RESEARCH PAPER

Investigation of Stability and Rheology of Produced Heavy-Oil Emulsions Formed due to Steam Injection

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Abstract

Water in oil emulsion is considered as one of the major challenges encountered during the production of heavy oil or applying enhanced oil recovery techniques whether thermal or chemical. In this study, the stability and rheological properties of hot and cold-produced heavy oil emulsions, formed due to steam injection processes in Kuwaiti reservoirs, were investigated thoroughly over a wide range of operation conditions. The effects of temperature, shear rates, and water cuts on the physical and chemical behaviors of the heavy oil emulsions were examined experimentally in detail. The results showed that the cold-produced heavy oil emulsion (CP-HO) is more stable than the hot produced heavy oil emulsions (HP-HO) because of its high salinity concentrations and low resin/asphaltene (R/A) ratios, and low PH value. Moreover, a new emulsion viscosity correlation was developed using the experimental data. The proposed model was validated against existing models. The results showed that the developed correlation i is more applicable than the existed one in predicting the viscosity of heavy oil emulsions with a percentage of the deviation of almost less than 5%.

Introduction

As the world's demand for oil increases, more attention is given to heavy oil (HO) reservoirs; however, heavy oil production brings new challenges. The formation of HO emulsions during production, recovery, treatment, and transportation of heavy crude oil is one of them. In conventional and HO production, emulsion occurs when crude oil and produced water or injected steam are mixed in the reservoir, wellbore, or surface facilities. A tight emulsion will be formed when HO fluid passes through choke valves, pumps, and lines causing viscosity to build up that might lead to pumping problems and difficulties in oil-water separation processes.

In general, emulsion occurs whenever there is enough shear force while heavy crude and produced water flow through the production path [1]. This phenomenon may be particularly crucial during the primary and secondary production of heavy oils where steam is used to reduce the viscosity of oil or in cases where submersible pumps are used to artificially lift the produced fluids. Presence of inorganic (sand, clays, and corrosion products) and organic materials (asphaltene, resins, and naphthenic acids) in HO act as natural emulsifiers and enhance the emulsion's stability [2]. In most cases, emulsions are undesirable because they have higher volume and viscosity than crude oil. They may also cause high pressure losses, resulting in transportation, pumping problems, and difficult separations that lead to an increase in capital and operating costs.

Moreover, the stability of emulsions is controlled by multiple factors such as temperature, demulsifier dosage, and resin to asphaltene (R/A) ratio in the crude oil. With the presence of

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fine solid particles that act as stabilizing agents, such as asphaltene and resins, the coalescence process could be delayed. The molecules of crude oil cannot form a stable film without distributing uniformly when the content of asphaltene is low. This, in turn, results in droplet coalescence and emulsions instability. At a high asphaltene concentration, it is more likely that the stable film around the droplets is formed, which in turn resists droplets coalescence and thus enhances the emulsion stability. However, the higher the resin-asphaltene ratio the looser the emulsion. High resin concentration keeps more asphaltene particles dissolved in oil allowing for more droplets coalescence, therefore, decreasing the stability of emulsions [3,4].

Pilehvari et al. [5] investigated the rheological characteristics of heavy oil emulsions and pointed out that in all water-oil ratios (W/O), emulsions show remarkable non-Newtonian shear thinning behavior. The study also indicated that the oil droplet size is the main factor affecting their rheological behavior. The data revealed that the smaller the emulsion droplets, the higher the viscosity.

In most emulsion fluids there is a certain point where phases are reversed and the viscosity of emulsion fluid drops dramatically. This point is called the phase inversion point (PIP) of an emulsion and it is a very essential parameter for the production engineers. PIP is a conditional parameter depending on various factors such as characteristics of heavy oil, water droplet size, chemicals, emulsifying conditions, etc. In general, the higher the density and viscosity of crude oil the greater the PIP. This may be due to the high content of its natural emulsifiers such as asphaltene, resin, organic acids, etc. As a result, more emulsifying molecules absorb on oil-water interface thus strengthening and increasing the film thickness around the droplets, which leads to more favorable conditions for dispersion of the water droplets. When the water content in the oil is large enough to destroy the oil-water interfacial film, water droplets may coalesce, and the W/O emulsion will reverse to an O/W with a lower viscosity and flow drag [6,7].

Duan et al. [8] studied the phase inversion properties of heavy oil-water emulsions with chemicals. They investigated the effect of heavy oil composition, chemical agent, and stirring on phase inversion using a microscopic image analysis system. They found that the phase inversion point (PIP) is a conditional parameter and controlled by oil composition and experimental conditions.

Maneeintr et al. [9] studied the effect of temperature, water content, and shear rate on the viscosity of heavy oil emulsions. Crude oil emulsion fluid samples were obtained from the fields in Oman and Japan that were exposed to steam injection. The results showed that the viscosity of the produced fluids decreases with increasing temperature and shear rate, and decreasing the water content. The results also revealed that increasing the temperature has a greater effect on decreasing the viscosity of emulsions with high dispersed phase volumes comparing with those of low dispersed phase volumes. Viscosity was reduced up to 86% when increasing the temperature from 25° to 60°C. The study also covered the relation between shear rate and droplet size. The results indicated that although increasing shear rate reduced the droplet size, the viscosity was lower at higher shear rates. This means that the shear rate has a predominant effect on viscosity. Finally, a new correlation describing the effect of temperature on viscosity was developed.

In the light of the above, it seems that more studies are needed to clarify the effects of several sensitivities on the viscosity, and stability of heavy oil emulsions. It is also essential to predict the viscosity and inversion point of HO emulsions accurately at different operating conditions. For this purpose, this study aims to investigate the effect of temperature, water cut, mixing rate, and shear rate on the viscosity, and stability of produced heavy oil emulsions. The generated data are used to develop a new viscosity correlation which is validated and compared with different existing correlations for HO-emulsion.

Materials and Methods

Three heavy oil emulsion samples with different API densities ranging from 11.65 to 14.65 were used in this study; one cold produced heavy oil (CP-HO) and two hot-produced heavy oil (HP-HO) emulsions samples collected at two different cycles of steam injection (HP-OH-1 and HP-HO-2). Table 1 summarizes the physical and chemical properties of the dry heavy crude oils. The basic sediments and water (BS&W %) were measured for the three emulsion samples using a standard method (ASTM 4007); the results are shown in Table 2. The separated formation water was characterized as shown in Table 3.

Heavy-Oil Emulsions Preparation

The emulsion samples were prepared by mixing the separated formation water with the original emulsion for five minutes using a heavy-duty mixer. Then, the sample was transferred to a preheated stainless steel cup connected to a temperature-controlled chiller to attain the equilibrium. The emulsion was heated to the needed temperature for 20 min to allow water separation and then cooled down to 60°C for condensation. The separated water was collected and the percentage of separation was measured based on the original water content. Table 4 shows the selected ranges of the operating conditions used in this study.

Viscosity Measurement

A temperature-controlled rotational viscometer-model (Haake-RS-600) was used for dynamic viscosity measurement of Newtonian and non-Newtonian fluids at different temperatures and shear rates, which can measure viscosities in the range of 2.0 to 200,000 cP using a cylindrical spindle (DIN 53018). The rheometer operates at shear rates ranging from 0 to 1000 s^1 and temperatures ranging from -10 to 180°C. Rheocal software is connected to the system providing the needed calculations and viscosity plots.

