論 説
 Original Article

Effect of Emulsification Process Conditions on the Properties of Water-in-Bitumen Emulsion

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Abstract : Steam or hot water injection into the bitumen reservoir leads to the formation of water-in-bitumen emulsions which exhibit higher viscosity compared to the original bitumen; and thereby affects production flow. The understanding of the effect of formation process conditions on the nature of this emulsion could assist in production improvement, design and simulation of post-production separation system. In this work, water was dispersed in bitumen phase at different temperatures (50 – 180 °C) and mixing speeds (11.7 – 23.3 s⁻¹). Emulsification properties such as percentage emulsification (extent of water dispersion into the bitumen), and the particle size of emulsion were analyzed to evaluate the effects of the process conditions. Ultimately, correlations have been presented to predict emulsion properties from the process conditions.

Keywords : bitumen, emulsification, formation temperature, mixing speed, particle size

1. Introduction

Emulsion is a popular term which is frequently encountered in the petroleum industries (Badolato *et al.*, 2008; Wong *et al.*, 2015). The popularly reported types of emulsion encountered in the petroleum industry include oil-in-water (O/W), water-in-oil (W/O), and their complex forms (Martínez-Palou *et al.*, 2011). Oil-in-water (O/W) emulsion is a liquid-liquid dispersed system in which the particles of oil are dispersed in continuous water phase. On the other hand, water-in-oil (W/O) emulsion contains water particles dispersed in a continuous oil phase.

It generally holds that emulsion is formed through the action of a surface active agent (known as surfactant) assisted by mixing force in destabilizing the interfacial tension between the two immiscible liquids. Emulsion has similarly been viewed as either the desired result of a mechanical process or the spontaneous result of favorable conditions of formation (Clausse *et al.*, 2005). Thus, emulsification process

needs an energy input, which is traditionally achieved through shaking, stirring or some other kind of intensive dynamic and/or static mixing processes (Fradette *et al.*, 2007; Hassan *et al.*, 2010). Furthermore, as a result of mixing force and the presence of the natural surfactants (asphaltene and resin) and clay, an undesirable water-in-oil emulsion is mostly formed during crude oil production (Antes *et al.*, 2015; Wong *et al.*, 2015). Emulsification, during petroleum production, occurs due to contact of two immiscible liquids, presence of surface active components, and availability of sufficient turbulence or mixing energy to cause dispersion (Wong *et al.*, 2015; Wen *et al.*, 2016).

Specifically, the in situ Thermal EOR (TEOR) methods including steam assisted gravity drainage (SAGD), cyclic steam stimulation (CSS) or Huff and Puff method, steam flooding, and their hybrids involves injection of steam (and additives including solvents and surfactants) into the heavy oil reservoir for the purpose of reducing viscosity and increasing mobility (Bennion *et al.*, 1993; Yamazaki *et al.*, 1994; Al-Bahlani and Babadagli, 2009). During these processes, the thermal energy possessed by the steam is transferred to the oil in situ. Then, following condensation, oil and water flow through the pores of the sand grains which produces shearing force. Thus, as illustrated in Fig. 1, emulsification occurs through the reduction of interfacial tension between the liquid and oil (and under the shearing effect of flow); thereby causes dispersion of water particles into the oil phase stabilized by

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Fig. 1 Illustration of in situ emulsification and formation of water-in-bitumen emulsion during steam assisted recovery process
Source: adapted from Mohammadzadeh and Chatzis (2010)

the natural emulsion stabilizers (asphaltene, resin, and clay) present in the oil (Alade *et al.*, 2016a).

