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Original article

Comparative study of ultrasound assisted water and surfactant flooding

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A B S T R A C T

Ultrasound technique is an economic advantageous and environmental friendly unconventional enhanced oil recovery (EOR) method that has been of great interest to researchers and reservoir engineers. The integration of ultrasound with water flooding and ultrasound with surfactant has been proven to be effective in increasing oil recovery by decreasing surfactant adsorption. Previous studies focused on the phase behaviour of surfactant-brine-oil to determine if ultrasonic with surfactant can actually decrease the rate of surfactant consumption. However, phase behaviour alone cannot answer this question. In this study therefore, the role of critical micelle concentration (CMC) in ultrasound assisted surfactant flooding, and the effect of surfactant concentration on oil recovery during ultrasound at different intensities were investigated. An unconsolidated sand-pack model placed inside an ultrasonic bath and ultrasonic radiation was used for this purpose. Ultrasound assisted water and surfactant flooding improve recovery up to 11% and 12% respectively. The formation of micro-emulsion (micelles) during surfactant flooding in the presence of ultrasonic wave was the most significant mechanism responsible for the increased recovery. Ultrasound vibration is more efficient at higher concentration of surfactant, preferably above CMC and at higher intensity of ultrasound.

1. Introduction

As most oil field in the world are entering into their tertiary stage of production, EOR methods are needed to boost production. To improve the performance of EOR processes, a better understanding of the mechanisms and influence of critical parameters on oil recovery methods is essential. Conventional EOR methods such as water and surfactant flooding have their limitations. Some are expensive employing wide range of surface materials while others can generate environmental concern couple with their technical limitations.

Ultrasonic technique is another unconventional EOR method which utilizes pressure wave to displace oil trapped in the reservoir. The idea behind this technology is as a result of kick in oil production prompted by earthquake (Mirzaei-Paiaman and Nourani, 2012). The idea is not new, but the dominant mechanism of this process is not yet explicit. Series of laboratory investigations and field applications has been conducted (Duhon and Campbell, 1965; Amro et al., 2007; Mirzaei-Paiaman and Nourani, 2012; Abramov et al., 2013; Mohammadian et al., 2013; Alhomadhi et al., 2014; Hamidi et al., 2017). But most field application has been limited to damage removal near wellbore area. Mirzaei-Paiaman and Nourani (2012) reported that when a 5.7 magnitude earthquake hit three gas condensate wells along the Persian Gulf, one well responded to the seismic wave and increased production but the other two did not. The responding well was reported to have a condensate dropout near the wellbore porous media while the other two wells had no condensate accumulation. This natural seismic wave is believed to be responsible for this damage removal.

1.1. Ultrasound oil recovery mechanisms

Various mechanisms have been proposed by different authors to be responsible for the increased oil recovery by ultrasound. Some of these mechanisms are cavitation (Guo et al., 2004; Hamida and Babadagli 2007); micro-emulsification (Abismail et al., 1999); and coalescence (Metting et al., 1997). These mechanisms are mostly controlled by the frequency and intensity of the ultrasound, capillary and viscous forces, rock elasticity, cementation, fluid properties, porosity and clay content (Hamida and

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Babadagli, 2007). For cavitation to be formed in a liquid, the negative pressure in the rarefaction region of the wave must overcome the natural cohesion force acting within the liquid. Hence, waves with higher amplitude and greater intensity are needed for the viscous liquid (Esminger, 1988). The use of ultrasonic in water flooding has been reported by Mohammadian et al. (2013). Their result showed a 3–16% increase in oil recovery during waterflooding. The mechanisms responsible for such increase in recovery were identified as emulsification, viscosity reduction and cavitation. Amro et al. (2007) on the other hand attributed the increase in recovery to wave stimulation and change in relative permeability. Alhomadhi et al. (2014) also emphasized that the change in permeability as a result of wave stimulation was the principal mechanism of increased oil recovery during ultrasonic assisted flooding.

However, the mechanism was found to be operational only in the horizontal wells. Vertical wells are usually affected by gravitational separation. It can also lead to sand production in unconsolidated formations with a compressive strength lower than 150 psi.

Surfactant flooding is another promising EOR method which can lower the interfacial tension (IFT) between oil and water, allowing emulsification and displacement of the trapped oil in the reservoir. The integration of surfactant with ultrasonic is very promising. Hamidi et al. (2015a) studied the phase behaviour of surfactant, brine and oil. Their results showed that the integration of ultrasound-surfactant flooding has the potential to decrease surfactant adsorption. Hamidi et al. (2015b) further investigated the effect of the period of ultrasound radiation on emulsification and demulsification of paraffin oil and surfactant solution in porous media. They concluded that emulsification could be one of the significant oil recovery mechanisms in porous media under short period of ultrasound application.

Suslick (1989) suggested that the sonochemistry of two immiscible liquid such as oil and water is due to the ability of ultrasound to emulsify the liquids. This is to enable the microscopic droplet of one liquid suspended in the other. The science behind this is the expansion and compressional stress exerted by the ultrasound on the liquid surface. This overcomes the cohesive force that holds a large droplet together. The ultrasound therefore, breaks the large droplets into smaller ones and the liquids are emulsified. Coalescence of surfactant solution droplet could also occur due to the enhanced collision frequency of small dispersed phase droplet, increase in acoustic streaming velocity, attractive forces acting between oscillatory droplets (Bjerknes forces). Others include continuous radiation of ultrasonic wave and heat generated, which led to improved recovery (Gaikwad and Pandit, 2008; Amro and Alhomadhi, 2006).

