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Oil in water characterization by dynamic optical fluid imaging technology

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ABSTRACT

Oil in water content is traditionally analyzed by spectrophotometer after being extracted with solvents. The analysis completed can only quantify the oil content in the water. In the enclosed study, dynamic optical fluid imaging (DOFI) technology is used to characterize the oil in produced water before and after treatment by three reverse emulsion breakers (REBs). The DOFI analysis is quick and can quantify the oil/solids content along with oil droplet sizes and size distribution using a small amount of sample. More importantly, the analysis can help understand the behavior and the performance of REBs in water clarification. The results from the DOFI analysis show that the application of REBs removed oil/solids from water by reducing the amount of oil droplets/solids of all sizes. A more effective REB helped remove more oil droplets of all sizes and removed larger oil droplets completely. As a result, the average oil droplet size became smaller after the application of REBs. The findings from the DOFI analysis suggest that in the deoiling process, REBs cause oil droplets of all sizes to coalesce, making them larger and easier to remove. An additional finding was that there is no correlation between interfacial activity and deoiling performance for the REBs used in the study.

1. Introduction

Oil–water separation is a routine operation in conventional, thermal and heavy oil production in which water and oil exist in the form of water-in-oil (W/O) emulsions, oil-in-water (O/W) reverse emulsions, or water-in-oil-in-water (W/O/W) complex emulsions. An effective water–oil separation is achieved by the application of demulsifiers, including emulsion breakers (EB) and reverse emulsion breakers (REB) or water clarifiers. EB aids the water separation process and dehydrates oil while REB clarifies water by removing dispersed oil and solids from water.

Water clarification is of great importance because dirty water causes problems in processes downstream of separation equipment such as water injection wells or in water reuse applications where the water is used for steam generation and re-injected. In conventional oil production, produced water is treated by water clarifiers and the treated water is then injected downhole to increase oil recovery or disposed offshore. In heavy oil production using cyclic steam stimulation and steam assisted gravity drainage methods, the produced water is treated by water clarifiers and hardness softeners and is then re-used to generate steam for continuous oil production.

As in the demulsification of W/O emulsions in which water droplets coalesce [1–4], breaking O/W emulsions relies on the coalescence of oil droplets [5–7]. The coalesced oil droplets then rise to the water surface and are skimmed off the water phase. REBs are able to coagulate oil droplets by neutralizing the surface charge of the charge-stabilized oil droplets, or by flocculating the destabilized oil droplets [8].

The performance of water clarifiers can be evaluated by a number of methods. A direct approach is to measure the concentration of oil and solids in the treated water. To measure oil concentration, the oil in water is first extracted by a solvent, and the extracted oil in the solvent is measured by a turbidity meter or UV-vis spectrophotometer [9]. The solids concentration is measured gravimetrically. The performance of water clarifiers can also be monitored by the ζ potential change of the emulsion as well as the change in size distribution of the oil droplets after emulsion treatment which is characterized by optical microscopy and dynamic light scattering [10–12]. In oilfield on site bottle testing, visual observations are usually used to quickly evaluate the performance of water clarifiers. The methods mentioned above provide a number of ways to evaluate water clarifiers. To understand the behavior of water clarifiers during water clarification, however, we need a method which can dynamically characterize the oil/solids content and the oil droplet size distribution.

Dynamic optical fluid imaging (DOFI) technology was originally used to monitor marine ecosystems. DOFI was used to characterize the organisms and particles along with their size distribution in seawater,

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Fig. 1. Portable FlowCAM.

which are important to the structure and function of marine ecosystems. Using the DOFI technology, Alvarez et al. determined the plankton community composition and size distribution in seawater [13]. Sterling Jr. et al. measured the diameter and size distribution of aquatic sediment – crude oil aggregates in nearshore water using DOFI technology to understand the factors affecting the size and morphology of the aggregates [14]. The interactions between crude oil and sediment may influence the transport of the aggregates and where the crude oil stays in the ocean [15]. Recently, Wilson and Manning summarized the application of the DOFI technology in quantifying the subvisible particles in protein therapeutic biopharmaceuticals which could potentially affect drug safety [16]. The DOFI technology was also used to measure particle shape and size in stormwater runoff for providing a quick assessment of the performance of devices that facilitate fine particulate removal [17].