Table 1. Physical and chemical properties of dry crude oil samples

Test Required	Method	Units	CP-HO	HP-OH-1	HP-OH-2
API Gravity @ 25°C	IP-2000		13.5	11.65	14.56
Micro-Carbon Residue (MCR)	D4530	wt%	12.03	12.58	11.76
Molecular weight		g/gmol	425	445	411
Wax content		Wt%	0.462	0.417	0.551
Salt content	D3230	PTB	>150	4.8	10.5
SARA analysis					
Saturates (S)	IP143	wt%	17.03	15.28	15.28
Aromatics (A)		wt%	70.33	65.27	63.79
Resins (R)		wt%	3.42	11.51	13.39
Asphaltene (A)		wt%	7.57	7.93	7.57
R/A ratio			0.45	1.45	1.77
Total sulfur	IP-160	wt%	5.351	4.96	5.550
Total nitrogen	D5762	wt%	0.207	0.210	0.146
Ni	D5708	ppm	28.73	32.5	33.3
V	D5708	ppm	98.26	106.5	107

API: American Petroleum Institute
SARA: Saturate, Aromatics, Resin, and Asphaltene

Measurement of the Droplet Size Distribution

The droplet size and their distributions of the prepared emulsion samples were measured using the dispersion technology DT1200 machine at room temperatures. The emulsion sample is separated first into two phases (dispersed phase and continuous phase). Then, 100 ml of each

phase is charged separately to the machine DT1200 to define the sound speed and the attenuation of each phase, and this data is stored in the database system. Table 4 shows the selected ranges of the operating conditions that were used for this study.

Table 1. Basic sediments and water measurement for emulsion samples

Sample Name	BS&W (%)
CP-HO	8
HP-HO-1	9-43
HP-HO-2	15-21

BS & W: Basic sediments and water

Table 2. Summary of a full API water analysis for the hot and cold heavy oil emulsion

Type of analysis	Unit	CP-HO (8%)	HP-OH- 1 (9%)	HP-HO- (40%)	HP-HO- (21%)	HP-HO- (19%)
Sodium (as Na)	mg/l	11,092	1,970	2,355	1,159	6139
Calcium (as Ca)	mg/l	2,343	487.71	557.66	115.89	-
Magnesium (as Mg)	mg/l	1,622	89.20	73.72	5.64	-
Potassium (as K)	mg/l	152	90.73	100.87	72.67	-
Strontium (as Sr)	mg/l	79	10.47	9.53	1.11	-
Barium (as Ba)	mg/l	1.63	0.29	1.013	0.363	-
Iron (as Fe)	mg/l	0.02	0.07	2.01	1.54	-
Boron (as B)	mg/l	2.10	3.48	3.717	4.81	-
Litium (as Li)	mg/l	0.81	0.33	0.368	0.18	-
Silicon (as Si)	mg/l	15.63	24.738	32.04	61.87	-
Chloride (as Cl-)	mg/l	27,767	3,395	4,323.9	1,846	17149
Sulphate (as SO_4^{2-})	mg/l	37.00	54.7	211.7	627.7	-
Dissolved H_2S and Mercaptans	mg/l	19.95	-	-	-	-
Bi-carbonate(HCO_3 -)	mg/l	716.05	160.5	288.41	160.8	324
Conductivity	mS/cm	57.40	10.42	12.65	5.68	35.3
TDS	mg/l	43,828	3,620	8,030.9	7,055	21400
Salinity (calculated)	mg/l	43,000	5,998	7,282	3,269	22,300
pH @ 25 ^{0}C		6.56	7.99	6.96	7.36	7.36
Density @ 25°C	g/cm^3	-	1.003	1.003	1.000	-
Hardness	mg/l	-	1,585	1,696.4	313	8636
Total Alkalinity	mg/l	-	160.55	288.41	160.8	324

Table 3. Selected ranges of the operating conditions for the stability and rheology

Test Parameters	Stability	Rheology
Temperature (°C)	140, 180	20, 60, 95, 140, 180
Water cut (vol%)	20, 40, 60	0, 40, 60
Mixing rate (RPM)	500, 1000, 1500	500, 1000, 1500
Demulsifier dose (ppm)	200, 300	-
Pressure (bars)	1.00	1.00
Shear rate (s^{-1})	-	100, 200, 300

Vol %: Volume Percent; RPM: Revolution per minute; ppm: Parts per million

Results and Discussion

Characterization of Crude Oil Emulsion

Table 1 shows that the separated water from (CP-HO) has the lowest pH value (6.56), which means it is more acidic, while the water separated from first hot produced water (HP-HO-1), which has a water cut of 9%, has the highest pH value of (7.99), which means it is more basic. Also, the salinity presented by total dissolved solids (TDS) of the formation of water separated from the (CP-HO) is much higher than the salinity of all the HP-HO samples. This is expected as the steam condensate and mixed with formation water thus decreasing the salinity of the aqueous phase.

Stability of Heavy Oil Emulsions

The stability of CP-HO emulsion samples was tested at different mixing rates (500, 1000, and 1500 rpm) and different temperatures (140 and 180°C) using standard bottle tests where samples are placed in a preheated water bath and water separation is observed and recorded up to 5 hours. Figs. 1a and 1b show that the emulsion samples were very stable at the water cut of 60% for all the three mixing rates with water separation less than 10% at 140 °C and 35% to 40% water separation was observed at 180°C. Maximum water separation of 60 % and around 65% was observed at 20 % water cut and 500 rpm at both 140 and 180 °C, respectively. The figures also revealed that the stability of emulsion increases as the water cut and the shear rate increases.

    The stability of the HP-HO-1 and HP-HO-2 emulsion samples were tested after the first cycle of steam injection at different times and a reservoir temperature of 60°C. Results are shown in Fig. 2. The results revealed that emulsion sample HP-HO-1 (9%) was more stable than HP-HO-2 (21%) when a dosage of 300ppm of chemical demulsifiers was used for a retention time of more than 4 h. This may be due to the low R/A ratio of 1.45 for HP-HO-1 compared to HP-HO-2 with a R/A ratio of 1.77.
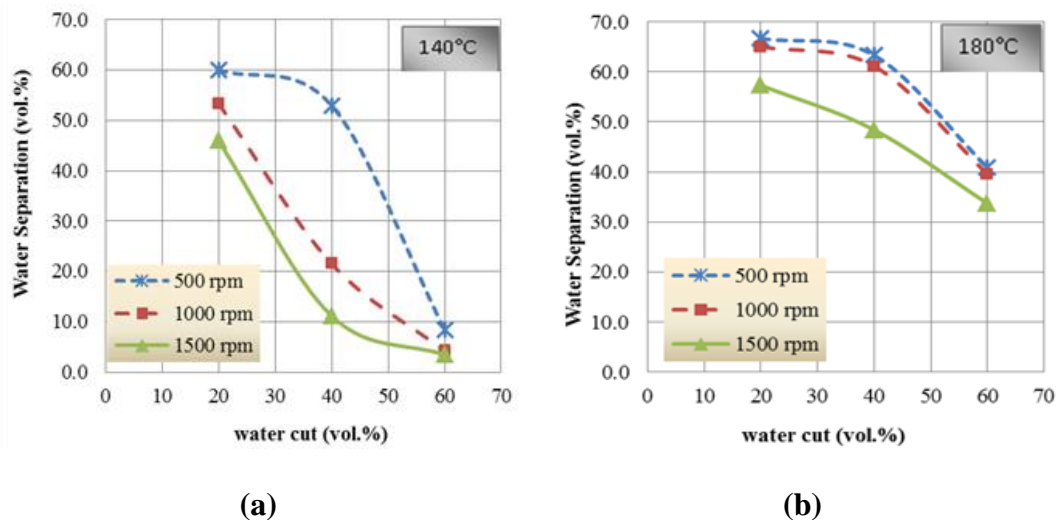