The integration of ultrasound with water flooding (Amro et al., 2007; Mohammadian et al., 2013) and Ultrasound with surfactant (Hamidi et al., 2015a,b) has recently become an interesting subject among researchers. Hamidi et al. (2015a) studied the phase behaviour of surfactant-brine-oil to determine if ultrasonic with surfactant can actually decrease the rate of surfactant consumption. But phase behaviour alone cannot answer this question and for us to come to a reasonable conclusion the effect of ultrasound on surfactant concentration should also be investigated. Hamida and Babadagli (2007) reported that ultrasonic is not effective in reducing IFT. Hamidi et al. (2015a) explained that, this could be due to the use of the surfactant close to the CMC. IFT is considerably reduced at this concentration and the effect of the ultrasound wave might not be felt. Hence, the use of surfactant concentration far from the CMC should be considered. In this study, the integration of ultrasound with water and surfactant flooding is compared. The role of CMC in ultrasound assistedsurfactant flooding is investigated and the effect of surfactant concentration on oil recovery during ultrasound at different intensities is also investigated. An unconsolidated sand-pack placed inside an ultrasonic bath and an ultrasonic transducer was used for this purpose.

2. Experimental set-up and procedure

2.1. Equipment

An ultrasonic bath (W: 21 cm × L: 50 cm × H: 30 cm) was used for the experiment. It was connected to a Crest ultrasonic generator device with a frequency of 40 kHz and intensity of 150 W, 300 W and 500 W. A centrifuge injection pump was used to inject the fluids into the sand-pack and a 2hp vacuum pump was used to vacuum the sand-pack before saturation. A digital pressure gauge was used to measure the pressure difference between the inlet and outlet of the sand-pack. The sand-pack was placed at the centre of the ultrasonic bath to ensure maximum exposure to the ultrasonic radiation. Fig. 1 shows the schematics of the experimental set-up.

2.2. Fluid properties

NaCl with a concentration of 50,000 ppm was used for the entire experiment. Paraffin was used as the non-wetting phase fluid in the experiment. Table 1 summarises the properties of the fluid used.

2.3. Porous media

Quartz sand grains of 125–450 μm size packed in a polyvinyl chloride (PVC) holder 15 cm in length and 3.56 cm in diameter represented the porous media. The sand was packed using the dry method in all experiments. A 100 μm mesh nets were fixed at both ends between the sand and the cap of the sand-pack to prevent sand production. The caps were drilled in the middle and fittings screwed at both ends (Fig. 2). The porosity and permeability of the sand pack were measured as 35.3% and 1.74D respectively. The porosity was measured using the gravimetric method, the bulk volume (V_b) of the core was calculated using the diameter (d) and

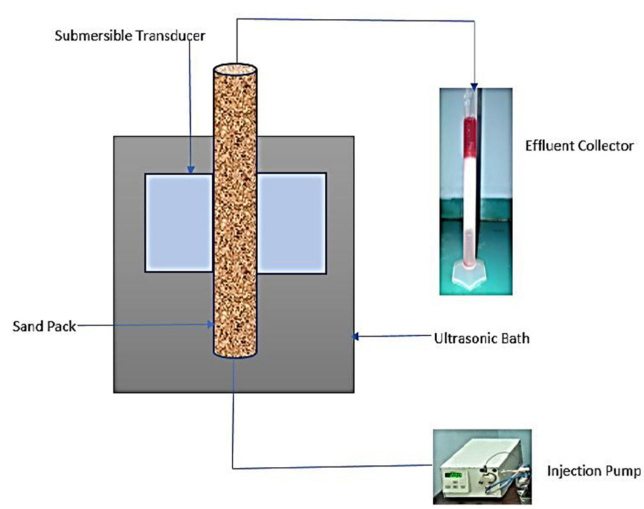

Fig. 1. Schematics of Experimental Set-up.

Table 1
Caption: Fluid Properties.

Name of Fluid	Viscosity at 27 °C (cp)	Density at 27 °C (gr/cm^3)	Colour
Paraffin Oil	28.00	0.90	Colourless
Name of Fluid	Viscosity at 27 °C (cp)	Density at 27 °C (gr/cm^3)	Concentration (ppm)
Brine	0.90	1.02	50,000

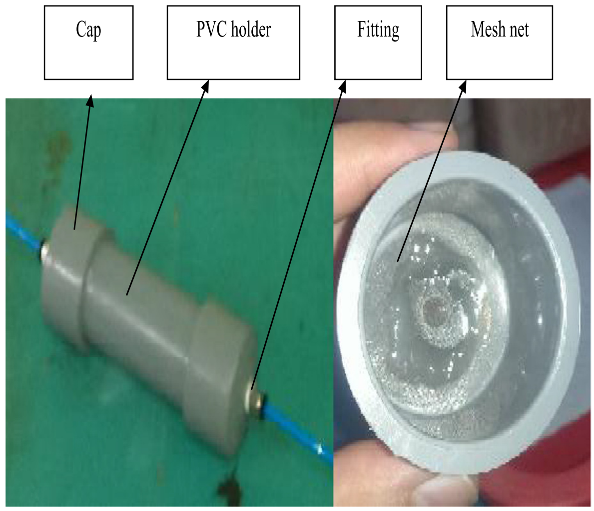

Fig. 2. Pictorial View of Porous Media.

length of the core holder. The sand pack without core holder was weighed to determine the volume of the grain (V_g). The pore volume (V_p) was calculated by subtracting V_g from V_b. The porosity (ϕ) was calculated using the equation:

$$\varphi = \frac{V_p}{V_b} \times 100 \quad (1)$$

The permeability of the sand pack was determined by saturating the core with brine at constant flow rate and the pressure drop recorded. The permeability was calculated by applying the Darcy flow equation:

$$K = \frac{\mu LQ}{A\Delta P} \quad (2)$$

where: K is the rock permeability (Darcy); Δp is the pressure difference (psig); A is the inner cross sectional of model (cm^2); L is the length of the model (cm); Q is the brine flow rate (ml/s); μ is the brine viscosity (cp). The pictorial representation of the porous media is shown in Fig. 2.