SAGD is one of the most popular TEOR methods which has been successfully established in the recovery of bitumen from the huge (estimated over 175 billion barrels of proven reserves) of Canadian oil sand resource (Takahasi and Ogino, 2005; Wada, 2006; Al-Bahlani and Babadagli, 2009; Kato *et al.*, 2013). As earlier described, the produced bitumen through SAGD is usually in form of water-in-bitumen emulsion which could exhibit remarkable increase in apparent viscosity and non-Newtonian behavior compared to the original bitumen (Bennion *et al.*, 1993; Al-Bahlani and Babadagli, 2009). Therefore, effect of in situ emulsification on the performance of SAGD process had been the focus of some previous investigations (Chung and Butler, 1987; Chun and Butler, 1989; Sasaki *et al.*, 2001; Sasaki *et al.*, 2002; Al-Bahlani and Babadagli, 2009; Kumasaka *et al.*, 2016). In addition, studies on the bitumen emulsification as a result of steam quality, pressure and reservoir geometry have been reported (Chung and Butler, 1987; Chun and Butler, 1989; Al-Bahlani and Babadagli, 2009). However, investigation on the effects of emulsification conditions (such as formation temperature, and mixing speed) that lead to the formation of emulsion downhole has not received significant attention. Prior to this study, process parameter including temperature and mixing speed have been linked with the particle size of bitumen-in-water emulsion which was formed in the presence of chemical surfactant using in-line static mixers (Gingras, *et al.*, 2005). Similarly, effects of process parameters was investigated on the characteristics of emulsion formed with the light crude (Wen *et al.*, 2016). However, such study as concerned formation of water-in-bitumen emulsion has rarely been reported. Therefore, in this work, the effects of the process conditions on emulsification properties such as the percentage emulsification (extent of water dispersion into the bitumen), and the particle size of emulsion were investigated. This is with the aim of providing quantitative information

which can be applied during steam injection operations for bitumen recovery; and post production separation of water-in-bitumen emulsion produced.

2. Materials and methods

Bitumen samples collected from an oil field in Canada (Oil C) and Nigeria (Oil N) were used in this investigation. The properties of the bitumen samples are presented in Table 1.

2.1 Bitumen emulsification

Batch emulsification experiments to generate water-in-bitumen emulsions were performed in a micro-reactor vessel with a volume of 50 mL under controlled high temperature and pressure conditions (MMJ-50, OM Labtech, Tochigi, Japan) with an anchor impeller for agitation (Fig. 2). In a batch emulsification process, 25 mL of the sample with a bitumen-water ratio of 1:1 ($C_B = 50\%$ w/w and $C_W = 50\%$ w/w) was mixed at a formation temperature (T_f) of 50 – 180 °C (saturation pressure = 0.03 – 0.89 MPa), and mixing speed (N_i) of 11.7 – 23.3 s⁻¹ for a mixing time (t_m) of 20 min.

Table 1 Physical properties of bitumen samples

	Canadian (Oil C)	Nigerian (Oil N)
Property of bitumen		
Viscosity (mPas) at 70 °C	1644	7860
S.G (15/15 °C)	1.016	1.038
Asphaltene content	13.40%	24.80%

Table 2 Experimental conditions

Parameter	Value
Formation temperature T_f (°C)	50 – 180
Mixing speed N_i (s ⁻¹)	11.7 – 23.3
Mixing time t_m (s)	1200
Bitumen content C_B (% w/w)	50

Fig. 2 Sketch of the high pressure and temperature micro-reactor (with anchor impeller)

Experimental conditions are presented in Table 2.

2.2 Particle size analysis

The particle size of emulsions were analyzed using optical/video microscopy method. Detail procedure is available in our previous publication (Alade *et al.*, 2016b). The average diameter of particles of emulsion was estimated using volume mean diameter, d_v , for a number of droplets (n_i) counted as i th diameter of the droplet (d_i) as given in equation (1):

$$d_v = \frac{\sum(n_i d_i^4)}{\sum(n_i d_i^3)} \quad (1)$$

The particle size distribution was expressed as the log-normal probability density function $f(x)$:

$$f(x) = \frac{1}{x\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln(x) - \omega)^2}{2\sigma^2}\right) \quad (2)$$

where x is the variable, σ is the shape parameter (and is the standard deviation of the log of the distribution), ω is the mean of the log of the distribution.