(a)   (b)

Fig. 1. Effect of water cuts on the water separation of the CP-HO emulsion at different mixing rates and 140°C and 180°C
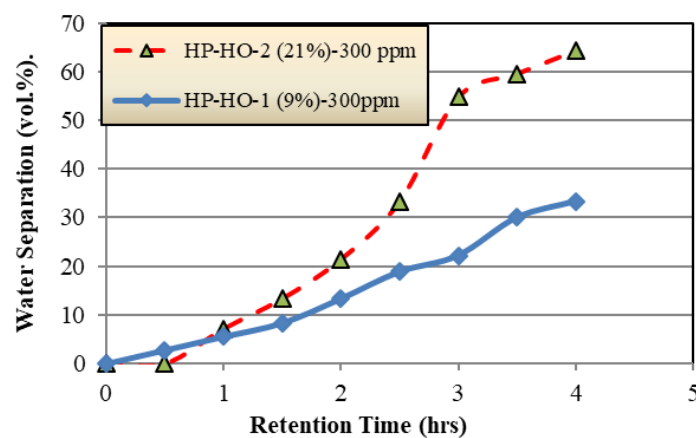

Fig. 2. The stability tests results of the HP-HO-1 and HP-HO-2 emulsion samples with chemical 300 ppm of demulsifier at 60°C

Fig. 3 shows the effect of the formation of water salinity on the stability of heavy oil emulsions. The water separation was observed for 5 hours at 60 °C. The data revealed that as the water salinity decreased from 43,000 ppm to 3,269 ppm due to the steam injection, the amount of separated water increased by triple as shown in Fig. 3, which means that the emulsion becomes less stable. Same observations were reported in previous studies conducted by Moradi et al. [10] and Douglas et al. [11].
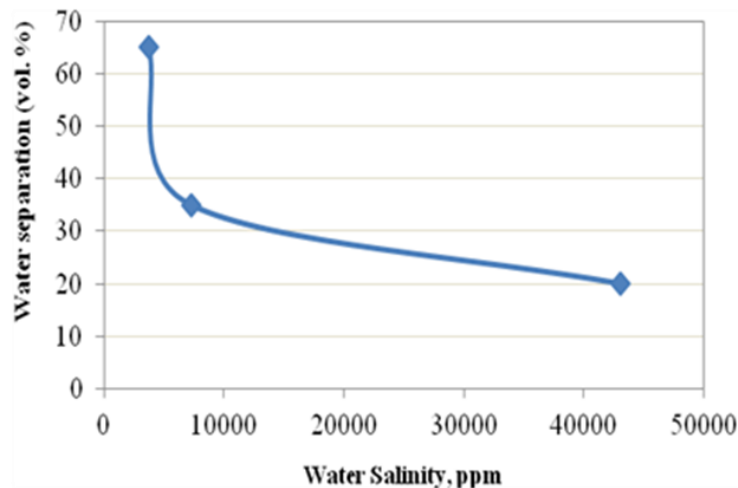

Fig. 3. Effect of formation water salinity on the water separation of heavy crude oil emulsions at 60°C and 300 ppm of chemical demulsifier

The effect of different dosages of chemical demulsifier on the stability of hot produced emulsions was investigated and the results are presented in Fig. 4. The data indicate that as the demulsifier dosage increases the water separation increases in both HP-HO-1 and HP-HO-2. However, HP-HO-1 seems to be more stable than HP-HO-2 for all ranges of demulsifier doses.

To understand the role of R/A and its effect on water separation, R/A versus the amount of separated water over 4 h at 60°C were shown in Fig. 5. It is clear that as the R/A ratio increases, the emulsion stability decreases, and the percentage of water separation increases. This is because resin acts as a good peptizing agent for asphaltenes, and at a sufficiently higher R/A ratio, c resin can substitute asphaltenes at the water-oil interface causing the interface to be more mobile and less likely to avoid coalescence of water droplets as was reported [12-14].
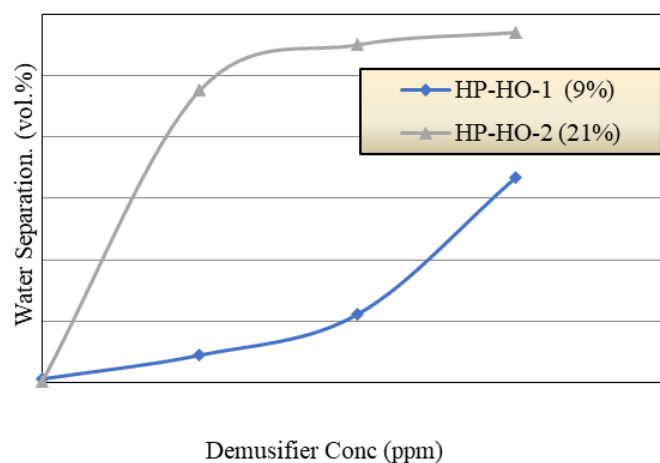

Fig. 4. Effect of chemical demulsifiers on the water separation of different emulsion samples after 5 h at 60°C

Results of SARA analysis indicate that CP-HP has the lowest resin to asphaltene ratio (R/A) of 0.45 while HP-HO-2 has the highest resin to asphaltene ratio of 1.77. That means the resin content in CP-HO is not sufficient to prevent asphaltene flocculation. Also, water analysis results indicate that CP-HO has the lowest pH and lowest salinity. Therefore CP-HO emulsion was found to be more stable than the HP-HO. A similar observation was highlighted in previous studies [10-14].
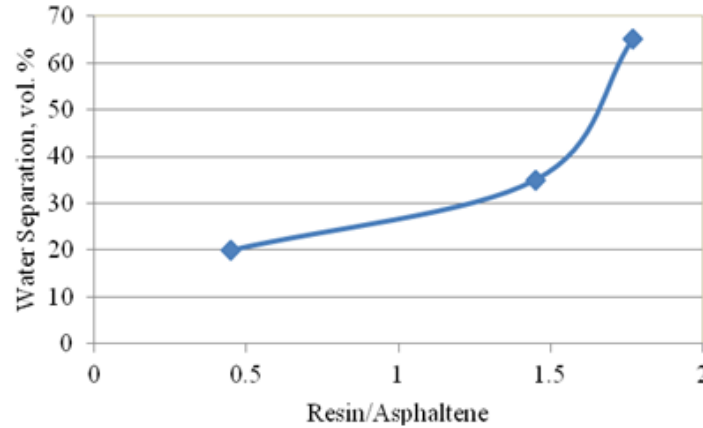

Fig. 5. Effect of resin to asphaltene ratio (R/A) on the stability of CP and HP-HO emulsions at 60°C

Particle size distribution (PSD) of HP-HO-1 and HP-HO-2 crude oil emulsion samples were evaluated using the acoustic dispersion technique at different conditions. These conditions including water cuts (WOR) and mixing rates. PSD tests were performed under ambient temperature and at atmospheric pressure. Fig. 6 shows that as the water cut increases, the droplet size decreases. Thus forming smaller droplets, which in turn enhances the stability of emulsions. This finding agrees with previous study conducted by Pilehvari [5].