The DOFI is an integrated system for rapidly analyzing particles in a moving fluid. The system automatically counts, images and analyzes the particles in a continuously flowing fluid. Fig. 1 shows a FlowCAM equipped with DOFI system which includes fluidics, optics and electronics. A sample fluid is drawn into the flow cell chamber by a peristaltic pump. When laser light passes through the flowing fluid, the fluorescence and laser light scatter detectors monitor the light scatter of the passing particles. If a particle passing through the laser path has sufficient fluorescence or laser light scatter, the camera is triggered to take an image of the field of view. The digital signal processor counts and processes images of the field of view [18]. The DOFI analysis can provide images of particles including oil droplets and solids in the fluid, particle sizes and particle size distribution along with the concentrations of particles in the fluid. Depending on the flow cell and microscope objective used, the DOFI can detect particles ranging from 2 to 2000 μm. The measurement is fast and can be done in situ with fresh fluids [18].

In the current study, we use the DOFI technology to measure oil droplet sizes, oil/solids concentrations, and particle size distribution in the produced water before and after treatment with water clarifiers. The produced water samples are from a polymer flooding enhanced oil recovery process. Due to the presence of water-soluble polymers from polymer flooding in the produced water, the oil in the water is harder to remove [19,20]. The DOFI analysis allows us to understand the behavior and performance of different water clarifiers in treating this type of produced water. The interfacial activities of the water clarifiers at the toluene/water interface are also studied to help understand their behavior in water treatment.

2. Material and methods

2.1. Materials

Produced water (oil-in-water emulsion) samples from a polymer flooding enhanced oil recovery process in Alberta, Canada were used throughout the work. The water contained 1500 mg/L oil and 6660 mg/L Na^{+}, 200 mg/L Ca^{2+}, 83 mg/L Mg^{2+}, 40 mg/L K^{+}, 9 mg/L Sr^{2+}, 6 mg/L Ba^{2+}, 3 mg/L Fe^{3+}, 10400 mg/L Cl^{-}, and 3 mg/L SO_4^{2-} with a pH of 7.4. Three reverse emulsion breakers: RBW1, RBW2 and RBW3, all water soluble polymers with pH $<$ 7 whose molecular structures belong to company intellectual property, were synthesized by Baker Hughes, a GE company.

2.2. Demulsification of oil-in-water emulsion

After collecting fresh produced water samples from the field, 100 mL of the produced water was introduced each to a series of 180 mL prescription bottles. At 20 °C, reverse emulsion breakers (REBs) at desired dosages based on the total volume of the water were then introduced to the water. After shaking 100 times by hand, the water was allowed to settle at 20 °C for 1–4 h before being sampled for characterization by DOFI technology. During hand shaking, special care was taken to keep shake strength as close as possible in all demulsification experiments. All of the tests were performed on site in the field to ensure that the best representation of fluids possible were evaluated.

2.3. Interfacial tension (IFT) measurement

The dynamic IFT of the REBs at the toluene–water interface was measured using the pendant drop method with an Attension Theta Optical Tensiometer (T200, Biolin Scientific, Finland). The IFT measurement was done with a hooked needle submerged in the aqueous phase containing REB at desired dosages. At the tip of the needle, a fresh toluene droplet was formed. The profile of the droplet was converted into a curve from which the IFT was calculated through iterative approximation to fit the Young-Laplace equation. Dynamic IFT was obtained through continuously monitoring the change of the droplet shape with time.

2.4. Oil/solids concentrations and particle size distribution measurement by DOFI analysis

The oil in water was characterized at 20 °C with a portable FlowCAM™ system which uses the DOFI technology (Fluid Imaging Technologies, Inc., Scarborough, ME) equipped with a 2 mm wide by 100 μm thick flow cell and a 10 × magnification objective, permitting measurement of particles having a size smaller than 100 μm. The water samples (2–3 mL) for analysis were collected from experimental bottles at the 40 mL level from the bottom (close to the middle of the water phase) after demulsification of the produced water for 1 h and 4 h. The samples were introduced from a funnel and pumped through the FlowCAM at 1 mL/min. Photographs were automatically taken at a constant rate of 20 frames/s. Before each measurement, the flow cell was cleaned to remove contamination using Simple Green detergent and deionized water or isopropanol.

In the DOFI analysis, the oil and solids concentrations were determined using Eqs. (1) and (2), respectively: