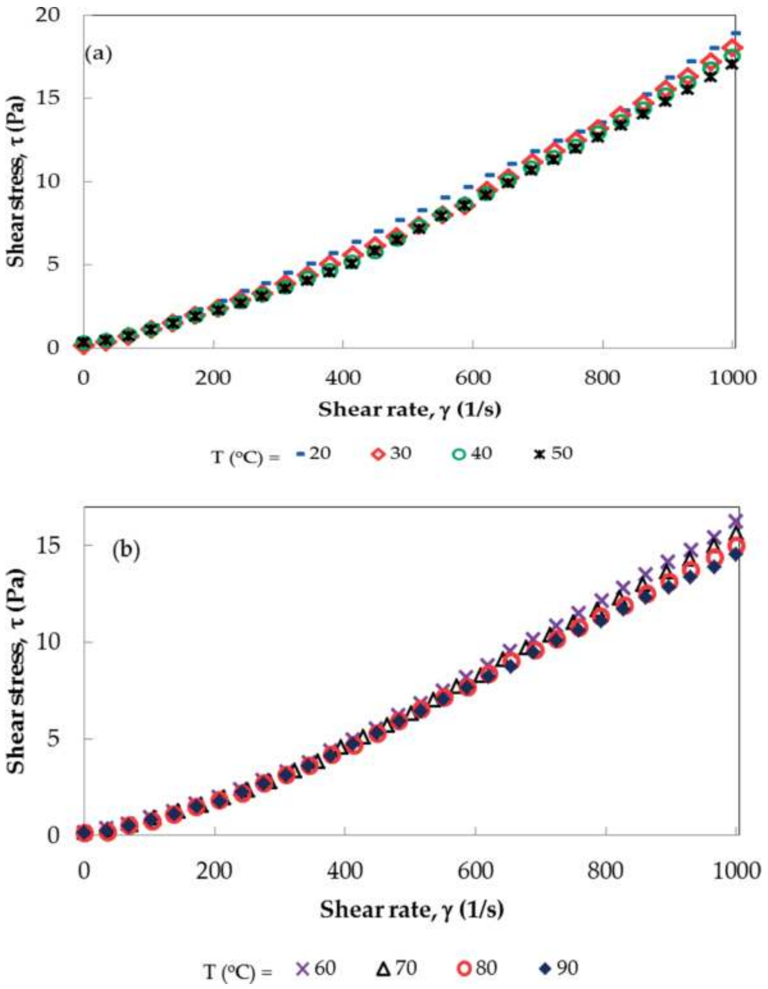

Figure 3. Rheogram behavior of crude oil emulsion at φ = 0.20. (a) Temperature (°C): ▬ = 20°C, ◇ = 30°C, ○ = 40°C and * = 50°C. (b) Temperature (°C): × = 60°C, Δ = 70°C, ○ = 80°C and ◆ = 90°C.

shear rate is nonlinear, the emulsion exhibits a non-Newtonian behavior. This confirmed the rheological model developed earlier. Furthermore, despite the shear rates measured by Meriem-benziane et al. [14] were up to only 120 s^{-1}, the profile of shear stress versus shear rate in the present chapter agrees well with Meriem-benziane et al. findings [14]. The increment change of shear stress, $\Delta\tau$, at two consecutive data points is not extreme, or of less than 5% difference (via manual calculation) reflected that the emulsion exhibits a shear thinning effect.