Viscosity of Heavy Oil Emulsions

The viscosities of all emulsion samples were determined using Haake Rotoviscometer RS-600 at various temperatures (20 to180°C) and various shear rates (100 to 300 s^{-1}). Apparent viscosity versus shear rate plots was established as a function of various parameters; namely, temperature, water cut, and mixing rates for all prepared emulsion samples. The results are shown in Tables 5 and 6.
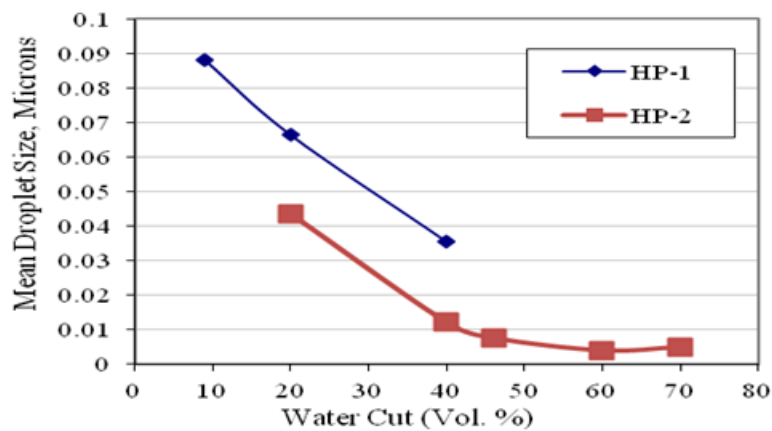

Fig. 6. Effect of water cut on the mean droplet size of HP-HO-1 and HP-HO-2 emulsion samples

Figs. 7a and 7b show that the viscosities of (CP-HO) and (HP-HO-2) decrease as the shear rate increases and it became more pronounced as the temperature increases from 60 to 180ºC. This indicates that the emulsion samples show a non-Newtonian shear-thinning behavior.

Table 4. Viscosity of CP-HO emulsion sample at different WOR, rpm, shear rates, and temperatures

T (°C)	Shear rate (s⁻¹)	Viscosity (cP) at different water cuts							
		0%	8%	40%			60%		
		0 rpm	500 rpm	500 rpm	1000 rpm	1500 rpm	500 rpm	1000 rpm	1500 rpm
20		1525	-	>5000	>5000	>5000	>5000	>5000	>5000
60			96.4	178	285	367.9	782.1	954.52	1154.4
95	100		-	91.6	91.4	108.9	171.9	190.19	273.3
140			-	29.7	35.2	37.26	67.56	59.80	71.45
180			-	21.4	19.5	20.86	17.68	20.00	26.68
20		1443	-	>5000	>5000	>5000	>5000	>5000	>5000
60			73.2	175.5	254.61	350.24	565.51	778.62	1008.1
95	200		-	86.13	87.56	98.54	138.4	149.0	238.15
140			-	27.8	32.58	35.24	56.96	52.12	61.30
180			-	15.9	13.00	18.59	13.03	10.00	21.11
20		1343	-	>5000	>5000	>5000	>5000	>5000	>5000
60			61.7	170.6	210.3	337.5	395.4	149.01	878.75
95	300		-	81.6	83.97	99.68	115.9	133.57	205.08
140				25.1	31.10	33.95	42.49	48.18	46.76
180				5.50	6.83	6.67	7.27	10.00	15.49

Table 5. Viscosity of HP-HO-1 emulsion sample at different WOR, shear rates, and temperatures

Temperature (°C)	Shear Rate (s⁻¹)	Viscosity at Different Water Cuts (cP)		
		9%	15%	43%
25		2451.0	3175.79	3800
60	100	234.0	265.37	628
100		23.8	56.55	83.0
150		15.4	21.37	45.6
25		2386.0	2995.79	3120
60	200	230.0	255.68	566
100		17.1	52.64	77.0
150		8.50	10.30	13.0
25		2290.0	2500.0	2850
60	300	226.0	251.5	521
100		8.7	49.9	76.0
150		3.5	5.7	8.6
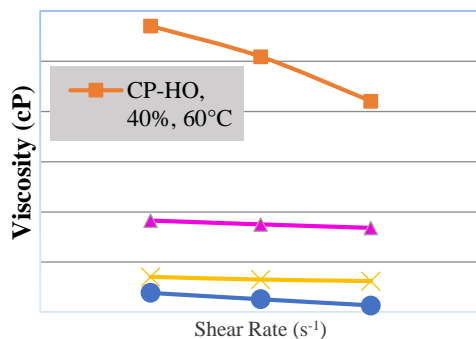
(a)
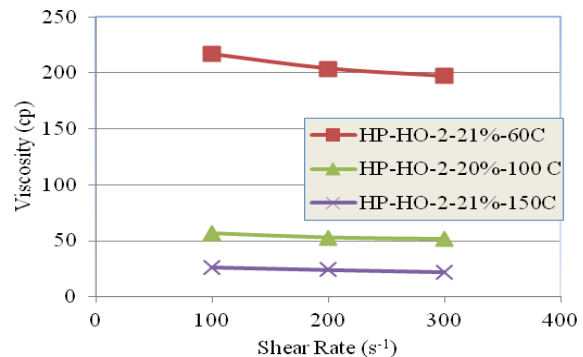
(b)

Fig. 7. Effect of shear rate on the viscosity of the CP-HO and HP-HO-2 emulsion samples at different temperatures

Figs. 8 and 9 show the effect of temperatures on the viscosity of the CP-HO and HP-HO-1 emulsion samples respectively. The results show that heavy oil emulsion's viscosity decreases as the temperature increases. The high temperature would break the π-π bonds and the hydrogen bonds that were formed due to the interaction among asphaltene and resin molecules in the heavy oil system leading to a significant reduction of the viscosity [15].
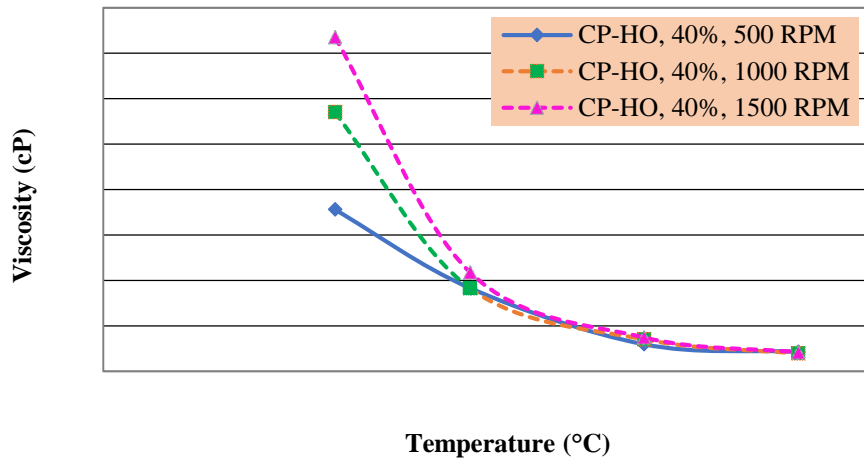

Fig. 8. Effect of temperature on the viscosity of the CP-HO emulsion sample with a water cut of 40% at different mixing rates and a shear rate of 100 s^{-1}
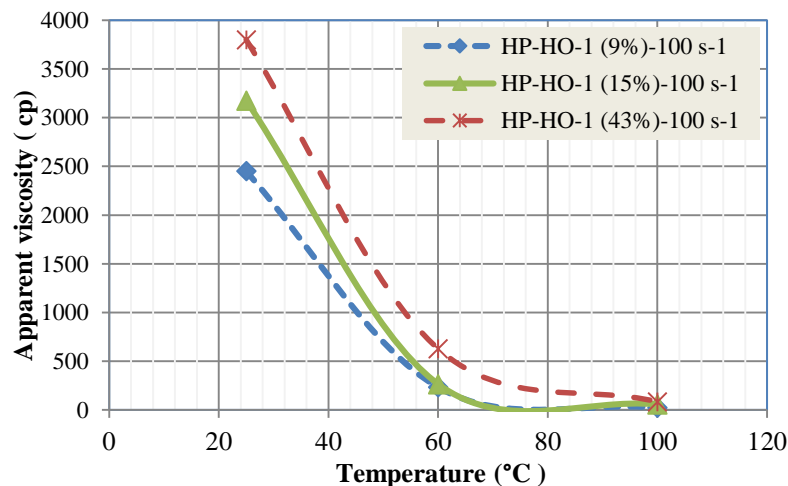

Fig. 9. Effect of temperature on the viscosity of the HP-HO-1 emulsion samples at different water cuts and a shear rate of 100 s^{-1}

Fig. 10 shows the effect of water cut on the viscosity of the CP-HO, HP-HO-1, and HP-HO-2 emulsion samples at a shear rate of 200 s^{-1} and temperatures of 50 and 60℃. The data illustrates that viscosity increases as the water cut increases by up to 60%. As the water cut increases, the number of water droplets per unit volume of emulsion increases, and the droplet-droplet interaction became higher, therefore, viscosity increases, similar findings were reported by reported Maneeintr et al. [9] and Yarri et al. [16]. This indicates that the emulsion samples were very stable and there was no phase inversion point (PIP) up to a water cut of 60%. However, for the hot produced emulsion samples, HP-HO-2, PIP took place at a water cut of 60% where viscosity drop dramatically. Fig. 11 shows that as the water cut increases, W/O emulsion droplet size becomes smaller with fewer changes of droplets coalescing, thus enhancing the stability of emulsions which intern resulted in increasing the viscosity. Hence, the droplet size can be considered as the main factor affecting the rheological behavior of heavy W/O emulsion.
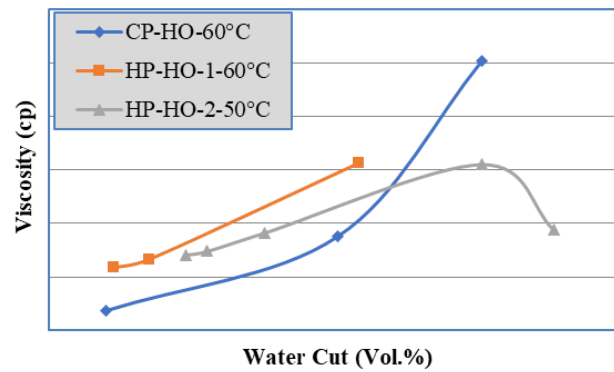
Fig. 10. Effect of water cut on the viscosity of the CP-HO, HP-HO-1, and HP-HO-2 emulsion samples at different temperatures and a shear rate of 200 s^{-1}
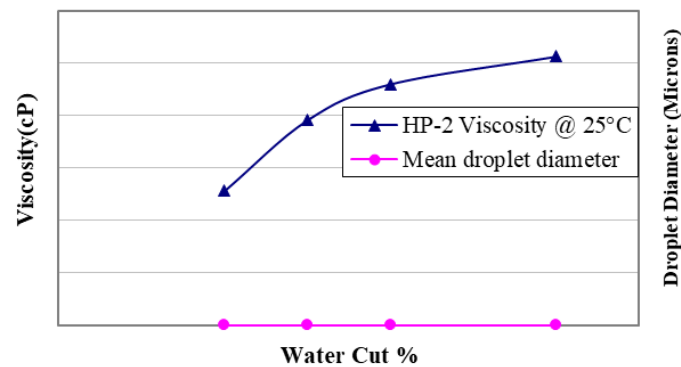

Fig. 11. Effect of water cut on the viscosity and droplet size of HP-HO-2 at 25ºC and 100 s^{-1}
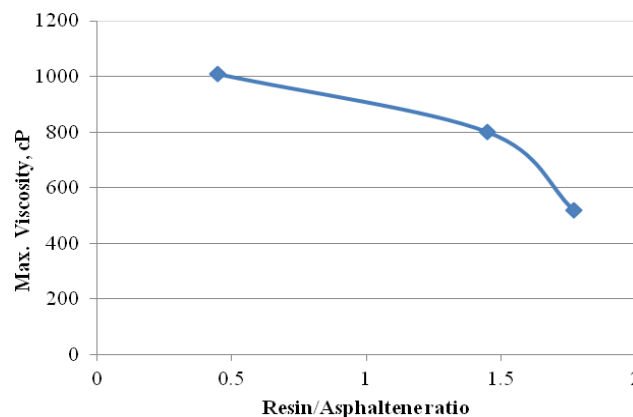

Fig. 12. Effect of resin to asphaltene ratio (R/A) on the max viscosity of CP-HO and HP-HO emulsions at 60% water cut, 60°C, 200 s^{-1}

It can be found from the data in Table 1 and Fig. 12 that, CP-HO has the lowest R/A ratio and highest viscosity. As the R/A ratio increases (which is the case in the HP-HO), the emulsion viscosity decreases. The increased viscosity of the oil-containing low R/A ratio is attributed to the fact that the presence of resins as peptizing agents for asphaltene decreases the formation of asphaltene aggregates and hence decreases the total dynamic shear viscosity [17].

Figs. 13a and 13b show the effects of water cut (WOR) on the viscosity of HP-HO-2 emulsions prepared at 1500 rpm and tested at different temperatures (25 to 50°C) and different shear rates (20 to 300 s^{-1}). In general, the results imply that, as water cut increases, viscosity increases. A phase inversion is observed at 60% water cut when tested at 25ºC and shear rates of 100s^{-1} and above where the viscosity dropped quite significantly (Fig. 13a). No inversion point was observed at a low shear rate of 20 s^{-1} and 25°C. At a higher temperature (50°C), the phase inversion takes place at higher shear rates (200 and 300 s^{-1}) as can be seen in Fig. 13b.

Validation of existing viscosity models for prediction of HO emulsion inversion point

The viscosity of the emulsion is directly proportional to the viscosity of the continuous phase. Therefore in almost all the previously proposed viscosity correlations viscosity of emulsion was presented in terms of relative viscosity, η_r, i.e. the ratio of the emulsion viscosity (η_e) to the viscosity of continuous phase (η_c). Since the most important factor that affects the viscosity of the emulsion is the dispersed phase volume fraction (Φ) more of the existing emulsion viscosity models correlate η_r as a function of Φ. In this study, four viscosity correlations were validated against the experimental data for one HO emulsion sample HP-HO-2 at different temperatures and different water cuts ranging from 19 to 70%.
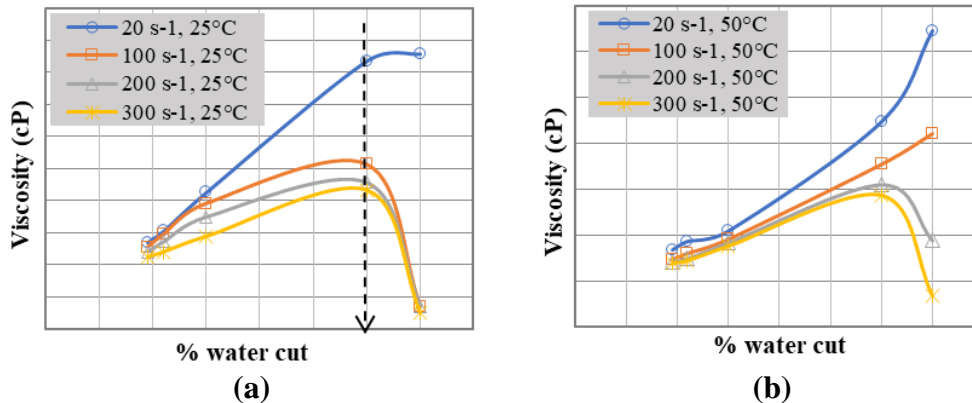

Fig. 13. Inversion Point of HP-HO-2 emulsion samples at different shear rates and temperatures

Einstein [18] showed that emulsion viscosity is a function of the dispersed phase volume fraction. The viscosity of the emulsion increases as the volume fraction of the dispersed phase increases. Einstein's model is suitable for very dilute emulsion with $\Phi<0.01$.

$$\eta_r = \eta_e/\eta_c = 1 + 2.5\Phi \tag{1}$$

In 1941 Eilers[19] developed the following model for poly-disperse bitumen emulsions:

$$\eta_r = [1 + (1.25\Phi/1 - k\Phi)]^2 \tag{2}$$

where k value is determined empirically and ranges between 1.28 to 1.30. For the concentrated suspensions Mooney [20] correlation is widely quoted in the emulsion literature:

$$\eta_r = \exp\left[\frac{2.5\phi}{1 - K\phi}\right] \tag{3}$$

where K is a constant varies from 1.28 to 1.30. Pal and Rhodes [21] presented an empirical equation for viscosity of emulsions based on the concentration of the dispersed phase and shear:

$$\eta_r = \left[1 + \frac{\dfrac{\phi}{\phi^*}}{1.187 - \dfrac{\phi}{\phi^*}}\right]^{2.492} \tag{4}$$

where Φ^* is the volume fraction of the dispersed phase when the viscosity ratio is 100. All the experimental viscosities are presented in Table 8 along with corresponding values predicted using the four mentioned correlations. The relative deviations from the experimental values are given for each correlation.

As opposed to Einstein[18] the three correlations by Eilers [19], Mooney[20] and Pal and Rhodes [21] have to be adjusted to two experimental values; i.e. the relative viscosity of pure oil (i.e. equal to 1) and the maximum water cut where the emulsion remained oil continuous. The maximum water cut was 70%. Since Eilers [19], Mooney [20], and Pal and Rhodes [21] are tuned to experimental values, they are expected to provide a better fit than Einstein. Deviations of 0% at the reference water cut are due to the tuning [22].

Figs. 14a, 14b, and 14c show a comparison of the different correlations with the experimental data of HP-HO-2 emulsion sample at a temperature of 50°C and different shear rates (20, 100, and 200 s^{-1}), respectively. As can be seen, Eilers [19], Mooney [20], and Pal and Rhodes [21] correlations described the experimental data quite adequately at lower shear rates of 20 s^{-1} and 100 s^{-1} with a maximum deviation of 17%. At a higher shear rate of 200 s^{-1}, Eilers [19], Mooney [20] and Pal and Rhodes [21] provide a reasonable estimate for water cut up to 30% with a deviation up to 36%. However, a significant deviation was obtained at 60% water. This is due to phase inversion.

Fig. 15a shows that at a higher temperature of 80°C and a low shear rate (20s^{-1}), only Mooney [20] and Pal and Rhodes [21] show a reasonable agreement with the experimental value. At a higher shear rate (100s^{-1}), none of the correlations was representing the experimental data at all ranges of water cuts as shown in Fig. 15b. The uncertainty of the predicted values was around 90%.
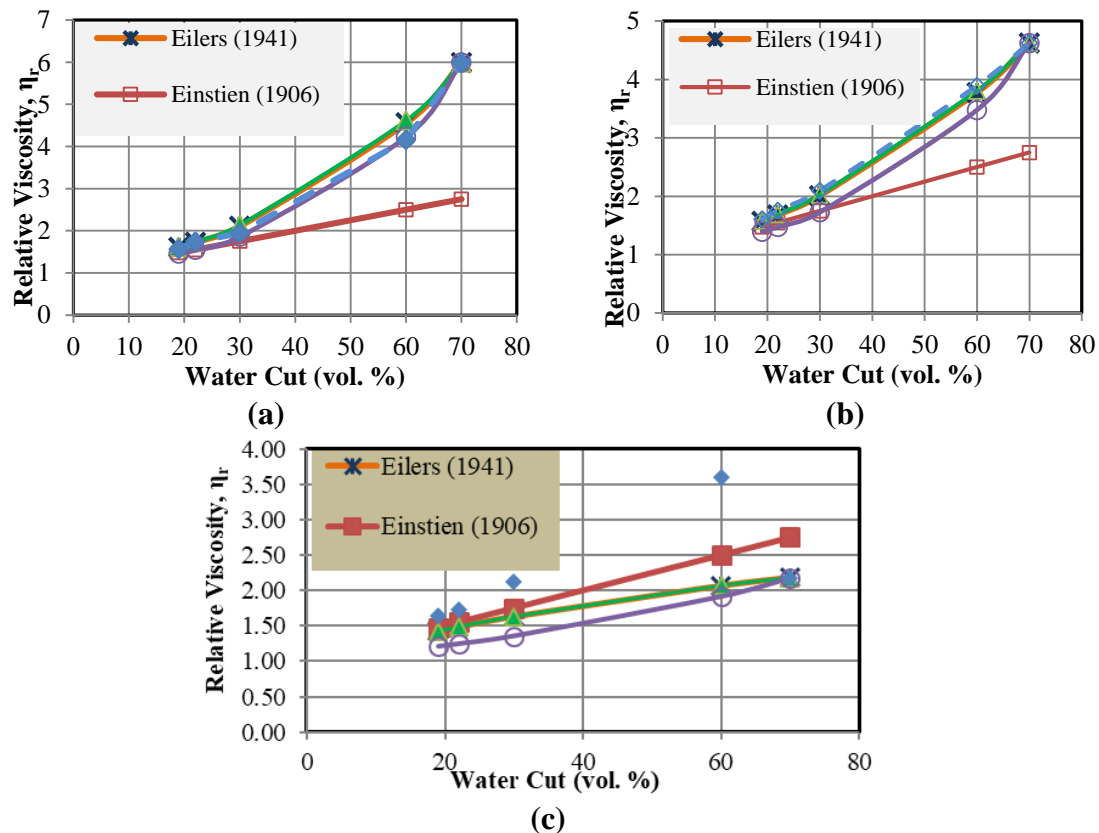

Fig. 14. Validation of different viscosity correlations with the experimental data of the emulsion sample HP-HO-2 at 50°C and different shear rates of: (a) 20 s^{-1}, (b) 100 s^{-1} and (c) 200 s^{-1}

Table 6. Validation of different viscosity correlations for HP-HO-2 emulsion sample at 50°C and 80°C

