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Controlled delivery and release of surfactant for enhanced oil recovery by nanodroplets

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ABSTRACT

Chemical-based oil recovery method has promising applications but suffers the problem of large quantity of chemical loss inside the reservoir. This work proposes an innovative concept of using nanodroplets as carriers for surfactants/polymers and control their release inside porous media to increase oil recovery in water-wet reservoirs. Comparing to conventional surfactant flooding, the proposed concept could not only reduce the adsorption of surfactant on rock surface, but also ease the problem of unstable surfactant slug injection and release surfactant slowly inside a reservoir. The oil recovery efficiency was evaluated for micelles and nanodroplet forms of surfactants blend in a customized core flooding system and the differential pressures were monitored to evaluate the injection stability of flooding fluids. The retention of surfactants was analyzed by high-performance liquid chromatography after the core flooding tests. The experiments confirm the advantages of nanodroplets as surfactant carriers. The results show that the new approach promoted tertiary oil recovery around ~8%, while reducing the adsorption of surfactants almost half on the surface of sandstone rock comparing to the micelle form.

Keywords: Enhance oil recovery, Controlled delivery, Nanodroplets, Surfactant retention, Micelles injection.

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1. Introduction

In recent years surfactant flooding have attracted a great deal of attention due to the progress in surfactant technology and its high efficiency in enhanced oil recovery (EOR). Surfactant flooding or surfactant/polymer flooding has been commercially used in pilot scale for EOR after the primary and secondary recovery, particularly in USA and China [1]. For example, the required 2-12 wt.% concentration of sensitive surfactant to high temperatures and high salinity (HT-HS) in initial development (1970-1980) has been dramatically decreased to the range of 0.5-2 wt.% of surfactant that resist over HT-HS. Surfactant flooding is becoming increasingly attractive for EOR applications [2-4]. Some recent studies have some the potential of cationic microemulsions for mobilization and displacement of heavy oils inside conventional Berea sandstones, artificially fractured and heterogeneous cores [5,6]. At low surfactant concentrations, the performance of surfactant solution and microemulsion was found to be similar for Berea sandstone and limestone cores, but increased oil recovery rate was observed by microemulsions at high surfactant concentrations.

Surfactant and/or polymers increase the oil recovery rate by targeting the capillary-trapped and un-swept oil. The capillary and relative permeability depends on the wetting behavior of the rock, which significantly affects the oil recovery efficiency. In strong water-wet rocks or at the end of water flooding stage in moderate water-wet rocks, a great proportion of oil droplets remains permanently trapped by capillary effects at the pore scale, which increases the residual oil saturation [7, 8]. This is because water formed a film on the rock surface, which ultimately leads to water bridging at the pore throats trapping oil droplets within the pores (Fig. 1a).

The process of surfactant flooding could be generally divided into three main stages: i) the surfactant solution is injected in the form of micelles to the reservoir; ii) the micelles flows through the pores of reservoir rock to reach the oil bank, where surfactant micelles contact with crude oil to form a bi-continues microemulsion phase formation at optimum conditions (e.g. salinity); and iii) bi-continues microemulsion phase pushes the oil bank to the production well after water post-flooding, which is schematically shows in Fig. 1b [9, 10].

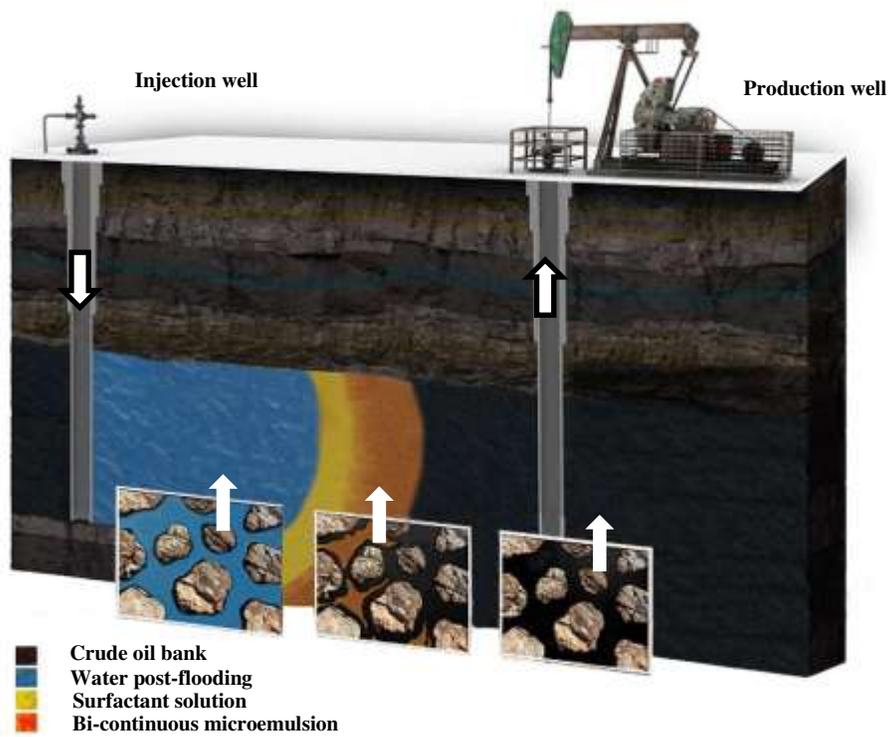
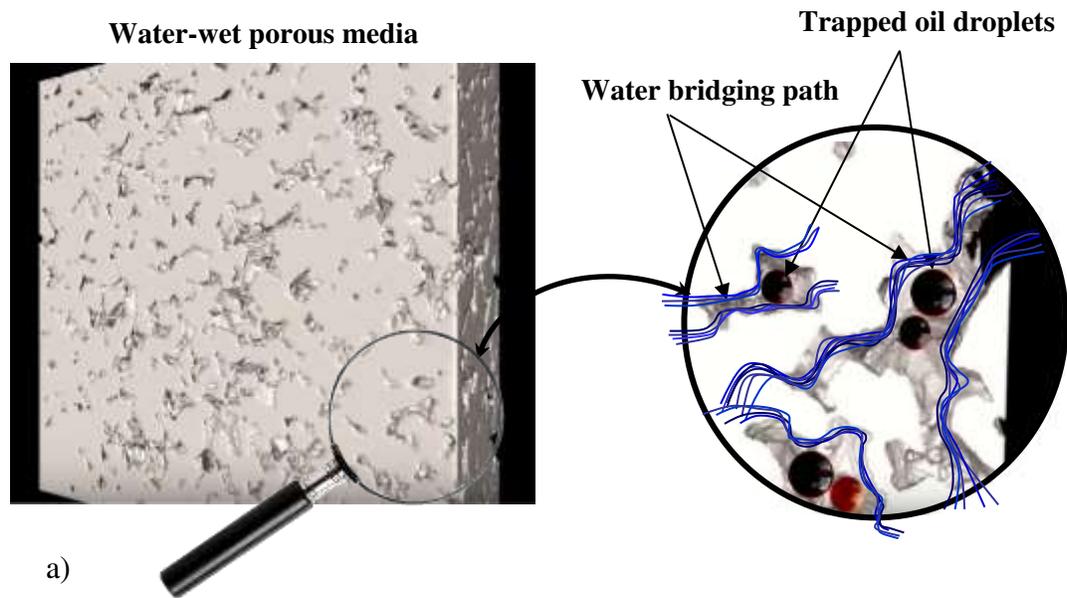


Fig. 1. (a) Oil droplets trapping in a water-wet rock, and (b) different stages of surfactant flooding.

One of the main challenges during this process is the high loss of surfactants due to the surfactant adsorption on rock surfaces before reaching the trapped oil. Moreover, the highly

concentrated micelles produce a cloudy and unstable surfactant slug, which is undesirable for the injection. All these increase the cost of tertiary flooding process and make it difficult for large scale application of surfactant-based flooding techniques [11, 12]. There are lots of research on the formation of bi-continues microemulsions at optimum conditions and phase behavior evaluation of crude oil with surfactants solution [13-15], however few has been focused on surfactants delivery to oil bank.

The application of nanodroplets as carriers to deliver drug substances has been intensively investigated in the nano-medicine area [16, 17]. Nanodroplets are unique carriers for drug ingredient because of high encapsulation rate, enhanced stability of the active ingredient, and enhanced ocular penetration. In this work, we borrow the concept of the controlled drug delivery, and propose an innovative concept of using nano-droplets as carriers for surfactants/polymer and control their release inside porous media to increase oil recovery. The surfactant molecules are encapsulated inside pre-synthesized oil nanodroplets via their hydrocarbon chains. For water-wet reservoirs, these nanodroplets would reduce the adsorption of surfactant molecules on rock surface, and prevent aggregation by distributing surfactant molecules on the interface of oil-nanodroplets. Furthermore, comparing to micro-droplets, it is expected that the increased total surface area of nanodroplets provides more surfaces for surfactants adsorption, which could lead to a transparent and stable injectable surfactant solution.

To validate the new concept, nanodroplets of n-hexane were synthesized in brine by using the synergic effect of sodium dodecyl sulphate (SDS) and Sorbitan monooleate (Span) blend at the optimum salinity. The blend of anionic-nonionic surfactants was used since the mixture of stabilizers play a key role in the formation of thermodynamically stable microemulsions [18, 19]. The surfactants adsorption and oil recovery efficiency were evaluated for surfactant flooding in the sandstone core in the forms of micelles and nanodroplets injection.

2. Experimental Procedure

2.1. Materials

Analytical grade materials including n-hexane, sodium chloride, Span 80, SDS and 2-butanol were purchased from Sigma-Aldrich and used without further processing. The mineral oil

(Keratech 24 MLP, viscosity on file is 24 cSt at 40 °C) were purchased from Kerax Ltd. (United Kingdom).

2.2. Nanodroplets and micelles synthesis

On the molecular level, emulsifiers should remain bounded to the surface of the oil droplets to reduce the interfacial tension (IFT) between oil and water. Moreover, bounded molecules at the interface should prohibit the coalescence of the droplets. Therefore, the selection of right surfactant is essential for the synthesis of any microemulsion. It has been shown that using a single surfactant alone is usually not effective to produce microemulsions [20]. Blending of surfactants with different hydrophile–lipophile balance (HLB) values is a versatile way to obtain an appropriate HLB value. Generally, blends of nonionic and anionic surfactants are used in nanodroplet formation. Based on our previous experience, SDS and Span 80 stabilizers were selected for the synthesis of microemulsion in this study.

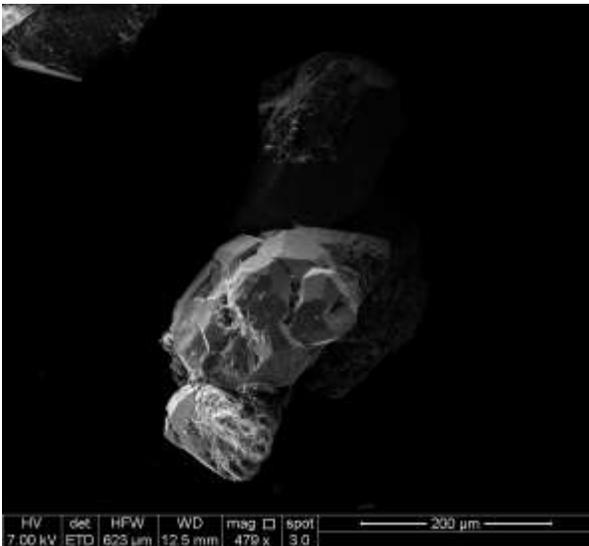
The HLB values of the chosen surfactants have been found to be the key factors for the formation of microemulsion [21, 22]. The HLB numbers of SDS and span 80 are 40 (highly hydrophilic) and 4.3 (highly oilphilic) respectively. Therefore, the adjustment of a wide range of hydrophilicity-lipophilicity becomes possibly adjusting the amount of SDS and span 80 [23]. In addition, SDS and span 80 are the most commonly used surfactants that are available with high purities. The retention time of SDS and span 80 surfactants is also different at the outlet of HPLC column [24]. High purity and different retention times are necessary factors for producing a reliable calibration plot and so as to the determination of each surfactant concentration.

The proper surfactants ratio (in the presence of 2-butanol as co-surfactant) for microemulsion synthesis was obtained based on several initial tests, which indicated a synergistic effect between SDS and Span 80 in forming stable O/W emulsions. The composition of emulsions was selected as 90 wt% brine (at different salinities), 3.6 wt% 2-butanol, 2.25 wt% n-hexane, 2.7 wt% SDS and 1.3 wt% Span 80. Different oil-in-water emulsions were synthesized at various salinities ranging from 0 to 10 wt% NaCl to find the optimum oil nanodroplets characteristics in brine. The optimum salinity was selected when the IFT between the emulsion and mineral oil reached to the lowest value. The IFT and hydrodynamic size of oil droplets in emulsion were measured using a goniometer (CAM 2008, KSV instruments Ltd. Finland) and dynamic light instrument (Zeta sizer

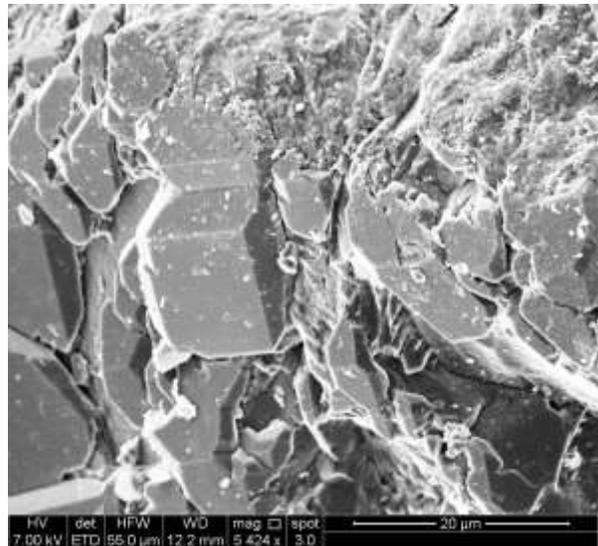
Nano ZS, Malvern), respectively. The optimum salinity was obtained as 5 wt.% NaCl in current study, and a comprehensive discussion about the salinity scan test is provided in section 3.1. The concentration of SDS and span 80 in surfactant solution (micelles slug) were set equal to microemulsion. The composition of surfactant solution was selected as 96 wt.% brine (at optimum salinity), 2.7 wt.% SDS and 1.3 wt.% Span 80. An Anton Paar MCR 301 rheometer equipped with a cone plate module CP75 was used for the measurement of viscosity of surfactant solution (micelles slug) and microemulsion (nanodroplets slug). The shear rate ($\dot{\gamma}$) was varied between 100 and 1000 s^{-1} at 22 °C. Dynamic measurements were performed with frequencies ranging between 1 and 100 rad/s (i.e., 0.159 to 15.92 Hz). The nanodroplets and micelles slug has shown in supporting document (Fig. S1).