2.3 Viscosity test of original samples of bitumen and water-in-bitumen emulsions

The viscosity of original bitumen samples were measured at atmospheric pressure and different temperatures (70 – 180 °C) using the plumbing type viscosity sensor (Cambridge Viscosity, Model SPL372 – see Fig. 3a). The operating principle is simply such that the instrument expresses the dynamic viscosity as a function of distance and time taken by the piston to move through the chamber. Temperature is measured with the platinum Resistance Temperature Detector (RTD) mounted at the base of the chamber. About 10 mL of heavy oil sample was fed into the sample container and was pushed into the sensor. The system was heated (in the presence of Nitrogen gas) to increase temperature at the

interval of 5 °C using the environment controlled oven (Alade *et al.*, 2016c; Kumasaka *et al.*, 2016).

The viscosity of water-in-bitumen emulsions were measured at 60 °C with a shear rate of 0.14 s⁻¹ (spindle number SC4-34) using Brookfield DV-I viscometer equipped with a programmable temperature controller (Model 106, Brookfield AMETEK, Inc., Middleboro, MA – see Fig. 3b). For each measurement, 9.4 mL of emulsion sample was transferred from the microreactor into the sample chamber in the thermocontainer. The samples were left to equilibrate to the desired T_e . The equilibration time was typically between 1 and 3 min. The viscometer was regularly calibrated with the appropriate standard fluids before use. The percentage error was typically in the range ±0.2–1.4%.

2.4 Evaluation of specific energy for emulsification

Since emulsification is essentially as a result of mixing, emulsification energy is considered as mixing energy supplied to the bitumen and water in the reactor. Thus, the specific emulsification energy (ε_v) is the energy input per unit volume of the bitumen and water in the reactor. Thus, ε_v is obtained as a product of mixing power (P_m) of bitumen and water system and mixing time (t_m) divided by volume (V) of the fluid.

$$\varepsilon_v = \frac{P_m t_m}{V} \quad (3)$$

In addition, for a batch mixing process in an agitated vessel, at laminar regime, the mixing power (P_m) is a function of bitumen viscosity (μ_b), mixing speed (N_i) and diameter of the impeller (D_i) as given in equation (4).

$$P_m = P_0 \mu_b N_i^2 D_i^3 \quad (4)$$

The power number (P_0) is a function of Reynolds number (R_{ei}) and can be obtained using equations (5) (Foucault *et*

Fig. 3 Viscometers used in measurements

al., 2005).

$$P_0 = f(R_{ei}) \quad (5)$$

And considering non-Newtonian pseudoplastic fluid using an exponential model relating the apparent viscosity with the mixing speed (N_i), shearing temperature (T_s) of water-bitumen emulsion, and the fraction of bitumen (C_B) present in the emulsion, Reynolds number, R_{ei} can be obtained using equation (6).

$$R_{ei} = \frac{N_i \rho(T_b) D_i^2}{V} \quad (6)$$

The bitumen density ($\rho(T_b)$) at a given temperature (T_b), and density of bitumen, ($\rho(T_{ref})$) at a reference temperature (T_{ref}) is calculated as given in equation (7).

$$\rho(T_b) = \rho(T_{ref}) \cdot \exp[-\delta(T_b - T_{ref})] \quad (7)$$

The apparent viscosity of bitumen is expressed by an exponential model as given in equation (8)

$$\mu_b = A_1 N_i^{A_2} \cdot \exp\left(\frac{\beta}{T_s} + \alpha C_B\right) \quad (8)$$

where A_1 and A_2 , β , and α are the viscosity dependent

model parameters quantifying the effects of mixing speed N_i , shearing temperature T_s and bitumen content C_B , respectively.

3. Results and discussion

3.1 Effect of formation temperature and mixing speed on emulsification energy

The specific energy of emulsification (ε_v) decreased with increasing formation temperature (T_f) and increased with increasing mixing speed (N_i) as shown in Fig. 4 (symbol represents experimental data). For Oil C, the value of ε_v decreased from $8.77\text{E}8 \text{ kJm}^{-3}$ to $2.31\text{E}6 \text{ kJm}^{-3}$ from the T_f of 50°C and 180°C , respectively, at the mixing speed (N_i) = 11.7 s^{-1} . In the case of Oil N, at the mixing speed $N_i = 11.7 \text{ s}^{-1}$ and the emulsion formation temperature (T_f) of 50°C , ε_v decreased from $5.78\text{E}9 \text{ kJm}^{-3}$ to $4.44\text{E}6 \text{ kJm}^{-3}$ at the T_f of 180°C . In addition, for Oil C, increased in N_i from 11.7 s^{-1} to 23.3 s^{-1} resulted into the increase in ε_v to $2.19\text{E}9 \text{ kJm}^{-3}$ at 50°C , and $7.98 \text{E}6 \text{ kJm}^{-3}$ at 180°C . Similarly, the increased in mixing speed (N_i) from 11.7 s^{-1} to 23.3 s^{-1} caused increase in the value of ε_v to $1.99\text{E}10 \text{ kJm}^{-3}$ and $1.54\text{E}7 \text{ kJm}^{-3}$ at 50°C and 180°C , respectively, for oil N. These observations are due to the fact that viscosity of the fluids decreases with increasing temperature (see Fig. 5). It

also indicates that the higher the temperature, the lower the resistant poses by the viscosity of the fluid to emulsification; and as a result of viscosity difference, emulsification energy was observed to be higher for the oil N compared to oil C at every temperature and mixing speed. Moreover, the specific emulsification energy (ε_v) was correlated with emulsion formation temperature (T_f) and mixing speed (N_i) using the power law relationship, equation (9). The calculated values of specific emulsification energy are represented using lines in Fig. 4. Correlation parameters are presented in Table 3.

$$\varepsilon_v = \varepsilon_{v0} T_f^\phi N_i^\tau \quad (9)$$

where ϕ and τ are the system dependent model parameters quantifying the effect of formation temperature (T_f) and mixing speed (N_i), respectively.

3.2 Effects of formation temperature (T_f), mixing speed (N_i) and water content (C_w) on the percentage emulsification (r_e) and viscosity of emulsion.

The extent of dispersing water particles in the bitumen phase at the given formation temperature and mixing speed is defined as the percentage emulsification (r_e). This is calculated as the percentage of water dispersed in the bitumen phase after the mixing time.

Fig. 4 Effect of emulsion formation temperature (T_f) and mixing speed (N_i) on the specific emulsification energy of Oils C and N

$$r_e = \frac{W_d}{W_i} \times 100 \quad (10)$$

Water dispersed in bitumen (W_d) is given in equation (11).

$$W_d = W_i - W_f \quad (11)$$

Fig. 6 is the graph of percentage emulsification (r_e) at different emulsion formation temperatures (T_f) and mixing speed (N_i), while the effect of water content (C_w) on the percentage emulsification (r_e) is shown in Fig. 7. It can be observed from Fig. 6 that at the mixing speed of 11.7 s^{-1} , an increase in emulsion formation temperature from 50 to 100°C caused the percentage dispersion of water into the bitumen (percentage emulsification) to increase from 30 to 61 %w/w for Oil N (asphaltene content of 24.8 %). However, at the formation temperatures of 150°C and 180°C , mixing speed of 11.7 s^{-1} , percentage emulsification decreased to 55 %w/w and to 25 %w/w, respectively. In addition, at the mixing speed of 23.3 s^{-1} , percentage emulsification increased to 39 %w/w at formation temperature of 50°C and at formation temperature of 100°C , percentage emulsification increased to 75 %w/w. This value decreased to 60 %w/w and 38 % w/w at formation temperature of 150°C and 180°C , respectively. In comparison, it was observed, for Oil C (13.4 % asphaltene content), that the percentage emulsification at 11.7 s^{-1} , increased from 44 % w/w to 72 % w/w, at the formation temperatures of 50°C and 100°C , respectively. At the formation temperatures of 150°C and 180°C , the value decreased to 33 %w/w and 20 %w/w, respectively. At the mixing speed of 23.3 s^{-1} and formation temperature of 50°C , the percentage emulsification was 50

Fig. 5 Change in viscosity of bitumen samples with temperature

Table 3 Correlation parameters in equation 9 for Oil C and Oil N.

Bitumen sample	ε_{v0}	ϕ	τ	R^2	AAD
Oil C	7.49E+14	-4.63	1.67	0.97	38.40
Oil N	2.24E+17	-5.67	1.79	0.99	42.57

%w/w. This increased to 90 %w/w at 100 °C ; and decreased to 45 %w/w and 33 %w/w at the formation temperatures of 150 °C and 180 °C, respectively.

From the descriptions above, it can generally be deduced that between the formation temperatures of 50 and 100 °C , there was an increase in the extent of emulsification for the two oil samples. However, the percentage emulsification decreased above 100 °C formation temperature. On the other hand, an increase in mixing speed resulted in increase in percentage emulsification at every temperature. In addition, Fig. 7 shows that the percentage emulsification decreased with increasing water content ($C_w = 25 - 75\%$ w/w). Furthermore, comparing the two oil samples, a more interesting behaviour of the system was observed below and above the formation temperature of 100 °C. It was observed that the percentage emulsification was higher for Oil C at the formation temperature below 100 °C, and above this temperature, percentage emulsification increased for the oil N. The observation concerning the increase in percentage emulsification due to mixing speed is consistent with the response of emulsification energy which was described

earlier. On the other hand, the response of the percentage emulsification to formation temperature could be corroborated considering the thermodynamics of the process. As presented earlier in Fig. 5, the viscosity of the continuous bitumen phase is very high at temperature below 100 °C, hence the observed low emulsification. It had been reported that the viscosity of crude oil affects the extent of emulsification (Fingas, 2014; Wen *et al.*, 2016). Interestingly however, above the formation temperature of 100 °C, the viscosity was significantly decreased; and together with the increase in kinetic energy of the particles of water (particle coalescence and Ostwald ripening), the separation of water during mixing at this condition was accelerated. Hence, the decrease in percent emulsification. For the different behaviour observed in the two oil samples, plausible explanations can be linked with the properties of crude oil including density, viscosity, asphaltene, resin content, clay content etc. According to Fingas (2014) due to variation in the properties of crude oil, different types of water-in-oil emulsion named as meso-stable, stable emulsions, entrained water-in-oil and unstable emulsions can be formed.

Fig. 6 Response of percentage bitumen emulsification (r_e) to the formation temperature (T_f) and mixing speed (N_i)

Fig. 7 Experimental values of the percentage bitumen emulsification (r_e) vs formation temperature (T_f) and water content (C_w)

Table 4 Correlation parameters in equation 12 for Oil C and Oil N.

Bitumen sample	X_1	X_2	X_3	τ_i	R^2	AAD
Oil C	1.53	0.031	-0.00016	0.42	0.92	11.44
Oil N	0.90	0.042	-0.00019	0.35	0.98	3.26

Therefore, in the present investigation, it can be said that there are possibly different viscosity windows during which emulsification is favored within the two oil samples. And it is more convenient to state that emulsification become more pronounced in the Oil C at the formation temperature below 100 °C when its viscosity is higher than 244 mPas, while at 150 °C and 180 °C, the viscosity became 28 and 10 mPas, respectively, which may be less favorable to stabilize water particles dispersed in the oil matrix. Similarly, in the case of Oil N, at the temperatures of 50 °C and 100 °C, the relatively high viscosity (88000 and 643 mPas) decreases the extent of emulsification due to inability of the water particle to penetrate and distribute within the bitumen matrix. However, at the higher temperatures (150 °C and 180 °C), the viscosity (65 and 40 mPas, respectively) of the oil become more favorable for emulsification compared to Oil C.