Experimental data				Einstien 1906		Eilers 1941		Mooney 1951		Pal and Rhodes 1989		New Eq.6	
T	shear	Water cut	μr(exp)	μr	Deviation	μr	Deviation	μr	Deviation	μr	Deviation	μr	Deviation
°C	s⁻¹	%			%		%		%		%		%
50	20	19	1.56	1.48	-5.58	1.6	2.61	1.61	3.23	1.45	-7	1.77	-13.77
		22	1.73	1.55	-10.6	1.73	-0.41	1.74	0.36	1.55	-10.63	1.9	-9.69
		30	1.94	1.75	-9.96	2.11	8.41	2.13	9.72	1.86	-4.51	2.27	-16.95
		60	4.15	2.5	-39.8	4.56	9.71	4.61	11.12	4.23	1.81	4.43	-6.81
*(ref)		70	5.99	2.75	-54.09	5.99	0	5.99	0	5.99	0	5.54	7.49
	100	19	1.61	1.48	-8.18	1.57	-2.11	1.58	-1.66	1.39	-13.24	1.53	5.06
		22	1.76	1.55	-11.8	1.68	-4.21	1.69	-3.67	1.47	-16.06	1.63	7.14
		30	2.1	1.75	-16.51	2.01	-4.07	2.03	-3.26	1.73	-17.6	1.95	6.95
		60	3.89	2.5	-35.78	3.78	-2.93	3.81	-2.21	3.48	-10.63	3.82	1.86
*(ref)		70	4.63	2.75	-40.56	4.63	0	4.63	0	4.63	0	4.77	-3.08
	200	19	1.64	1.48	-10.28	1.42	-13.33	1.43	-13.24	1.21	-26.53	1.78	8.29
		22	1.73	1.55	-10.17	1.48	-14.04	1.49	-13.93	1.25	-27.78	1.87	8.52
		30	2.13	1.75	-17.73	1.63	-23.43	1.63	-23.32	1.36	-36.22	2.14	0.70
		60	3.6	2.5	-30.56	2.07	-42.62	2.07	-42.58	1.92	-46.66	3.55	-1.48
*(ref)		70	2.18	2.75	26.06	2.18	0	2.18	0	2.18	0		Error very high
80	20	19	3.26	1.48	-54.7	1.63	-50.05	2.21	-32.22	2.97	-8.89	3.72	-13.97
		22	3.68	1.55	-57.84	1.76	-52.12	2.79	-24.25	3.71	1.02	3.89	-5.81
		30	4.16	1.75	-57.95	2.19	-47.48	3.5	-15.9	4.7	12.94	4.38	-5.24
		60	7.76	2.5	-67.77	5.39	-30.53	7.5	-3.31	8.5	9.58	6.89	11.25
*(ref)		70	7.65	1.75	-77.13	7.65	0.00	7.65	0	7.65	0	7.99	-4.44
	100	19	16.2	1.48	-90.89	1.7	-89.48	1.73	-89.29	1.78	-89.02	16.91	-4.41
		22	17.73	1.55	-91.26	1.88	-89.41	1.92	-89.15	1.97	-88.87	17.73	0.03
		30	19.88	1.75	-91.2	2.49	-87.47	2.61	-86.89	2.67	-86.58	19.93	-0.25
		60	33.88	2.5	-92.62	12.45	-63.24	14.14	-58.26	13.73	-59.46	31.35	7.46
*(ref)		70	34.56	2.75	-92.04	34.56	0	34.56	0	34.56	0	36.37	-5.24

*(ref) means that the experimental value at this water cut is used for tuning of the actual correlation.

(a) Shear rate = 20 s^{-1} **(b)** Shear rate = 100 s^{-1}
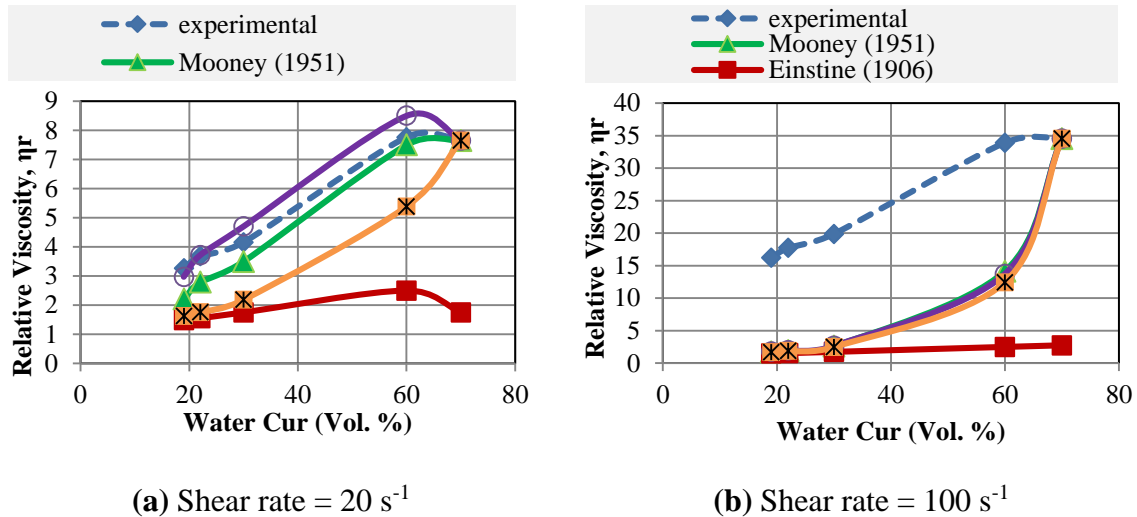
Fig. 15. Validation of different viscosity correlations with the experimental data of the emulsion sample HP-HO-2 at 80°C and different shear rates of: (a) 20 s^{-1} and (b) 100 s^{-1}

New Viscosity Correlation as a Function of Temperature, Shear Rate, and Water Cut

A new viscosity correlation for heavy crude emulsion (HP-HO-2) was developed using the experimental data. The new correlation presents the viscosity as a function of temperature, water cut, and shear rate. The proposed correlation, given below, showed a good fit to the experimental data as illustrated in Figs. 16, 17, and 18.

$$\eta_r = exp[aT + b\,\gamma + c\Phi + d] \tag{6}$$

where T is the temperature in °C, γ is the shear rate in s^{-1}, and Φ *is* water cut in vol. %. However, while attempting to fit all the data at all ranges of temperatures, water cuts, and shear rates, a very high percentage of error was observed for high temperature and high shear rate ($T>80°C$, $\gamma >200s^{-1}$). Therefore, the four coefficients in the proposed equation were defined under four groups:

1) Low temperature (20°C -50°C), low shear rate (20s^{-1} -1 00s^{-1})
2) Low temperature (20°C -50°C), high shear rate (200s^{-1} - 300s^{-1})
3) High temperature (80°C), low shear rate (20s^{-1} - 100s^{-1}), and
4) High temperature (80°C), high shear rate (200s^{-1} - 300s^{-1})

The coefficients and the units of variables T, shear rate, and ϕ are shown in Table 8. Figs.16 and 17 reveal that the developed equation can predict very reasonable values that nearly match the experimental values with a maximum deviation of 7% at temperatures of 50 and 80°C and shear rate of 100s^{-1}.