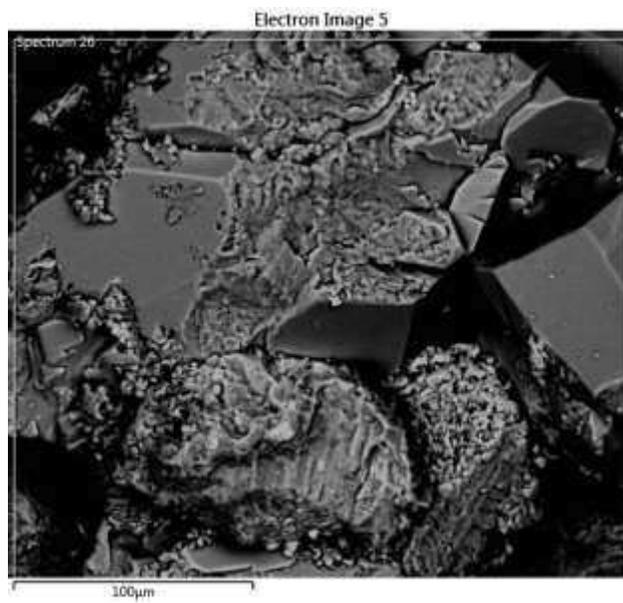
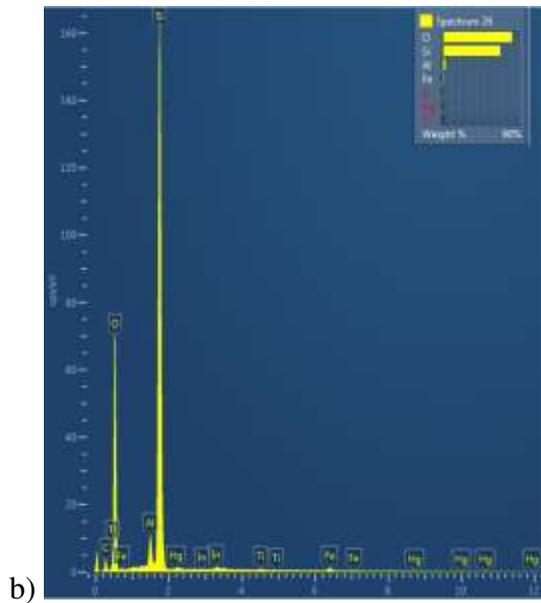
2.3. Porous medium preparation

For preparation of porous media, the sandstone rock was crushed into single grains, sieved into narrow grain size fractions (ASTM Standard Testing Sieves, Retsch Ltd) and washed with water for several times, which was followed by settling and decanting to remove all dust particles. The residual wet sand particles were dried at 80 °C for 5 days. The SEM (FEI Quanta FEG 650) and EDX (80mm X-Max SDD detector) analysis of particles are shown in Fig. 2a & c.

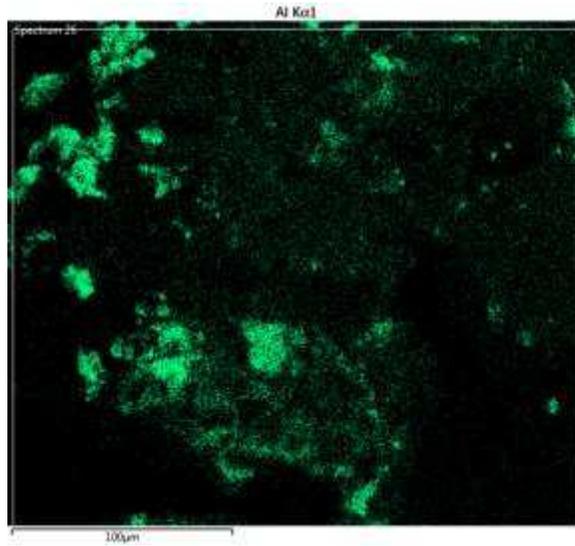


a)

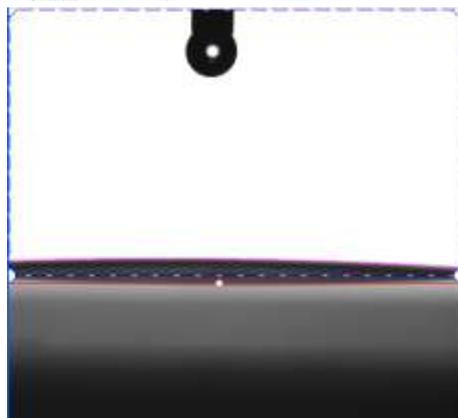




b)



c)



d)

Fig. 2. a) SEM photos sandstone particles, b) Elemental mapping of rock using an energy dispersive X-ray spectroscopic, c) distribution of aluminium components in analyzed section, d) wettability of sandstone rock, CA= 20.09°, which were used in experiments.

The Edx micrographs vividly show the existence of major fraction of silicate crystals and minor fraction of aluminosilicate mineral. A large part of each rock was polished for contact angle experiment. The wettability of rock was measured by a goniometer (CAM 2008, KSV instruments Ltd. Finland), which shows the strong water-wet surfaces of sandstone particles (CA= 20.09°, Fig. 2d). The BET surface area of sandstone were calculated equal 0.877 ± 0.001 (m²/g) using a Micromeritics TriStar 3000 gas adsorption instrument.

The initial bulk of particles was divided to different portions (each 50 g) using a sample splitter (Fig. S2). For each core flooding test, one portion of grain sample (250-425 micron) was packed into glass tubes to create unconsolidated sand packing column. The dried particles were first saturated in saline water (5 wt.% NaCl), and then deposited into a glass column in 1.5 cm increments with 0.5~1 cm thick of water on the top of particles. After the formation of a layer of 1.5 cm, vibration was accomplished for 3 minutes using a vortex mixer (Scientific Fisher), with the amplitude of vibration represented by 8 on the vibrating table's dial. The column was kept vertically and particle bounce was avoided during vibration. To prevent particles migration during the core flooding test, a PTFE filter with the pore size of 10 μ m (Mitex membrane filter LCWP02500, Millipore Ltd. UK) was placed at both ends of the column. The parameters for the packed porous media was illustrated in Table 1.

Table 1. Characterization of porous media for surfactant retention experiments.

Porous media property	Value
Length (mm)	72 ± 2
Diameter (mm)	24
Bulk volume (mL)	37.4 ± 0.9
Pore volume, (mL)	13.25 ± 0.32
Porosity (vol %)	35.4 ± 2.5
Absolute permeability (mD)	90-110

2.4. Core-flooding experiments for surfactants retention evaluation

The experiments for the evaluation of surfactant retention were performed in a core-flooding set-up, as shown in Fig. 3. A piston pump (Series I, Cole-Parmer Instrument Co. Ltd.) was used to inject brine during the flooding process. A syringe pump (KDS 410, KD Scientific Inc. USA) was used for injecting mineral oil, surfactant solution and microemulsion with different syringes to avoid overlap contamination. A pressure transducer (PX409-150DWUV, Omega Engineering Ltd.) was used to measure the pressure drop during experiments.



Fig. 3. Experimental core flooding set-up.

Different stages of flooding for surfactant retention measurement have been performed sequentially as follows:

- 100 mL brine flooding at the optimum salinity (5 wt.%) at a flow rate of 2 mL/min in order to make sure that the column is fully saturated by brine and allow enough time for sand grain depositing.
- 20 mL nanodroplet or micelles slug was injected at flow rate of 0.5 mL/min (total surfactants amount equal to 800 mg).
- 40 mL brine post flooding (5 wt.%) was conducted at a flow rate of 1 mL/min.

The effluents liquid for chemicals slug injection and brine post flooding were collected to determine the surfactant concentration. It was important to develop sensitive and reliable analytical methods to measure concentration of anionic-nonionic surfactants blend, and then to evaluate the performance of controlled surfactant delivery by the synthesized microemulsion. Chemical oxygen demand (COD), potentiometric titration or spectroscopy method were used in previous studies for the estimation of surfactant concentrations before and after equilibration with rock surfaces [25-27]. However, all of these methods have their limitations and could not give a correct estimation for the amount of surfactants blend adsorption on rock surface when the emulsion is formed in porous media [28]. For instance, both COD and potentiometric titration method are not compatible with organic phases, and the spectroscopy method could not measure the component concentration for a mixture of different classes of surfactants.

High-performance liquid chromatography (HPLC), which has good compatibility with organic and aqueous phases in emulsions, was selected as a reliable and accurate method. In this method, different retention time of surfactants in the outlet of HPLC's column is used to estimate the concentrations of different classes of anionic and nonionic surfactants separately. The use of HPLC to characterize surfactant concentrations in emulsions has been the subject of some considerable previous works [29-31], but none has been used for the evaluation of surfactant retention in the form of micelles and nanodroplets in a saline# environment.