2.4. Surfactant

Anionic surfactant Sodium Dodecyl Sulfate (SDS) with 96% purity and molecular weight of 288.38 g/mol was supplied by Acros Organic Company. The SDS at concentrations of 0.1wt% (below CMC) and 1wt% (above CMC) were used for all the experiments.

2.5. Experimental procedure

Two sets of experiments were performed in this study, water flooding and surfactant flooding. 3 wt% NaCl brine was injected into the sand-pack until residual oil saturation was obtained. Paraffin was then injected into the sand-pack at an injection rate of 2 ml/min. until saturation was reached. The water saturation (S_w) and oil saturation (S_o) were calculated from the volume of water and oil that came out of the sand-pack. The water flooding started and continued until 2 pore volume (PV) before the residual oil saturation was reached. The effluents were collected, and the oil recovery calculated. The procedure was repeated but this time the sand-pack was immersed in the water bath to provide a suitable surrounding for the ultrasound radiation. Another set of experiment was performed with surfactant. The experiments were conducted with two concentrations of 0.1wt% (below CMC) and 1wt % (above CMC).

3. Results and discussion

3.1. Water flooding

The oil recovery at the end of the initial water flooding was calculated in percent of PV and in percent of original oil in place (OOIP). The water flooding process recovered 46% of OOIP at a breakthrough time of 30 min, as shown in Fig. 3. Upon application of ultrasonic radiation, the oil recovery increased to 57% OOIP (Fig. 4). Ultrasonic improved the recovery by 11% of OOIP. The experimental result during water flooding is shown in Table 2.

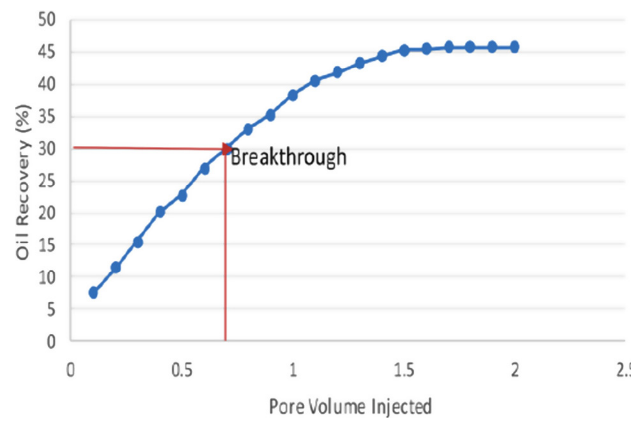

Fig. 3. Oil Recovery in the Absence of Ultrasound.

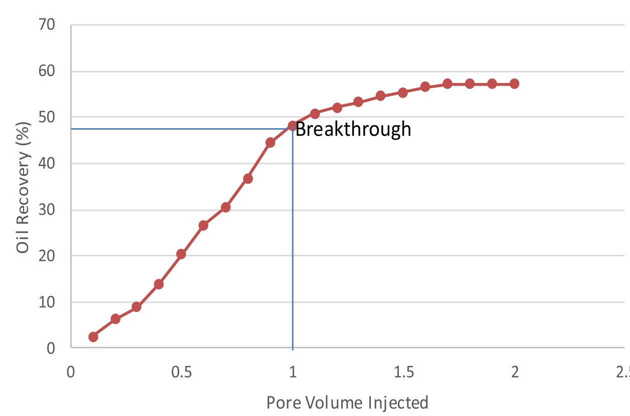

Fig. 4. Oil Recovery in the Presence of Ultrasound.

Table 2
Caption Experimental Results during Water Flooding.

Absence of Ultrasonic			Presence of Ultrasonic		
Time (min)	PV	Recovery (%)	Time (min)	PV	Recovery (%)
5	0.1	7.6	3	0.1	2.5
7.5	0.2	11.4	5.5	0.2	6.3
9.5	0.3	15.5	7.5	0.3	8.8
15	0.4	20.1	10	0.4	13.9
19	0.5	22.8	14	0.5	20.3
23	0.6	26.9	18	0.6	26.6
30	0.7	30	22	0.7	30.5
36	0.8	33	29	0.8	36.8
40	0.9	35.3	35	0.9	44.4
43	1.0	38.4	39	1.0	48.3
49	1.1	40.6	44	1.1	50.8
54	1.2	41.9	48.5	1.2	52.1
60	1.3	43.2	55	1.3	53.3
70	1.4	44.4	62	1.4	54.6
80	1.5	45.3	70	1.5	55.5
90	2.0	45.7	90	2.0	57.2

One possible mechanism responsible for the additional recovery is a stable displacement front due to the pore vibrations and localized pressure perturbations. This increase in recovery could be attributed to the reduction in viscosity of the paraffin from 28cp to 20.89cp after applying ultrasound, which is about 25% reduction of the viscosity of paraffin oil. Similar result of about 25–30% reduction in viscosity was also reported by Huang (1993) and Xianghong and Zhang (1996). These results generally showed that ultrasonic wave could effectively decrease the viscosity of heavy oil and therefore, increase mobility ratio. Our result showed that ultrasonic wave increased the temperature of the system by 5 °C from an initial temperature of 27 °C to 32 °C. This could be the reason for the decrease in viscosity of paraffin oil (Mohammadian et al., 2013). Also, the pressure gradient decreased when ultrasound was applied. Fig. 5 shows that after applying ultrasound (500 W, 40 kHz), the slope (m) of the trendline (Regression line) decreased from 0.9946 to 0.9865. The Figure also demonstrates that pressure gradient along the sand-pack decreased when ultrasound was applied, which enhanced fluid flow through the porous media. It also shows that with increased ultrasound power, the pressure gradient decreases. The finding is consistent with previous studies of Aarts et al., 1999 and Hamidi et al. 2014. The decrease could also be attributed to the thermal effect of the ultrasound which caused reduction in viscosity of the liquid. This is consistent with previous studies by Poesio and Ooms (2005); Poesio et al. (2002); Hamidi et al. (2014). They suggested that pressure drop decreases due to decrease in liquid viscosity caused by rise in temperature of liquids.