The percentage emulsification (r_e) at different emulsion formation temperature (T_f) (°C) and mixing speed (N_i) was correlated using equation (12). The calculated values (shown using lines) are compared with the experimental values (symbols) as presented in Fig. 6. Correlation parameters are presented in Table 4.

$$r_e = \exp(X_1 + X_2 T_f + X_3 T_f^2) \cdot N_i^{\tau_i} \quad (12)$$

Furthermore, the relationship between the percentage water content of emulsion (C_t), given in equation (13), and the apparent viscosity of water-in-bitumen emulsion (μ_e) measured at 60 °C and shearing rate of 0.14 s⁻¹ is presented in Fig. 8. C_t is defined as the weight percent of the water dispersed in bitumen over total weight of emulsion.

$$C_t = \frac{W_d}{W_d + W_b} \times 100 \quad (13)$$

As expected, Fig. 8 shows that water-in-bitumen emulsions produced have higher viscosity compared to the original bitumen.

3.3 Effect of formation temperature and mixing speed on the particle size of emulsion

Particle size of emulsion (and its distribution) is a crucial factor determining its characteristics. This affects the stability and viscosity; and ultimately assists in design and simulation of separation system. The average particle size of emulsions and its distribution according to the variation in formation temperature and mixing speed are presented in Fig. 9 and 10. It was generally observed that the particle size decreases with the increase in both formation temperature and the mixing speed. From Fig. 9, in the case of Oil C, at

Fig. 8 Apparent viscosity of emulsion (μ_e) vs water content (C_t)

the formation temperature of 50 °C and mixing speed of 11.7 s⁻¹, the particle size was 44.5 μm. This decreased to 16.9 μm at the mixing speed of 23.3 s⁻¹. At the formation temperature of 180 °C and mixing speed of 11.7 s⁻¹, the particle size was 6.1 μm and decreased to 4.5 μm at 23.3 s⁻¹. For Oil N, from Fig. 10, at the emulsion formation temperature of 50 °C, the particle size decreased from 35 μm at the mixing speed of 11.7 s⁻¹ to 16.6 μm at the mixing speed of 23.3 s⁻¹. At formation temperature of 180 °C, the particle size decreased from 9.7 μm at the mixing speed of 11.7 s⁻¹, to 5.5 μm at the mixing speed of 23.3 s⁻¹. The observed smaller particle size of emulsions at higher temperatures is due to the fact that emulsification at the higher temperature above 100 °C occurs under high turbulent mixing environment (due to increase in saturation pressures – see Fig. 11) which brakes the particle further. The photomicrographic images of the emulsions are presented in Fig. 12 and 13.

Moreover, the average particle size is correlated with the formation temperature and the mixing speed using an exponential relationship, equation (14). The agreement between the experimental and calculated particle size is presented in Fig. 13. Table 5 presents the correlation parameters.

Fig. 9 Average particle size and particle size distribution of water-in-bitumen emulsion (Oil C)

Fig. 10 Average particle size and particle size distribution of water-in-bitumen emulsion (Oil N)

Table 5 Correlation parameters in equation 14 for Oil C and Oil N.

Bitumen sample	d_{vo}	$\ominus$	δ	R^2	AAD
Oil C	1.54	105.2	14.3	0.89	21.5
Oil N	2.43	78.6	13.0	0.95	9.8

$$d_v = d_{vo} \cdot \exp \left(\frac{\ominus}{T_f} + \frac{\delta}{N_i} \right) \quad (14)$$

4. Conclusion

The following conclusions can be drawn from the investigation:

1. The specific emulsification energy (ε_v) decreases as the emulsion formation temperature, T_f increases and increases with the mixing speed. For Oil N, at mixing speed $N_i = 11.7 \text{ s}^{-1}$, ε_v decreased from $5.78\text{E}9 \text{ kJm}^{-3}$ to $4.44\text{E}6 \text{ kJm}^{-3}$ as the emulsion formation temperature (T_f) increased from $50 \text{ }^\circ\text{C}$ to $180 \text{ }^\circ\text{C}$, while at the mixing speed of 23.3 s^{-1} , the specific emulsification energy (ε_v) decreased from $2.10\text{E}10 \text{ kJm}^{-3}$ at emulsion formation temperature of $50 \text{ }^\circ\text{C}$ to $1.54\text{E}7 \text{ kJm}^{-3}$ at $180 \text{ }^\circ\text{C}$. Similarly, for Oil C, at mixing speed of 11.7 s^{-1} , the specific emulsification energy