A Thermo Acclaim surfactant plus HPLC column (Thames Restek Ltd., UK) of dimensions 3 mm×150 mm and particle size of 5 μm was used in this study. This type of column is compatible with aqueous and organic phases and is appropriate for the analysis of a wide variety of surfactant types at high salinity [32-34]. HPLC measurements were performed in an Agilent 1290 Infinity UHPLC. Chemstation and Chromeleon software were used for instrument control and processing the chromatograms, respectively. Different primary methods of analysis were examined with UV and ELSD detector to find the appropriate condition of HPLC analysis. Finally, the mobile phase of MeCN/0.1% Ammonium Acetate, Gradient of 25-85% MeCN over 30 mins then holding at 85% for 10 mins, flowrate of 0.6 mL/min, column temperature of 34 $^{\circ}\text{C}$ and UV (diode array detector, $\lambda=254$ nm) were selected as appropriate conditions for SDS and Span 80 surfactants analysis.

As generating a proper calibration plot is essential for the measurement of surfactant concentration, a series of standard samples within the concentration range of 0.005-0.3 g/mL were prepared from a stock solution of 0.4 g/mL for each stabilizer separately. The standard surfactant solutions were prepared using SDS in brine and span 80 in n-hexane. The standard solutions were analyzed by HPLC to obtain the calibration plot, from which it was possible to calculate chromatogram areas as a linear function of the surfactant concentration. The area peak of each sample was specified by Chemstation software. Some of selected chromatograms of standard samples have been illustrated in supporting information (Fig. S3). The area peak values versus standard concentrations and fitted line through the data are shown in Fig. 4. The coefficients of determination (R^2) higher than 0.95 confirm the good linearity between the standard concentrations and the responses of the HPLC detector. After core flooding experiments, the collected effluent (i.e., from the outlet of coreholder) was analyzed with HPLC method. The concentration of each surfactant was determined by comparing the related peak area in effluent's chromatogram with the calibration plot (Fig. 4).

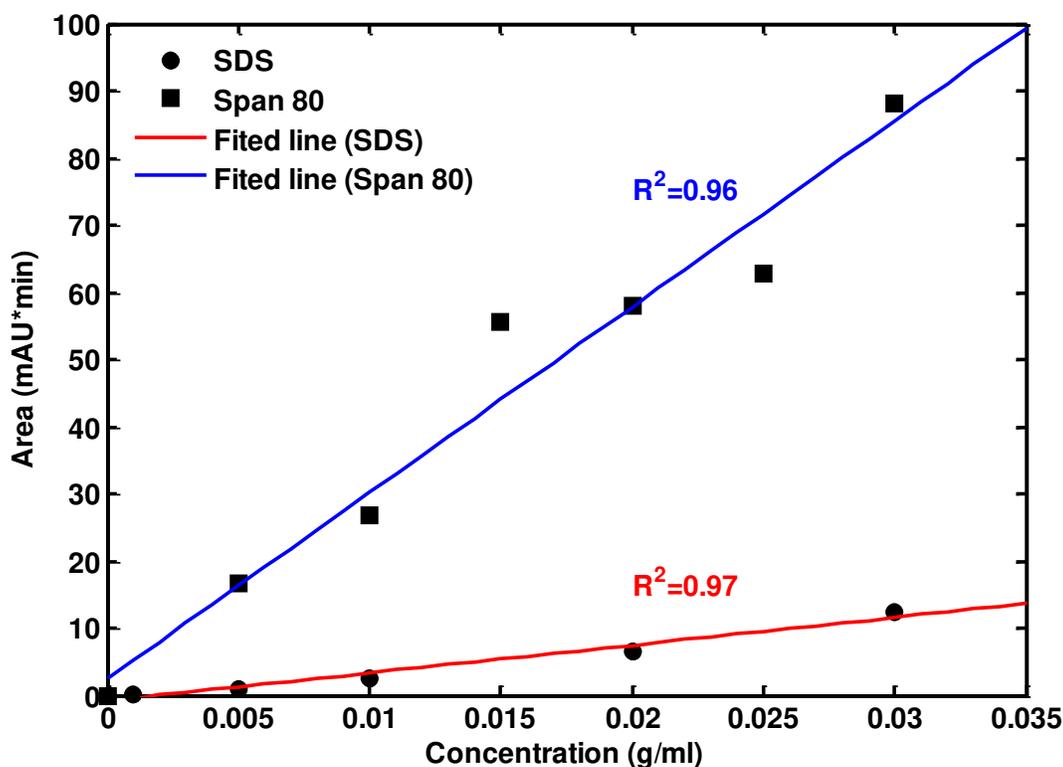


Fig. 4. HPLC calibration data for SDS in brine and Span 80 in n-hexane.

2.5. Core-flooding experiments for oil recovery evaluation

Three main flooding stages were accomplished in all experiments as follow:

- 100 mL injection of brine at optimum salinity (5 wt.%) into the glass column at a flow rate of 2 mL /min in order to make sure the column is fully saturated by brine and allow enough time for glass beads depositing.
- Oil saturation was performed by injecting mineral oil at a flow rate of 0.5 mL/min until an irreducible water saturation of $S_{wi} = 30\%$ was achieved.
- Brine flooding for initial stage of oil recover was performed with 1 mL/min flow rate was fixed at. The brine injection was continued for 3 pore volume (PV) when the oil production became negligible (secondary oil recovery).
- Tertiary flooding at a flow rate of 1 mL/min was done according to Table 2.

Table 2. Tertiary core flooding condition for evaluation of oil recovery efficiency.

Main fluid	Volume injection of Main fluid (mL)	Initial water saturation (%)	OOIP (mL)	Post brine flooding (mL)
Micelles	20	12.8	8.7	30
Nanodroplets	20	12.8	9.0	30

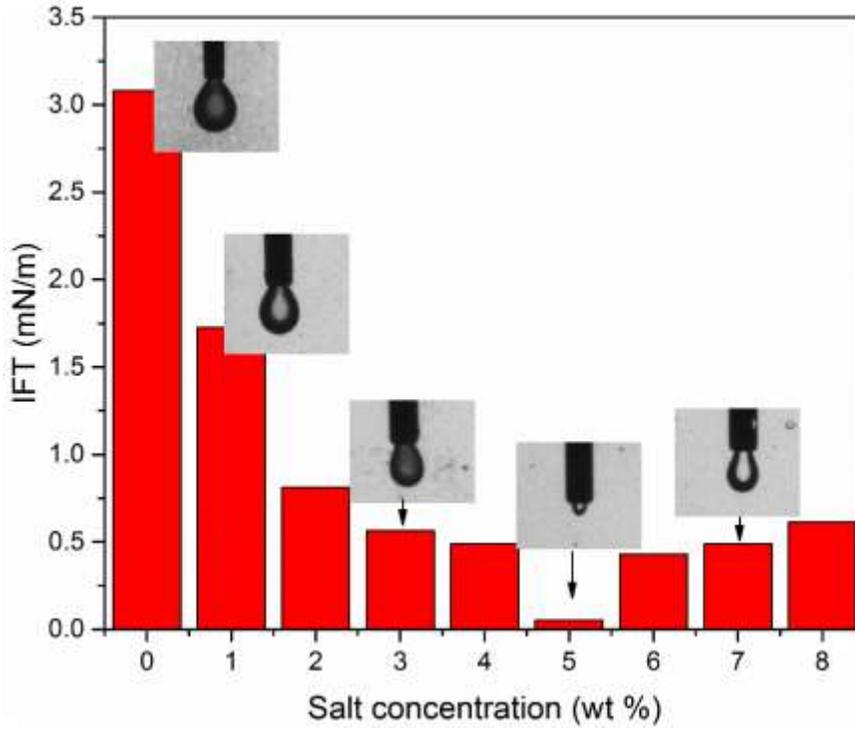
The effluent was collected in a 50 mL graduated cylinder marked in 0.1 mL divisions in order to determine the accumulate oil recovery (Fig. S4).