Table 7. Coefficients for the proposed correlation for predicting w/o emulsion viscosities

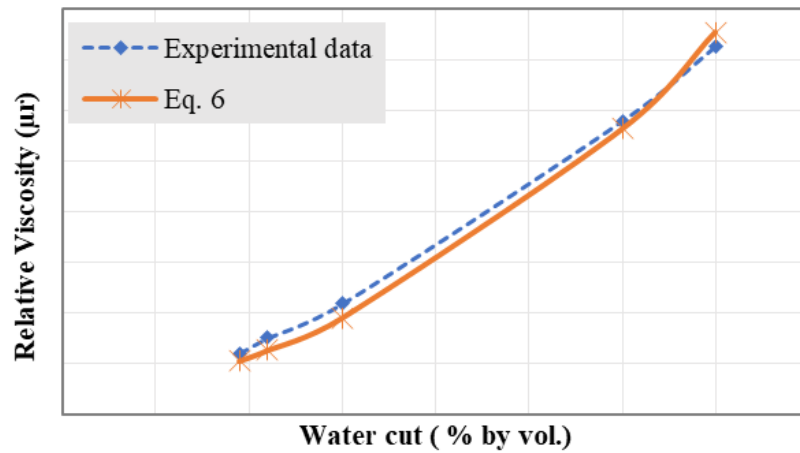| Coefficients	Low T (25-50°C) ϕ (19-60) %vol.		High T, 80°C ϕ (19-70) %vol.	
	γ (20-100) s^{-1}	γ (200-300)s^{-1}	γ (20-100) s^{-1}	γ (200-300) s^{-1}
a	8.17E-03	1.52E-02	8.32E+11	8.10E+11
b	-1.38E-03	1.86E-04	1.90E-02	-2.84E-03
c	2.18E-02	1.68E-02	1.49E-02	1.07E-02
d	-0.25722	-0.53846	-6.7E+13	-6.5E+13

Fig. 16. Validation of new viscosity correlation with the experimental data of the emulsion sample HP-HO-2 at 50°C and shear rates of 100 s^{-1}
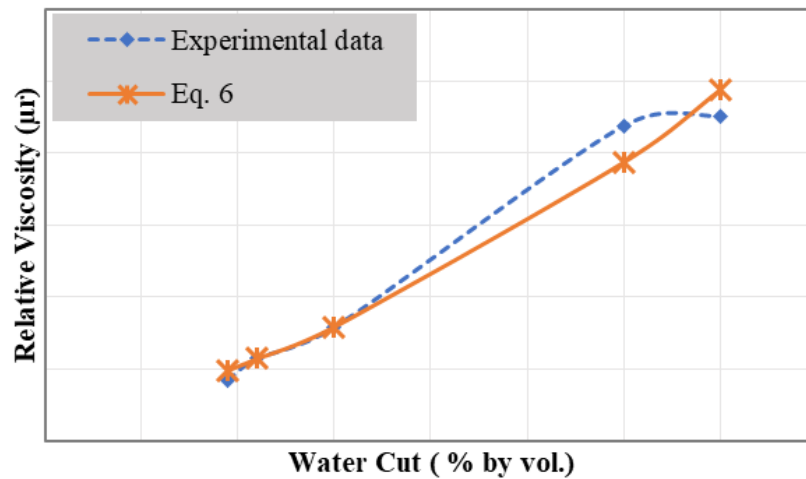

Fig. 17. Validation of new viscosity correlation with the experimental data of the emulsion sample HP-HO-2 at 80°C and shear rates of 100 s^{-1}
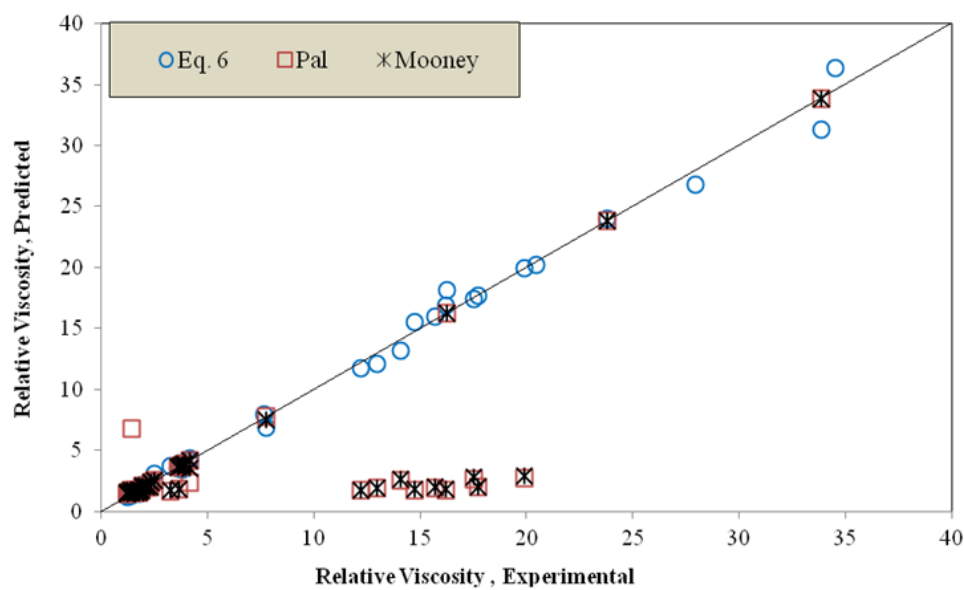

Fig.18. Experimental vs predicted relative viscosities for different viscosity correlations for HP-2 at different water cuts, T, and shear rates

Fig. 18 shows that the relative viscosity data obtained from the newly proposed correlation (Eq. 6) less deviates from the experimental data than the predicted values using Mooney [19] and Pal and Rhodes [20] correlations. This suggests that the new correlation can be used adequately for a wide range of shear rates (100 to 300 s^{-1}), temperature between 25 to 80°C and water cut up to 70 % with a maximum deviation of 13%, and no tuning is required.

Conclusions

Stability and rheology of 3 heavy crude oil emulsions, one cold produced (CP) and two hot produced (HP) in terms of physical properties, SARA, stability, and viscosity under different operation conditions have been conducted. The stability test results revealed that the R/A ratio has a significant effect on water separation. Emulsions became more stable at a low R/A ratio since the ability of the resin to replace asphaltenes at the water-oil interface decreased, subsequently decreasing the chances of coalescence of water droplets. The stability and viscosity measurement conducted on the HP-emulsions showed that the steam injection process decreases the salinity thus decreasing the stability and viscosity of the produced emulsion. CP-HO emulsion was found to be more stable than HP-HO since it has the lowest R/A, highest salinity, and lowest PH values. Also, the effects of water cut, water droplet size, emulsifying conditions, and temperature were tested on the viscosity of HP-HO-2. The results indicated that as the water cut increased, droplet size decreased, therefore viscosity increased.

Moreover, four emulsion viscosity correlations (single and multiple-parameter) were validated on one HO emulsion sample. The multiple-parameter correlations [19-21] showed an adequate prediction at a low shear rate (around 20s^{-1}). However, at a higher shear rate (100s^{-1}), none of the correlations showed a good fit. Therefore, a new correlation suitable for predicting the viscosity of heavy crude emulsion for a wide range of temperatures (25$^{°}$C to 80$^{°}$C), water cuts (19% to 70%), and shear rates (20s^{-1} to 300s^{-1}) was developed. The developed correlation showed a better fit to the experiments with high accuracy compared to the existed correlations and it does not require any tuning.

In general, the newly developed correlation from this study would help in predicting viscosity of the produced heavy emulsion fluid due to the steam injection process that will assess in setting a good operation plan for producing and transferring such fluid.

Acknowledgments

Nomenclature

ηr	Relative viscosity,
Φ	Volume fraction of the dispersed phase
ɤ	Shear rate
R/A	Resin to Asphaltene ratio
bbls	Billion barrels
bopd	Barrel oil per day
BPD:	Billion barrel per day
BS&W	Basic sediment and Water
CSS	Cyclic steam stimulation

GOR   Gas oil ratio
HO   Heavy oil
IFT   Interfacial Tension
IR   Infra Red
PIP   Phase Inversion Point
OPEC   Organization of Petroleum Exporting Countries
Rpm   RPM: Revelation per minute
SARA   Saturates, aromatics, resins and asphaltene
SF   Steam flood
STO   Stock tank oil
T   Temperature
TSS   Total suspended solids
TDS   Total dissolved solids
W/O   Water in oil
WOR   Water oil ratio

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