Fig. 11 Saturation pressure in the reactor during emulsification vs formation temperature (T_f)

2. The extent of emulsification (ε_p) *i.e.* percentage bitumen emulsified (water dispersed in the bitumen phase) is affected by the emulsion formation temperature and (ε_v) decreased from $8.77\text{E}8 \text{ kJm}^{-3}$ to $2.31\text{E}6 \text{ kJm}^{-3}$ as the emulsion formation temperature increased from $50 \text{ }^\circ\text{C}$ to $180 \text{ }^\circ\text{C}$. And at the mixing speed $N_i = 23.3 \text{ s}^{-1}$, the specific emulsification energy (ε_v) decreased from $2.19\text{E}9 \text{ kJm}^{-3}$ at emulsion formation of $50 \text{ }^\circ\text{C}$ to $7.98\text{E}6 \text{ kJm}^{-3}$ at emulsion formation of $180 \text{ }^\circ\text{C}$.

Fig. 12 Particles photomicrographs from emulsions using Oil C: $b_1 - b_3$ ($T_f = 50^\circ\text{C}$ and $N_i = 11.7 - 23.3 \text{ s}^{-1}$), $b_4 - b_6$ ($T_f = 100^\circ\text{C}$ and $N_i = 11.7 - 23.3 \text{ s}^{-1}$), $b_7 - b_9$ ($T_f = 150^\circ\text{C}$ and $N_i = 11.7 - 23.3 \text{ s}^{-1}$) and $b_{10} - b_{12}$ ($T_f = 180^\circ\text{C}$ and $N_i = 11.7 - 23.3 \text{ s}^{-1}$)

Fig. 13 Particles photomicrographs from emulsions using Oil N: $a_1 - a_3$ ($T_f = 50^\circ\text{C}$ and $N_i = 11.7 - 23.3 \text{ s}^{-1}$), $a_4 - a_6$ ($T_f = 100^\circ\text{C}$ and $N_i = 11.7 - 23.3 \text{ s}^{-1}$), $a_7 - a_9$ ($T_f = 150^\circ\text{C}$ and $N_i = 11.7 - 23.3 \text{ s}^{-1}$) and $a_{10} - a_{12}$ ($T_f = 180^\circ\text{C}$ and $N_i = 11.7 - 23.3 \text{ s}^{-1}$)

Fig. 14 Change in emulsion particle size (d_v) with formation temperature (T_f) and mixing speed, (N_i)

the mixing speed. Percentage emulsification initially increased with the formation temperature (from 50 – 100 $^{\circ}\text{C}$) and decreased with formation temperature thereafter. For Oil N, mixing speed of 11.7 s^{-1} , an increase in emulsion formation temperature from 50 $^{\circ}\text{C}$ to 100 $^{\circ}\text{C}$ caused the percentage emulsification to increase from 30 %w/w to 61 %w/w while at the formation temperatures of 150 $^{\circ}\text{C}$ and 180 $^{\circ}\text{C}$, percentage emulsification decreased to 55 %w/w and to 25 %w/w, respectively. In comparison, for Oil C, the percentage emulsification at 11.7 s^{-1} , increased from 44 %w/w to 72 %w/w, at the formation temperatures of 50 $^{\circ}\text{C}$ and 100 $^{\circ}\text{C}$, respectively; and decreased to 33 %w/w and 20 %w/w, at the formation temperatures of 150 $^{\circ}\text{C}$ and 180 $^{\circ}\text{C}$, respectively.