3. Results and discussion

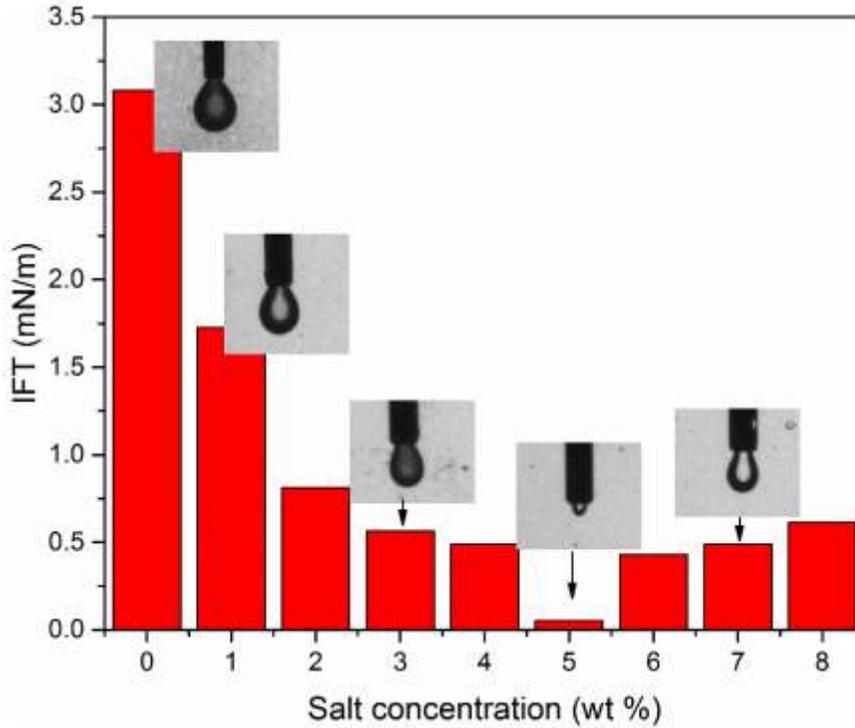
3.1. Formation of oil nanodroplets at optimum salinity

As explained in section 2.2, the emulsion was fabricated under different salinities. The transparency of emulsion samples containing NaCl at 5 and 7 wt% show the formation of oil nanodroplets inside the emulsion, whereas when the amount of NaCl was in different values, the emulsion was not fully formed and the oil/water phase, even became segregated at 10 wt.% of

NaCl (Fig. 5. (a) Image of O/W microemulsion samples containing NaCl from 0 wt% to 10 wt%, (b) average size of oil nanodroplets at different weight percent of NaCl.

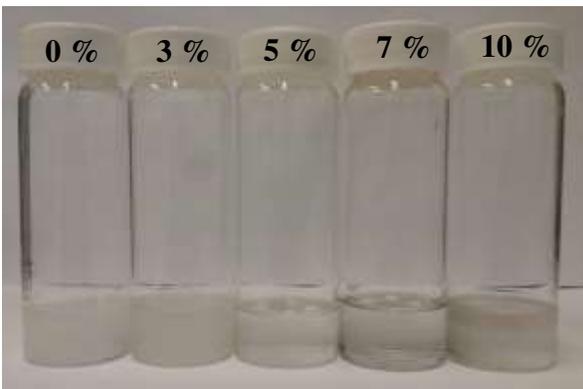


a). Corresponding to the macroscopic image of transparence shown in Fig. 5. (a) Image of O/W microemulsion samples containing NaCl from 0 wt% to 10 wt%, (b) average size of oil nanodroplets at different weight percent of NaCl.

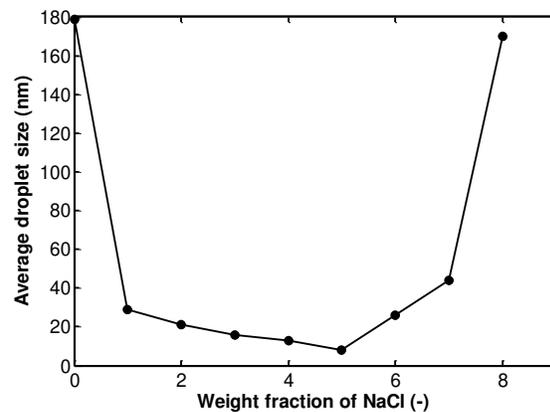


a, the IFT results in

Fig. consistently show that with the presence of 5 wt% of NaCl, the IFT between microemulsion and mineral oil was reduced to very low value, i.e., <0.01 mN/m, with a tiny drop hanging on the syringe tip, due to the sufficient formation of microemulsion. Therefore 5 wt% of NaCl was selected as the optimum salinity in next experiments. By diverting away from 5 wt%, the IFT increased, and when the salinity increases to 10 wt%, the emulsion became unstable and oil/water phases were eventually segregated. Similarly, the size determined by DLS method in Fig. 5b shows the same trend with transparency and IFT.



a)



b)

Fig. 5. (a) Image of O/W microemulsion samples containing NaCl from 0 wt% to 10 wt%, (b) average size of oil nanodroplets at different weight percent of NaCl.