According to **Figure 3(a)**, the non-Newtonian behavior was not affected by emulsion temperature, between 20 and 50°C, when the water cut is 20%. However, the non-Newtonian behavior

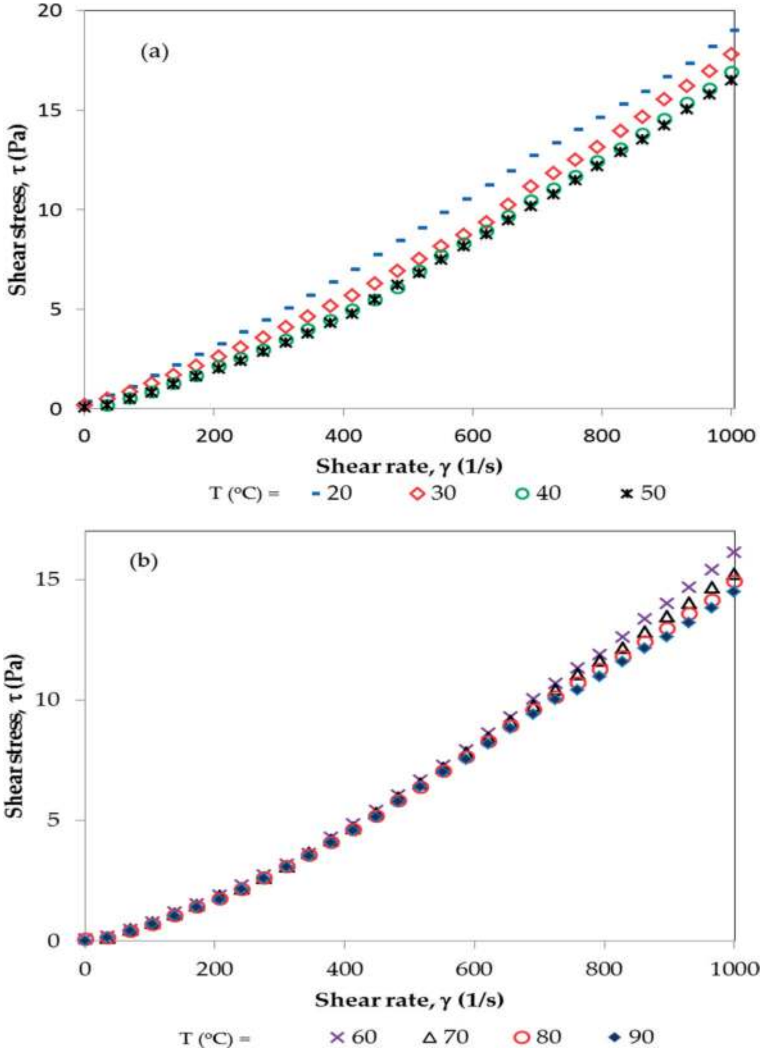

Figure 4. Rheogram behavior of crude oil emulsion at φ = 0.30. (a) Temperature (°C): ▬ = 20°C, ◇ = 30°C, ○ = 40°C and * = 50°C. (b) Temperature (°C): × = 60°C, Δ = 70°C, ○ = 80°C and ◆ = 90°C.

showed an increasing tendency toward shear thinning effect at 60–90°C (see **Figure 3(b)**). At higher temperatures, the measured shear stress was lower than that of lower temperatures. In terms of stability, the non-Newtonian shear thinning behavior is mimicking an unstable emulsion condition [18–20]. Obviously at high shear rates, the attractive interactions between water-water molecules, oil-oil molecules and oil-water molecules are deformed due to the energy exerted by shear dissipated in the water-in-crude oil emulsion. The conditions were then amplified by the higher temperatures.

The effect of temperature toward the shear thinning behavior is much evident when the water cut is 30% [see **Figure 4(a)** and **(b)**]. Within the temperature range here evaluated, we found that the rheology of crude oil emulsion was affected by temperature. Changes in the rheological property were due to the increment of thermal energy in which the structure of the interfacial film formed at the emulsion droplet interface is broken as the temperature increases. This ratifies our earlier work [21]. Furthermore, when temperature is increased, the shear thinning behavior of the emulsion is enhanced. This is inferred by a significant reduction in the shear stress profiles over the shear rate region. In terms of emulsion morphology, the optical images and the shear stress profiles (in **Figures 3** and **4**) showed the low-viscous emulsion is a single morphology (W/O emulsion) and it has uniform structural droplets that determine a single type of rheological properties. To characterize the shear thinning effect in terms of viscosity reduction, we plotted the oilfield emulsion viscosity profile as a function of temperature.