3. The particle size of water dispersed in the bitumen phase decreased with an increase of formation temperature and mixing speed. In other words, the particle size decreased with increasing emulsification energy. For Oil N, increase in mixing speed from 11.7 to 23.3 s^{-1} decreased the particle size from $35 \mu\text{m}$ to $16.6 \mu\text{m}$, at the emulsion

formation temperature of 50 $^{\circ}\text{C}$. At the formation temperature of 180 $^{\circ}\text{C}$, the particle size decreased from 9.7 to $5.5 \mu\text{m}$ as the mixing speed increased from 11.7 to 23.3 s^{-1} . For Oil C, increase in mixing speed from 11.7 to 23.3 s^{-1} decreased the particle size from $44.5 \mu\text{m}$ to $16.9 \mu\text{m}$, at the emulsion formation temperature of 50 $^{\circ}\text{C}$. At the formation temperature of 180 $^{\circ}\text{C}$, the particle size decreased from 6.1 to $4.5 \mu\text{m}$ as the mixing speed increased from 11.7 to 23.3 s^{-1} , respectively.

4. Moreover, correlations have been developed to predict the effects of the process conditions on the emulsion properties viz. percentage emulsification and particle size.

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List of symbols and abbreviation

C_B	: Bitumen content (%w/w)
C_W	: Water content (%w/w)
C_t	: Percentage water content of emulsion (%w/w)
D_i	: Impeller diameter (m)
d_i	: ith diameter of droplet (μm)
d_v	: Particle size (diameter) of water dispersed in bitumen (μm)
d_{vo}	: Pre-exponential factor of particle diameter (μm)
ε_v	: Specific emulsification energy (kJ/m^3)
ε_{vo}	: Temperature independent pre-exponential factor (kJ/m^3)
r_e	: Percentage emulsify (%w/w)
N_i	: Mixing speed (s^{-1})
n_i	: Number of the droplets
P_m	: Mixing power (kJ/s)
P_0	: Power number
Re_i	: Reynolds number
t_m	: Mixing time (s)
T_b	: Bitumen temperature ($^{\circ}\text{C}$)
T_{ref}	: Bitumen reference temperature ($^{\circ}\text{C}$)
T_s	: Emulsion shearing temperature ($^{\circ}\text{C}$)
T_f	: Emulsion formation temperature ($^{\circ}\text{C}$)
V	: Volume (m^3)
W_b	: Weight of bitumen (g)
W_d	: Water dispersed in bitumen (g)
W_f	: Free water not dispersed into the bitumen (g)
W_i	: Initial water content feed into the reactor (g)
X_1, X_2, X_3	: Formation temperature dependent model parameter
$\rho(T_b)$	: Density of bitumen (kg/m^3) at temperature T_b
$\rho(T_{ref})$	: Density of bitumen (kg/m^3) at reference temperature T_{ref}
μ_b	: Viscosity of bitumen (mPas)

A_1, A_2, β, α	: Viscosity dependent model parameter
ϕ, τ	: System dependent model parameter
μ_e	: Viscosity of emulsion (mPas)
δ, Θ	: Constants (depend on the system)
β, α	: Viscosity dependent model parameters
AAD	: Percentage Average Absolute Deviation
TEOR	: Thermal Enhanced Oil Recovery
C	: Canadian bitumen
N	: Nigerian bitumen

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油中水滴型ビチューメンエマルションにおける エマルション生成プロセスの影響

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オイルサンドなどのビチューメン貯留層への水蒸気圧入などによって生成される油中水滴型エマルションの粘度などの物理特性は、生成後の水分含有量やその時点でのエマルション温度に注目した研究が多くなされてきたが、エマルション生成時の温度や攪拌混合（せん断）速度あるいは生成時のエネルギーなどの生成プロセス条件の影響を評価した研究は見当たらない。本研究では、ナイジェリア産とカナダ産のビチューメン油試料を使用し、生成温度範囲（50～180℃）およびマイクロ反応器内の攪拌混合速度範囲（11.7～23.3 s⁻¹）においてビチューメン相に水滴を分散させ、エマルションの粘度、水滴の粒子サイズおよびエマルション化率（ビチューメン相中の水滴の分散程度）などのエマルション特性に対する生成プロセス条件の影響評価を実験によって測定し、最終的に従来提案されている粘度の予測式に対して、ビチューメンのエマルション化率や水滴の粒径分布に影響を与える生成温度およびせん断速度条件を考慮した修正式を新たに提示した。