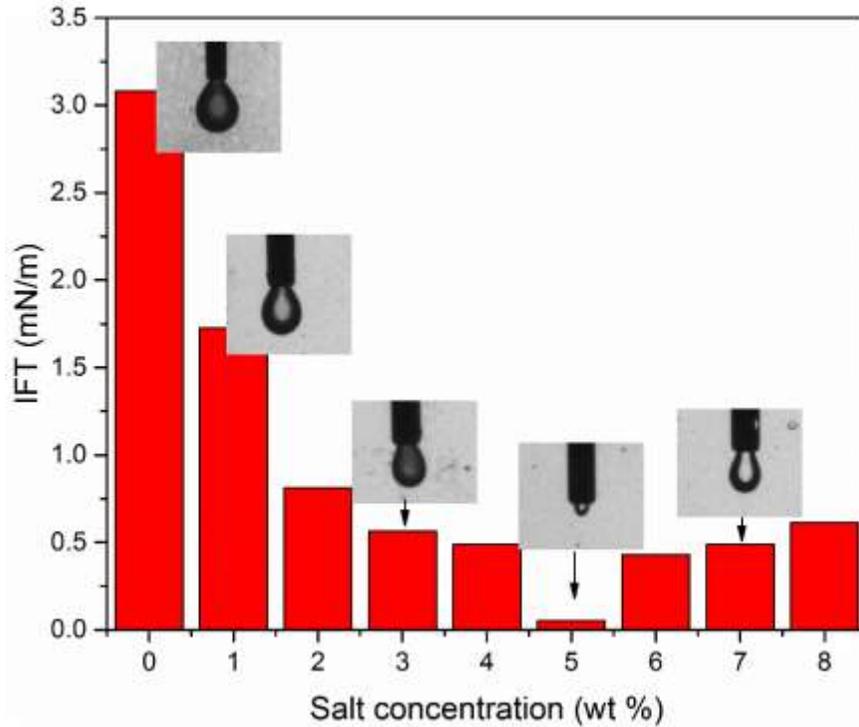


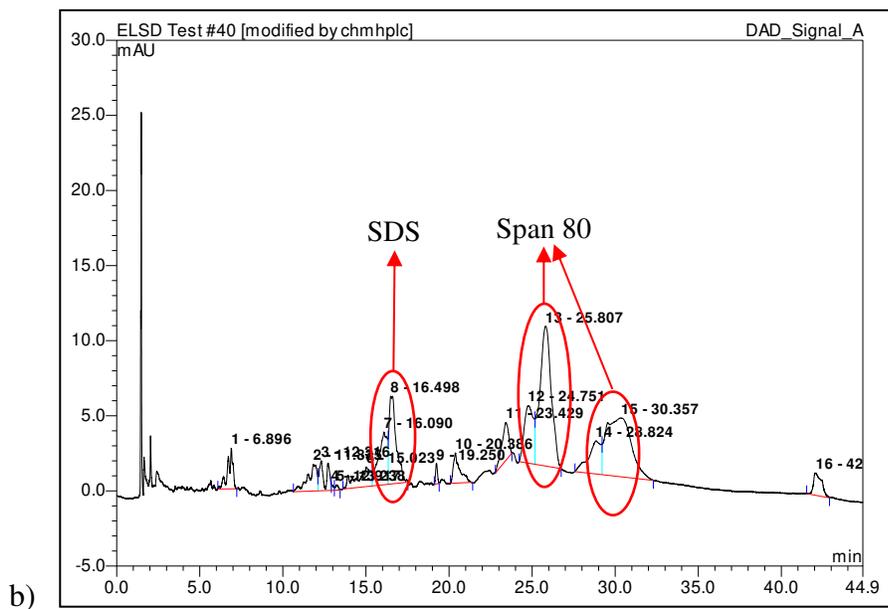
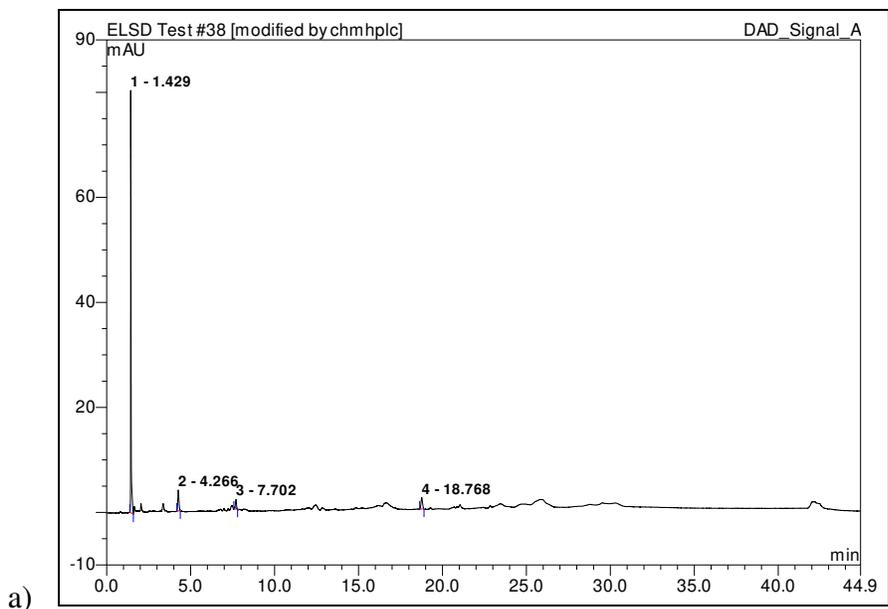
Fig. 6. The interfacial tension between microemulsion and mineral oil. Insets are images of microemulsion samples hanging on the needle tip. The volume of microemulsion sample is consistent with the trend of IFT.

Increasing salinity could decrease the mutual solubility between water and surfactant. At lower salinities (i.e., <3 wt %), more surfactant molecules are dispersed in water phase. Therefore the steric and electrostatic repulsion between oil droplets is too weak and unable to overcome the hydrogen bonds of water molecules. As the salinity increases, the distribution of surfactant in water and oil phase is changed, which leads to the decrease of IFT and formation oil nanodroplets. At very high salinity values (e.g. 10 wt %), the screening impact of the extra electrolytes compress the electrical double layers around droplets, leading to the separation of the O/W phases.

3.2. Evaluation Surfactant Adsorption

The higher surfactant concentration in effluent solution implies on lower adsorbed surfactant on packed surface for surfactant solution. Fig. 7 shows the chromatogram of collected solutions from the core holder after injecting surfactants blend in forms of micelles and nanodroplets. According to the chromatogram, there is no obvious peak in collecting samples after the flooding stage (Fig. 7a & c). At this stage, the surfactant molecules diffuse inside pores during the chemical slug flowing through the core. A part of surfactant molecules was adsorbed on rock surface and no molecules were extracted from the column during chemical flooding. Some tiny peaks in Fig. 7a & c are signal noises which may appear in the chromatogram of HPLC method. The surfactant molecules reached the outlet of column and started to leave the porous media during the brine post flooding stage. The retention time of surfactants peaks were specified by red ovals in the collected solution chromatogram (Fig. 7b & d) after comparing with pure surfactant chromatogram (Fig. S3, supporting document). There are a few extra peaks in collected solution chromatograms compared to pure surfactants, which is due to existence of impurities in the effluent solution. Probably some unknown minerals in silica grains carried by displacing fluids were collected at the outlet, which leads to appearance of extra peaks at chromatogram.

The retention time and area of chromatogram peaks for each surfactants in collected solutions are illustrated in Table 3. The surfactants adsorption amount on surface rocks were calculated based on the area of peaks, which also was provided in Table 3. Higher surfactants concentration were found in collected solution after nanodroplets injection comparing to the micelles form, which shows a more efficient delivery of surfactant in the form of nanodroplets.



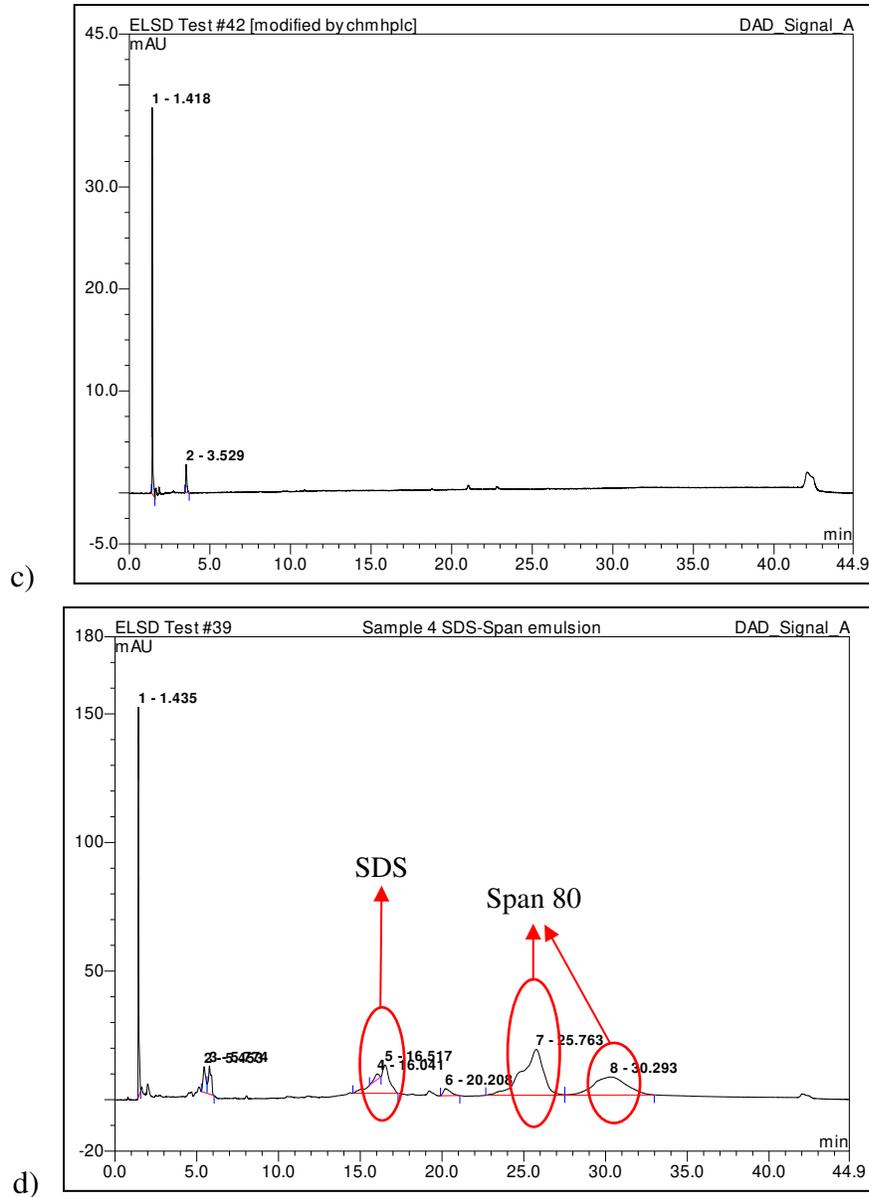


Fig. 7. Chromatogram of collected solution after (a, b) nanodroplet flooding and post brine flooding; (c, d) micelles flooding and post brine flooding.