The mechanism created by acoustic cavitation is the conversion of sound energy to thermal energy in the porous media. Cavitation releases a lot of thermal energy at the point of bubble collapse and at high frequency. Also, there is strong absorption of the sonic energy by the medium, which resulted to heating of the medium and greater boundary friction. Therefore, strong intensity of ultrasound can lead to violent cavitation and thermal effect (Guo et al., 2004; Hamida and Babadagli, 2007). Boundary friction can lead to increase in temperature at the interface of the porous media. The difference in the vibration velocity of the fluid and solid results in sound energy been converted to heat energy at the boundary plane of fluid and solid. It can also take place at the interface of liquid and suspending particles streams (acoustic streams) (Guo et al., 2004). The sound energy also reacts with the intermolecular force of the fluid setting it in motion (Brownian motion) by the molecule hitting it self and the walls of the porous media. Ultrasonic wave propagation in medium makes particles to vibrate alternatively, which causes stress and acoustic pressure to change. When high amplitude ultrasonic wave propagates through the medium, a zig-zag (Brownian motion) periodical shock waves can be formed. This causes pressure gradient on the wave face and series of effect will be produced, such as high temperature and pressure. This nonlinear vibration causes adhesion and particle collision which results to cohesion affinity and orientation of particle streams (Guo et al., 2004). Fig. 6 shows the comparison between water flooding in the presence and absence of ultrasonic. The figure exhibits a clear difference in recovery performance for both cases. The ultrasound caused rapid movement of the trapped oil within the zones that have been bypassed by water flooding. Another interesting result is the formation of emulsion. The two phases were completely separated and the interface between the two phases could easily been seen.

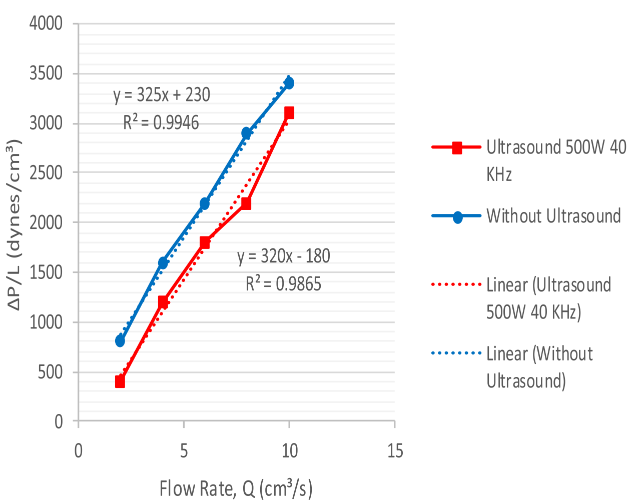

Fig. 5. Paraffin Oil Viscosity Measurement with and without Ultrasound.

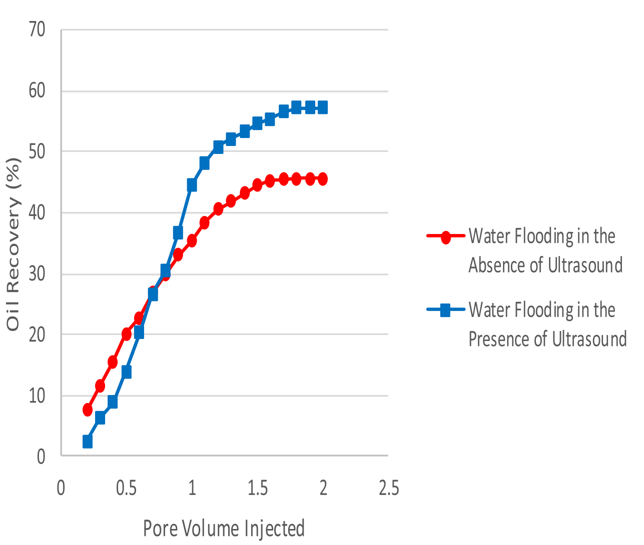

Fig. 6. Oil Recovery for Water Flooding in the Presence and Absence of Ultrasonic.

3.2. Surfactant flooding

The oil recovery for surfactant flooding at 0.1 wt% concentration (below CMC) was 56% OOIP as shown in Fig. 7, while it was 68% OOIP in the presence of ultrasonic. Which is an increment of 12% OOIP at a breakthrough time of 39 min (Fig. 8). The breakthrough time is the time interval needed for the surfactant to reach the collector.

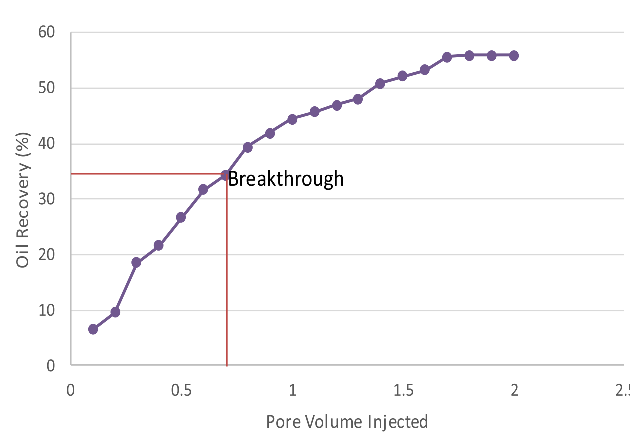

Fig. 7. Oil Recovery for Surfactant Flooding in the absence of Ultrasonic.