Figures 5 and **6** showed a rheological behavior of the emulsion plotted as viscosity, Pa s, versus shear rate, s^{-1} at 20 and 30 w/w% water cut, respectively. First, we found that temperature does not affect the non-Newtonian behavior of the oilfield emulsion. Previously, temperature was reported to affect the non-Newtonian behavior of heavy-light-crude oil mixtures (HLCO) and leads to Newtonian behavior. At temperature >45°C, the Canada crude oils changed its behavior toward Newtonian when 10% of light crude oil was added to the heavy crude oil. Surprisingly, the Newtonian behavior was reported for as low as 25°C when 20% of light crude oil was added.

At 20–90°C temperatures and water cut = 20%, the viscosity curve visibly showed no significant increment on the viscosity measurement (see **Figure 5**). The findings depict the characteristic of a shear thinning effect in terms of viscosity factor. At increasing temperature, the experimental data of viscosity showed only two decimal places of viscosity reduction.

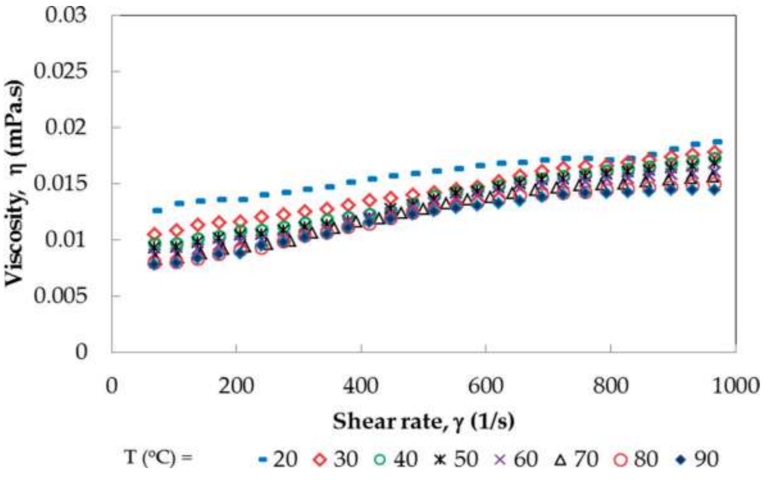

Figure 5. Rheogram behavior of crude oil emulsion at φ = 0.20. (a) Temperature (°C): ▬ = 20°C, ◇ = 30°C, ○ = 40°C, * = 50°C, × = 60°C, Δ = 70°C, ○ = 80°C and ◆ = 90°C.

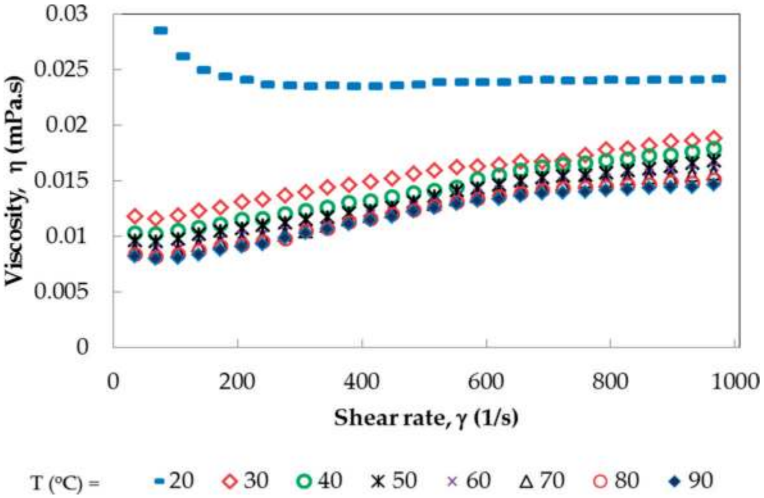

Figure 6. Rheogram behavior of crude oil emulsion at φ = 0.30. (a) Temperature (°C): ▬ = 20°C, ◇ = 30°C, ○ = 40°C, * = 50°C, × = 60°C, Δ = 70°C, ○ = 80°C and ◆ = 90°C.

This reflects that the temperature factor does not significantly affect the structural droplets or deformation of the structure of the droplet interfacial film. Previous researchers concluded that the viscosity of W/O emulsion depends on shear rate, droplet size, water cut and temperature, where the last two factors are the most influential [22, 23]. Surprisingly, we determined that temperature does not exert any influence on the viscosity of the non-Newtonian emulsion (see **Figure 5**). To the best of our knowledge, it is the first time that the rheology of emulsions is not affected by temperature; usually it is the droplet size that was reported in the literature about not affecting the rheology [24]. Furthermore, at higher shear rates, of more than 700 s^{-1}, the viscosity data are almost plateau. This diverse structural change toward a Newtonian behavior is attributed by either the emulsion stability effect or the less elastic behavior of the emulsion.

Despite increasing the water cut by 10% (**Figure 6**), the viscosity curves for temperatures 30–90°C showed no dramatic reduction. The shear-thinning effect is much stronger only in the case of T = 20°C. Between 10 and 200 s^{-1}, the drop of the viscosity is obvious as it reflects the low resistance flow toward the spindle (of the equipment) movement. Emulsion droplet geometry is changing from spherical to stretched droplets of elliptical cross sections [10]. While at 30–90°C, the overall viscosity profiles slump toward a region of less than 15 mPa s viscosity. At this condition of water cut = 30%, increasing temperature significantly affects the structural droplets or the deformation of the structure of the droplet interfacial film. This is depicted by an evident reduction of viscosity curves at the measured temperatures, as shown in **Figure 6**. The increment in temperature reduced both the viscous and the interfacial forces, reduced the thixotropic properties and increased the droplet cavities [25]. Furthermore, it is possible that a number of transient cavities were increased as temperature increased as well. We believe this finding reinforced the development of oilfield emulsion treatment technology whereby oilfield emulsion at water cut 20 and 30% exerts a similar shear thinning behavior and is independent of temperature.

From the thermodynamic point of view, temperature is the main attribute toward emulsion instability. Water droplets in the crude oil phase are unstable at high temperatures. It is because when the viscous force and interfacial force of droplets decrease in the application of heat, the internal thermal energy of the crude oil droplets increases and thus promotes coalescence rate. Eventually, oilfield emulsion is destabilizing. This thermal method is practiced in the oil refinery industry [26]. However, high temperatures will also reduce the viscosity of the bulk phase where it will increase the joining rate and size of the droplet will increase, respectively. In conclusion, the effect of temperature on the emulsification process is a complicated matter.

Although viscosity of emulsion is reduced at high temperatures, there is an optimum value for the effective separation process. If the temperature is too high or beyond the optimum temperature [27], the light hydrocarbon components of crude oil will evaporate out and eventually reduce the selling price of the crude oil. Another impact is the uncontrolled formation of air bubbles, which adversely reduces the phase separation efficiency and the crude oil and water phases will be re-emulsified.

4. Conclusion

Research on rheological behavior of crude oil emulsion is vital due to complex behavior of crude oil. 20 and 30 w/w% of low-viscous emulsion showed that it exhibits a non-Newtonian shear thinning behavior and the experimental data fitted the Herschel-Bulkley model. Results also showed that the shear thinning non-Newtonian behavior of the water-in-crude oil is temperature dependent. The influence of shear rate on the viscosity is observed to increase as the temperature of the emulsion increases. The present chapter revealed oilfield emulsion rheological behavior at very high shear rate measurements, of up to 1000 s^{-1}. Also, this is the first time we revealed that the viscosity of emulsion is not affected by temperature.

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