Table 3. Areas of peaks and surfactants adsorption on rock surface.

Main fluid	Retention time (min)	Area (mAU×min)	Adsorption on rock surface (mg/g _{rock})	Adsorption on rock surface (mg/m ²)
SDS-nanodroplets Injection	16.52	6.41	1.53	1.74
SDS-micelles	16.50	5.06	3.49	3.98

Injection				
Span 80-nanodroplets Injection	25.76	20.93	1.75	1.99
Span 80- micelles Injection	25.81	9.88	4.14	4.72

Fig. 8 proposes the adsorption mechanism of surfactant blends on rock surfaces in the forms of micelles and nanodroplets. The surfactants are captured inside oil droplets by their hydrocarbon chains, reducing the chance of molecule attaching on rock surface by hydrophilic heads. However, when the wettability of the rock is oil-wet the attachment of oil droplets is increased, which leads to more surfactants retention compared to micelles form.

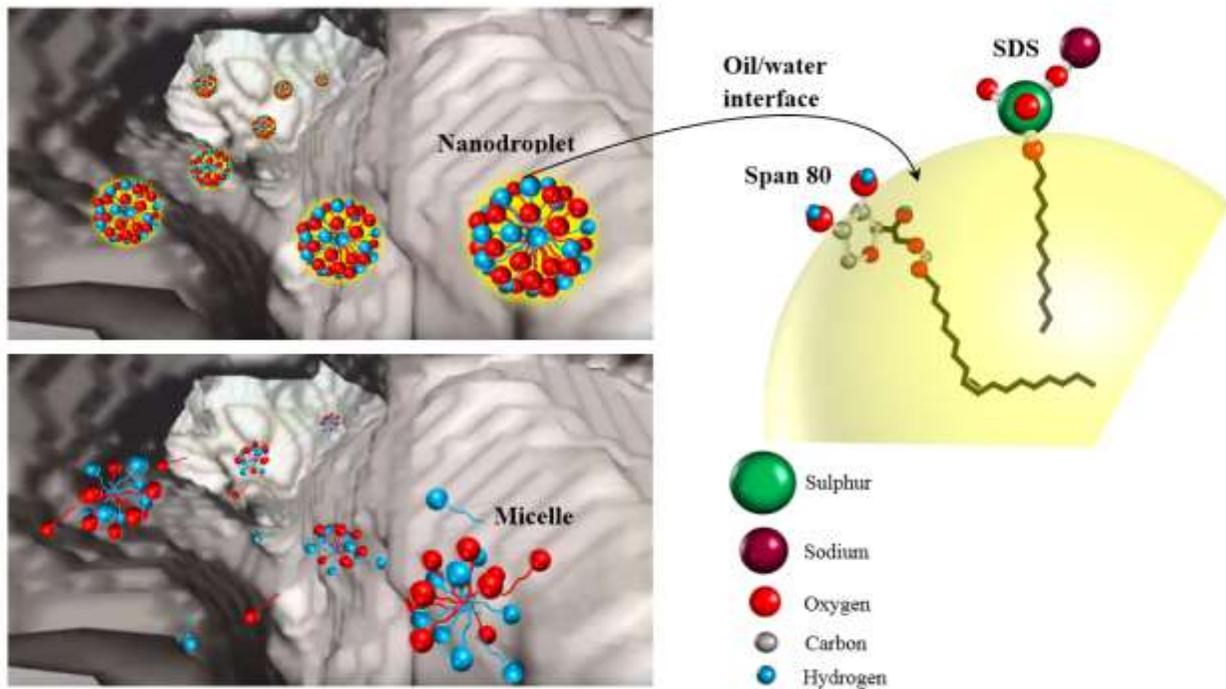


Fig. 8. The proposed mechanism for the adsorption of micelles form and nanodroplets on rock surface.

3.3. Oil recovery efficiency

The results of oil recovery efficiency by the injection of surfactants blend in forms of micelles and nanodroplet are presented in Table 4. Fig. 9 also shows the accumulate oil recovery

efficiencies, which is relative to the original oil-in-place (OOIP) after oil saturation, for three different stages: brine flooding, tertiary recovery and brine post-brine flooding. For more accurate estimation of oil recovery efficiency, 2.25 wt% of n-hexane (0.45 g in 20 mL of initial sample) which was used for synthesis of nanodroplets was added to OOIP in case of nanodroplet injection. It can be seen that, even though having the similar oil recovery efficiencies for these two scenarios, nanodroplet considerably improved the oil recovery efficiency by 15.9% OOIP (from 68.7% to 84.6%) in tertiary flooding stage whereas micelles only saw 8.1% OOIP incensement. The photos of collected oil amount after each stage of flooding have been shown in Fig. S4.

Table 4. Oil recovery efficiency by using surfactants blend in form of micelles and nanodroplets.

Main fluid	Efficiency after secondary flooding, % OOIP	Efficiency after tertiary flooding, % OOIP	Ultimate Efficiency after brine post flooding, % OOIP	Enhanced oil recovery efficiency, %
Micelles	66.6	70.1	74.7	8.1
Nanodroplets	68.7	80.4	84.6	15.9

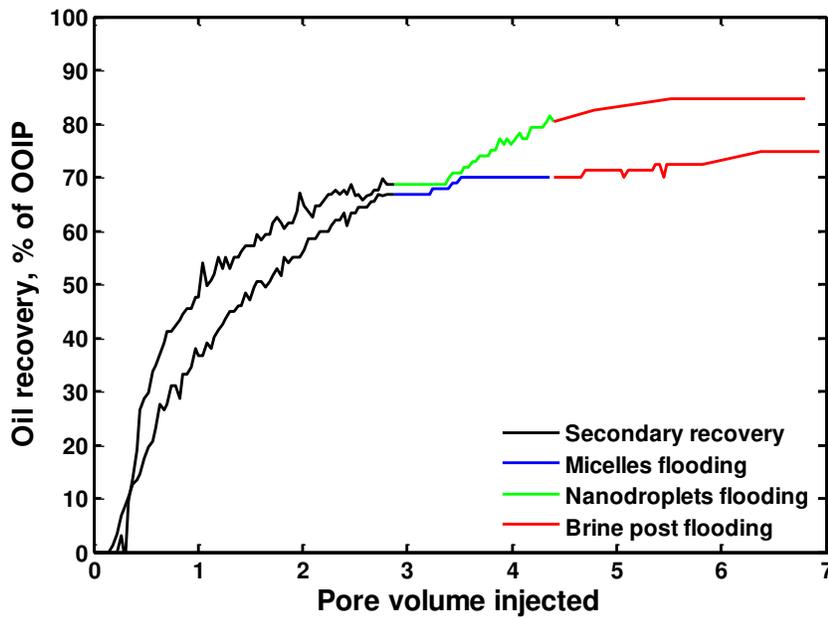
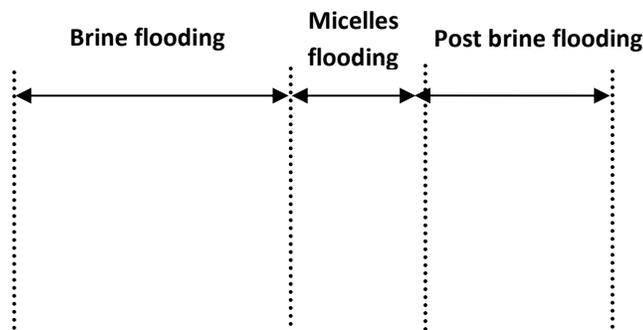


Fig. 9. Tertiary oil recovery obtained by micelles and nanodroplets injection.