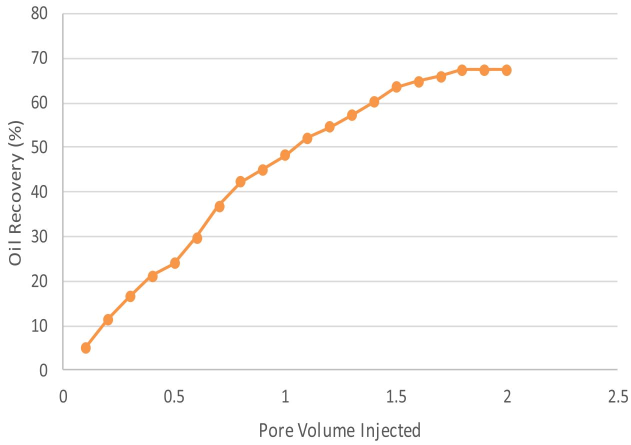

Fig. 8. Oil Recovery for Surfactant (0.1 wt%) Flooding in the Presence of Ultrasonic.

Several mechanisms can be responsible for this increase in recovery. The formation of micro-emulsion (micelles) under ultrasound could be responsible for this. After 30 min of the flooding a semi-transparent and foggy micro-emulsion was observed as the surfactant diffuses and spread into the paraffin. Similar observation was reported by Hamidi et al. (2015a,b). They concluded that the formation of the microemulsion can be attributed to the agitation by the ultrasonic radiation. Fig. 9 shows the microemulsion of paraffin oil and surfactant under ultrasonic exposure.

It was observed that (Fig. 9b), as the radiation continues the paraffin also starts to diffuse into the surfactant which demonstrates the oil-water emulsion generation. This result is consistent with the studies of Li and Fogler (1978); and Hamidi et al. (2015b) when they reported that the diffusion could also be as a result of the destruction and interfacial instability of paraffin oil and surfactant solution interface and acoustic streaming. The oil and surfactant solution interface were disrupted by the ultrasonic wave which resulted in the vibration of surfactant solution droplet that penetrated the phases. Compressional and expansion force of the ultrasonic wave also apply force on the liquid surface which overcome the force holding the molecules together forming emulsion (Suslick, 1989). Fig. 10 shows the comparison between surfactant flooding in the presence and absence of ultrasonic wave.

The dispersion of surfactant solution into the oil and the breakage of surfactant solution droplet suspended in the paraffin oil are facilitated under ultrasound (Lin and Chen, 2005). This could be clearly seen (Fig. 10) as the recovery was higher in the presence of ultrasound. Also, wave damping can result to acoustic streaming. This could induce a net steady flow, which could result to a bulk motion of the liquid (Poesio et al., 2002).

3.3. Effect of surfactant concentration

To determine the effect of surfactant concentration on recovery during ultrasonic wave exposure, the CMC of the surfactant was determined from the plot of surface tension against concentration. The breakpoint of the graph indicates the CMC as shown in Fig. 11. The CMC was determined at 0.2 wt%. Two concentrations of 0.1 wt % (below CMC) and 1wt% (above CMC) were used. The concentration of 1wt% was chosen because it was determined as the optimum concentration above CMC as higher concentration did not yield any significant change (Hamidi et al., 2015a). This is because as higher concentration slug moves through the reservoir, it is diluted by the formation fluid and the process reverts to a lower concentration (Gogarty, 1976). Therefore, to have a successful surfactant flood the CMC must be between 0.1 and 2 wt% (Abbas et al., 2017). Fig. 13 shows that using a surfactant with concentration above the CMC resulted in higher oil recovery compared to surfactant with concentration below CMC (Fig. 12).

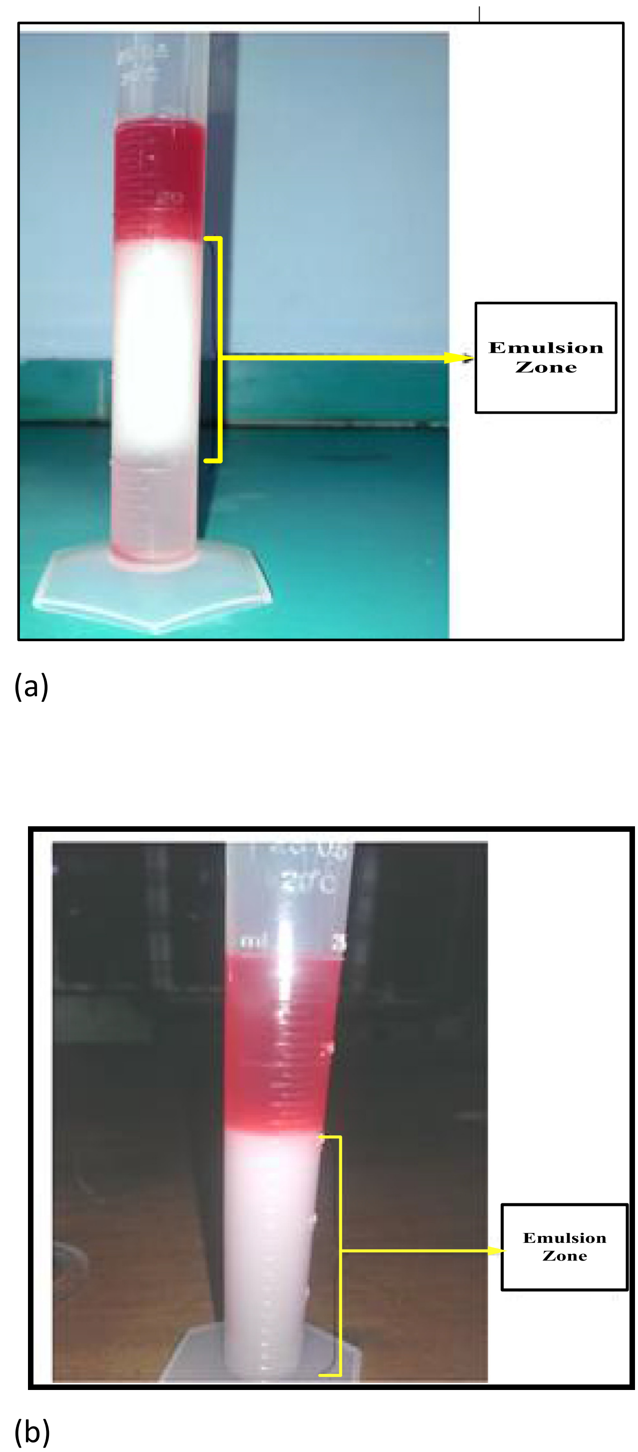

Fig. 9. (a) Emulsion of Paraffin oil under ultrasonic Radiation. (b) Emulsion of Paraffin Oil during Surfactant Flooding (1 wt%) in the Presence of Ultrasonic.

Fig. 9b shows the surfactant flooding at 1 wt% effluent in the presence of ultrasonic. It can be seen that the surfactant with concentration above CMC (Fig. 9b) has a larger emulsion zone (15 ml) compared to surfactant with concentration below CMC (Fig. 9a) with 11 ml of emulsion zone. It can be observed that at 0.1 wt% concentration (Fig. 9a), there were three different zones; oil zone (9ml), emulsion zone (11 ml) and the brine zone (5ml), while with

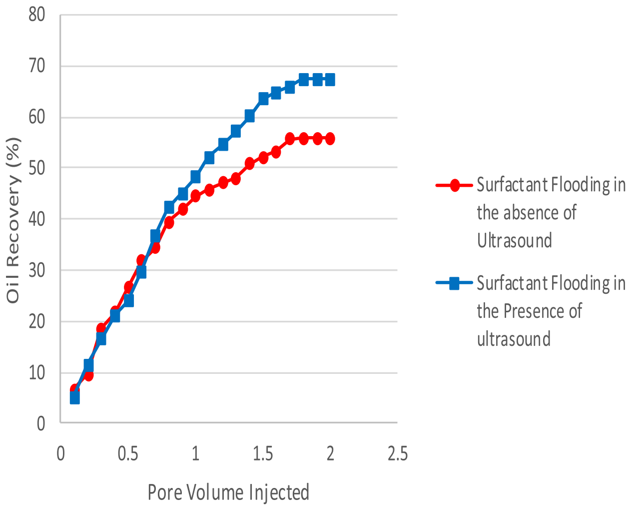

Fig. 10. Oil Recovery for Surfactant Flooding in the Presence and Absence of Ultrasonic.

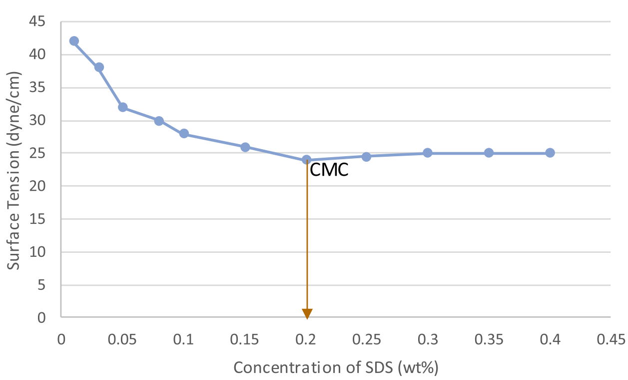

Fig. 11. Determination of CMC.

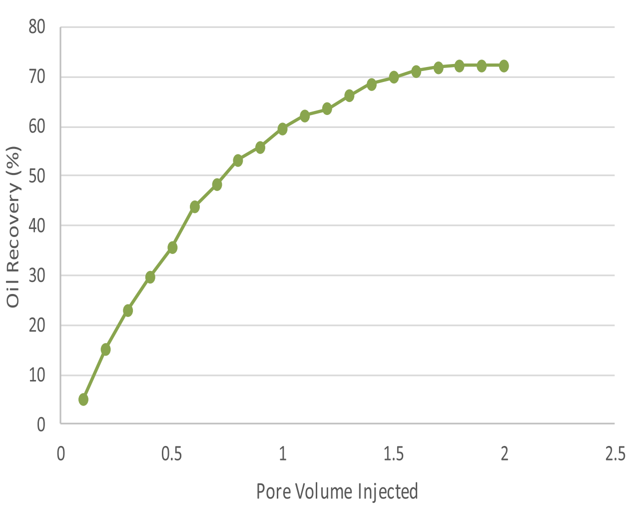

Fig. 12. Oil Recovery for Surfactant Flooding (1 wt%) in the presence of Ultrasonic.

1wt% concentration (Fig. 9b) there are two zones; oil zone (10 ml) and emulsion zone (15 ml) which shows complete emulsification. It can therefore be concluded that ultrasonic wave is more efficient with surfactant flooding at higher concentration of surfactant, which is in agreement with previous study by Hamida and Babadagli (2007). Fig. 13 shows a comparison of oil recovery using

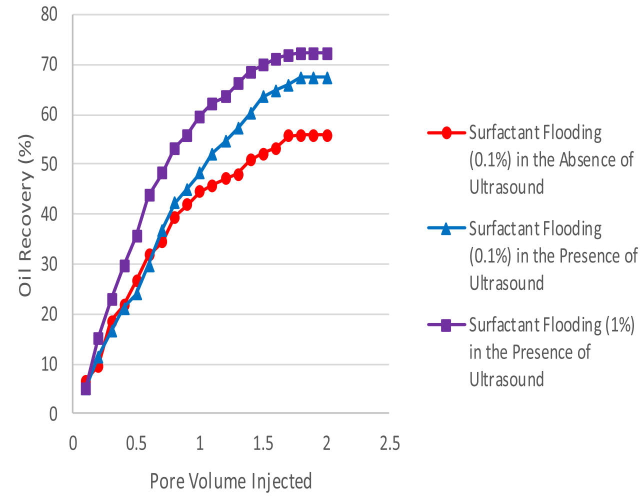

Fig. 13. Oil Recovery for Surfactant Flooding at different Concentration in the Presence and Absence of Ultrasonic Wave.

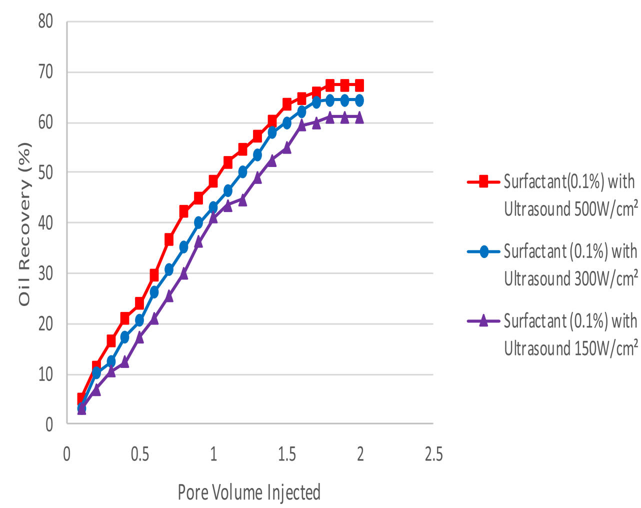

Fig. 14. Effect of Ultrasound Intensity on Oil Recovery for Surfactant Flooding (0.1 wt%).

surfactant with different concentration in the presence and absence of ultrasonic wave exposure. The result shows a substantial increase in recovery when the surfactant concentration was above CMC compared to concentration below CMC and no ultrasound. The possible explanation could be Bjerknes forces which could be responsible for this increase in recovery (Naderi and Babadagli, 2010), as more stable displacement front is formed due to pore vibration and localized pressure perturbation. Development of micelles under ultrasound as operating ultrasound at surfactant concentration above CMC accelerates the generation of micelles which may have enhanced the oil recovery.

3.4. Effect of ultrasound intensity on oil recovery

Three different intensities were considered for this experiment, a low intensity of 150 W/cm^2, medium intensity of 300 W/cm^2 and a high intensity of 500 W/cm^2. The oil recoveries below CMC and above CMC for different intensities are presented as Figs. 14 and 15 respectively. The summary of the experimental results is presented in Table 3. The oil recovery increased with increase in inten-

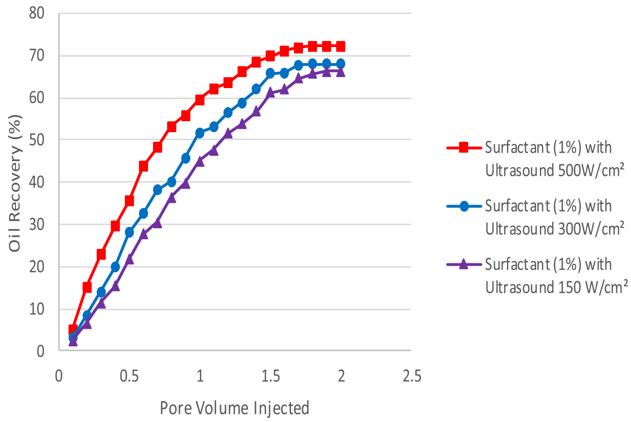

Fig. 15. Effect of Ultrasound Intensity on Oil Recovery for Surfactant Flooding (1 wt %).

sity of the ultrasound, from 61.1% (150 W/cm^2) to 67.4% (500 W/cm^2) below CMC Fig. 14.

The oil recovery increased further above CMC from 66.3% to 72.4% (Fig. 15). This is in agreement with previous studies by Gulseren et al. (2007) when they observed that high power ultrasonic wave increase surface activity and hydrophobicity of the interface between two liquids. Ultrasound may increase the solubility of surfactant in the porous media, which can result to favourable changes in interfacial properties. A decrease in interfacial tension will cause a change in wettability, reduction in capillary pressure generated by the trapped oil droplet in the pores which mobilized the oil. Similar result was also observed by Hamida and Babadagli (2007). Ultrasound may have also reduced the adsorption rate of the surfactant onto the rock matrix, which will in turn increase the solubility of the surfactant, resulting in weakening of the surface film generated at the pore throat (Hamida and Babadagli, 2007).

3.5. Effect of the principles of ultrasound on oil recovery

The basic principles governing the propagation of ultrasound wave through porous medium during the experimental process can be listed as follows; acoustic streaming, absorption, attenuation, reflection, refraction, frequency, distance from the source of ultrasound. Acoustic impedance is formed under difference in a radial direction during ultrasound. When wave propagates through the medium, particle streams are produced along the direction of sound wave propagation. The velocity is related to the shear viscidity coefficient, volume factor and adsorption of the sound wave. This acoustic impedance can lead to vibration and subsequently reduction in viscosity. As oil droplet that are stock in the nooks and cranies of the porous medium were dislodged by vibration and carried by the water flow (Langnes, 1972; Alhomadhi et al., 2014). The energy absorbed increased with decrease in fluid viscosity and decreased as the fluid viscosity increases. Which induces the change of the sound wave to heat energy as noticed in the ultrasonic assisted water flooding. The higher the intensity of ultrasound, the stronger the adsorption effect and greater boundary friction. Rise in temperature can also be observed as the intensity is increased. The size of cavitation is diminished, and the number of cavitation is increased. Which led to decrease in viscosity and subsequently increased recovery with ultrasound. The increase in recovery by ultrasonic wave can also be attributed to the low attenuation as a result of high frequency (40 Hz), which is believed to be generated as harmonics of low-frequency seismic waves as they penetrate the reservoir (Naderi and Babadagli, 2010). The penetration could also be attributed to the destruction of interfacial instability of paraffin oil and surfactant solution inter-

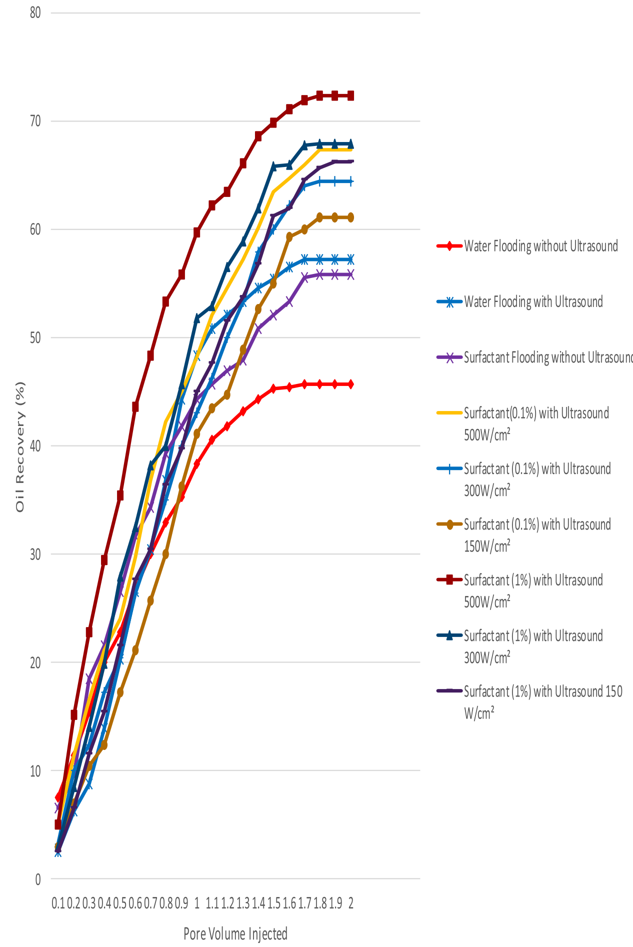

Fig. 16. Comparison Plot of Experimental Results.

Table 3
Caption Summary of Experimental Results.

Absence of Ultrasonic			Presence of Ultrasonic (0.1%)				Presence of Ultrasonic (1%)			
Time (min)	PV	Rec (%)	Time (min)	Rec (500 W) (%)	Rec (300) (%)	Rec (150 W) (%)	Time (min)	Rec (500 W) (%)	Rec (300 W) (%)	Rec (150 W) (%)
6	0.1	6.5	3	5.1	3.2	3	3	5	3	2.5
13	0.3	18.5	11	16.5	12.4	10.5	12	22.8	14.1	11.5
27	0.6	31.7	23	29.7	26.4	21.2	26	43.7	32.5	27.7
39	0.8	39.4	38	42.3	35.1	30	36	53.3	40.1	36.4
49	1.0	44.4	48	48.2	43.1	41.2	49	59.7	51.8	45
55	1.2	47	57	54.6	50	44.7	57	63.5	56.7	51.5
66	1.4	50.8	65	60.2	58	52.6	65	68.6	62	56.8
75	1.6	53.3	75	64.8	62.2	59.4	75	71.1	66	62
90	2.0	55.9	90	67.8	64.5	61.1	90	72.4	68	66.3

face and acoustic streaming (Hamidi et al., 2014). The oil and surfactant interface were distrusted by the ultrasonic wave that stimulated the vibration of the surfactant solution droplet and facilitated the penetration of the oil phase as observed in Fig. 9.

In summary, surfactant flooding at a concentration (1 wt%) above CMC, with ultrasound of high intensity (500 W/cm^2) were observed to have formed a more stable micelle. The difference can be observed clearly from Fig. 16. Fig. 16 summaries the ultimate recovery in all the experiments. Water flooding in the absence of ultrasound produced the least recovery. It can therefore be concluded from this experimental work that oil recovery increases with increase in intensity of ultrasound and surfactant concentration above CMC.

4. Conclusions

This study was aimed at comparing the effect of ultrasonic waves on water and surfactant floodings, from the experimental results, the following conclusions were drawn;

1. Ultrasonic wave exposure is recommended for enhancing water and surfactant flooding process as it can increase oil recovery up to 11 and 12% respectively.
2. Ultrasonic wave stimulation affected the viscosity by two different ways; (a) temperature change as the sound energy changes to thermal in the porous media. (b) intermolecular effect of the sound energy on the molecules resulting in Brownian motion.
3. The formation of microemulsion (micelles) during surfactant flooding in the presence of ultrasonic wave was the most significant mechanism responsible for the increased oil recovery.
4. Ultrasonic wave is more efficient for surfactant flooding at concentration above CMC and at high intensity.

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