Fig. 10 shows the differential pressure for core flooding during oil recovery experiments. The average pressure for micelles injection was mainly around 27 psi and fluctuated very heavily, with the highest value up to 68 psi. The high fluctuation of pressure is probably because of aggregated surfactant micelles, which behaved like large particles. These aggregated micelles carrying momentum from one part of the liquid to another by their motion or even maybe sediment in porous media. While starting from 6.1 psi, the pressure for nanodroplets injection was slightly higher than the brine flooding at the beginning, and experienced rapidly increase in 1.5 PV, however overall it kept under 20 psi for the whole flooding process. Using nanodroplets prevented the formation of aggregated micelles by distributing surfactants on large O/W interface. However, structure of nanodroplets phase was changed when contacting with the oil bank, which terminate to higher pressure. The processes of phase change and slurry formation are much slower than those happened for surfactant micelles, which introduced a gradually increasing trend instead of heavy fluctuations.



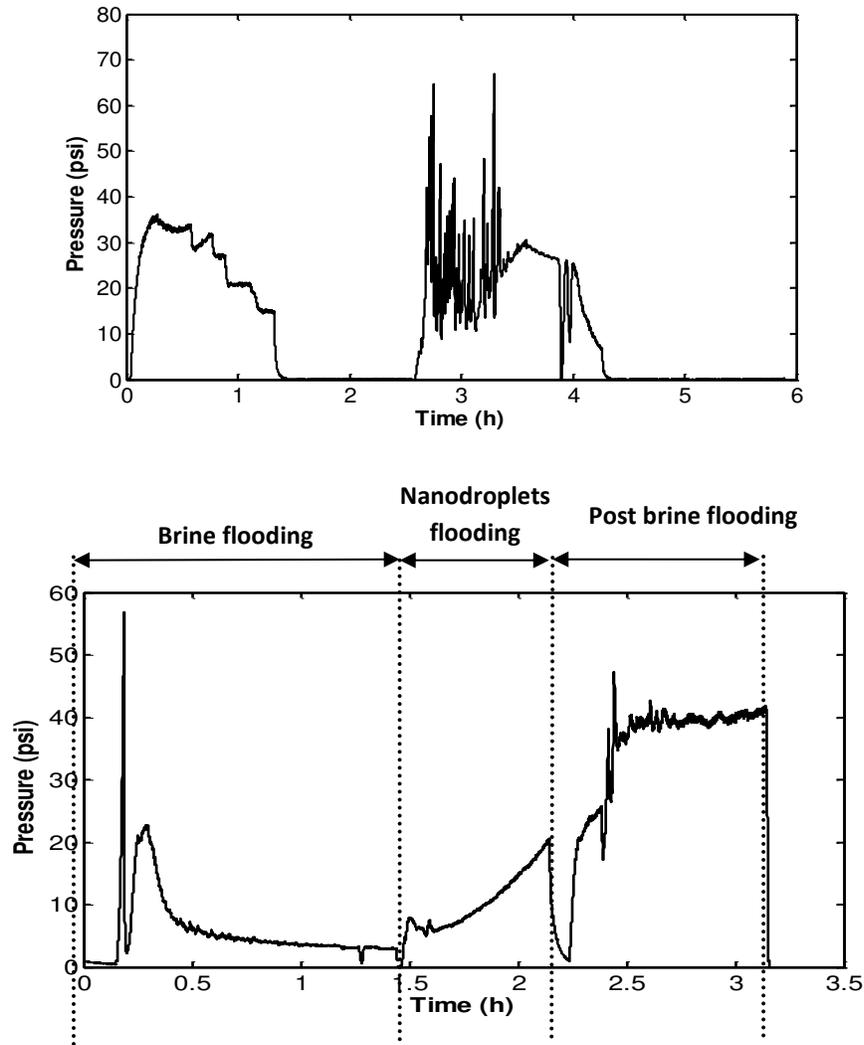


Fig. 10. The differential pressure for (a) surfactant solution, (b) microemulsion.

One of the other factors leading to higher oil recovery rate is higher viscosity of nanodroplets slug compared to the micelles form [35-37]. Several parameters (e.g. type of surfactant head polarity, microemulsion phase type) could influence the viscosity of microemulsion [38]. The effect of microemulsion viscosity on oil recovery efficiency needs in-depth analysis before applying microemulsion in field-scale EOR. Significantly higher viscosity of microemulsion (especially bi-continuous phase) relative to the brine and oil phases could result in viscous fingering phenomena since unfavorable mobility ratios occur between the phases [39, 40]. Fig. 11 shows the viscosity of injection solution in the forms of microemulsion and micelles in current

study. According to Fig. 11, the formation of oil nanodroplets in continuous brine phase improve the viscosity, which is beneficial for the mobility control during slug injection.

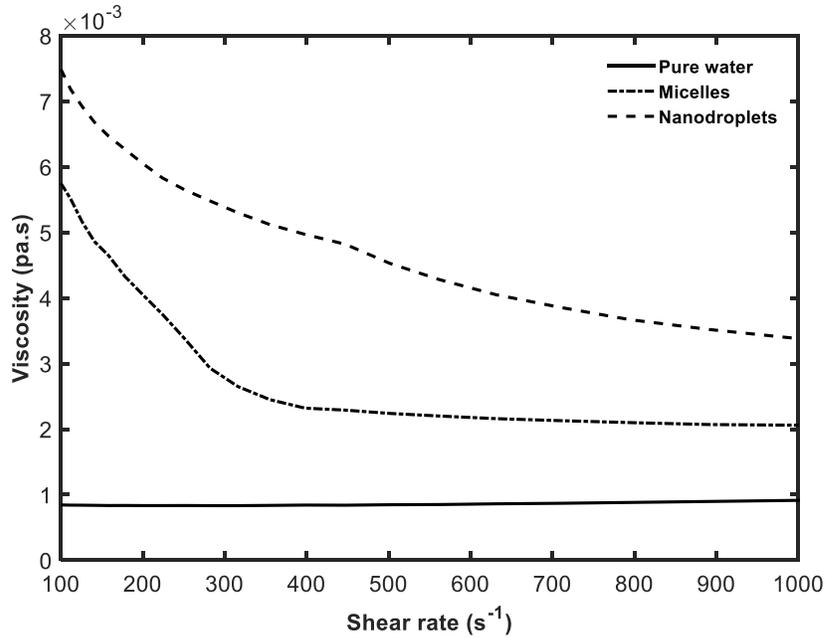


Fig. 11. Viscosity of displacing fluids (a) surfactant solution, (b) microemulsion.

4. Conclusion

The new concept of using nanodroplets as carriers for controlled delivery and release of surfactants/polymer inside porous media was investigated in this work. The surfactants retention and oil recovery efficiency of surfactants blend in the forms of micelles and nanodroplets were investigated. The accuracy and capability of the HPLC method allowed us to efficiently quantify the adsorption of the surfactant blends of sodium dodecyl sulphate and Sorbitan monooleate on silica porous media. The results show that the new concept, surfactant delivery by nanodroplets, reduced the adsorption of surfactants in the porous medium by nearly 50%, comparing to micelles flowing through the porous media packed with crushed sandstone rock grain. The lower and more stable pressure drop for nanodroplet in core-flooding indicate that surfactants were released slowly, resulting in ~8% OOIP higher oil recovery rate than that for the micelle form. In addition, much smoother pressure profile was observed, contrasting to the large pressure fluctuations related to micelles, in the stage of surfactant blend injection, which shows the good injectability of the

nanodroplets. All these support that the use of using nanodroplets for surfactants delivery could have great potential for EOR applications.

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