Jurnal Teknologi, 56 (Sains & Kej.) Keluaran Khas (1), Dis. 2011: 123–138

IMPROVED OIL RECOVERY BY APPLICATION OF ULTRASONIC STIMULATED WATERFLOODING

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Abstract. Application of ultrasonic waves as an unconventional enhanced oil recovery method has been a point of interest for some decades. However, despite number of researches on ultrasonic applications, the influencing mechanisms are not fully comprehended. The aim of this study is to experimentally investigate the effects of ultrasonic waves on recovery of waterflooding and to discuss the mechanisms involved. Series of straight (normal) and ultrasonic stimulated waterflooding experiments were conducted on a long unconsolidated sand pack using ultrasonic transducers. Kerosene, vaseline and engine oil were used as non wet phase in the system. Moreover, a series of supplementary experiments were conducted using ultrasonic bath in order to enhance the understanding about contributing mechanisms. 2-16% increase in the recovery of waterflooding was observed. Emulsification, viscosity reduction and cavitation were identified as contributing mechanisms.

Keywords: Ultrasonic waves; enhanced oil recovery; waterflooding; emulsification

1.0 INTRODUCTION

The interest in using seismic waves as an improved oil recovery (IOR) method starts in the early 50's when noises from the railroad trains and earthquakes resulted in increasing oil recovery. Due to limited distance ultrasonic waves can travel in the reservoir, most of the field applications were limited to damage removal in near wellbore area. Application of ultrasonic waves on different processes such as gravity drainage, imbibitions and waterflooding has been investigated by several authors. Despite number of publications, patent and some field trials on the subject, the exact mechanisms of are not fully comprehended.

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In the early work, Albert and Bodine (1948) invented a system for increasing the recovery by application of sonic waves. Duhon and Campbell (1965) conducted a comprehensive research on long and short cores to find out about the possible utilization of ultrasonic waves in waterflooding. They observed a considerable effect on displacement efficiency resulted from creating a more uniform displacement front as a result of sonication. Simkin *et al.* (1991) observed the major growth of oil droplets immediately after the beginning of excitation in a laboratory experiment. They attributed the growth to sonically induced coalescence. Poesio *et al.* (2002) investigated the influence of acoustic waves on liquid flow through Berea sandstone and found out that pressure gradient inside the cores decreases under acoustic energy the effect was attributed to the reduction of fluid viscosity. Amro *et al.* (2007) attributed the increase in the recovery of ultrasonic stimulated waterflooding to the changes of relative permeability of both phases. Guo (2009) discussed field application of ultrasonic waves in China. He also conducted experiments to show the effects of ultrasonic waves on viscosity and realized that the viscosity is temporarily reduced due to exposure to ultrasound waves. Najafi (2010) analytically and experimentally investigated the effect of ultrasound on gravity drainage and percolation of oil by using fluids of different viscosity. 20°C rises in the temperature were observed during his experiments in 1000 minutes time.

A theory about the generation of ultrasonic waves was developed by Nikolaevskiy and Stepanova (2005). He postulated that as a result of nonlinear effects associated with seismic and low frequency acoustic waves in porous media saturated with fluid, under conditions of long-short-wave resonance, the nonlinear generation of high ultrasonic frequencies by seismic waves is possible. Based on this theory, ultrasonic energy (high frequency waves) could be the main reason of enhancement of oil recovery after artificial or natural seismic activities. Therefore, understanding the effects of high frequency waves on recovery of oil is of a great importance. One way to do so is direct application of high frequency waves to sandpack model and studying the results. This research concentrates on the involving mechanisms which lead to increase in the recovery of waterflooding stimulated by ultrasonic waves. Therefore dynamic experiments were conducted to see the effects of ultrasonic waves on the recovery of oil and supplementary tests were carried out to investigate the mechanisms of ultrasonic waves in more detail.

2.0 EXPERIMENTAL SETUP AND PROCEDURES

2.1 Equipment

Two types of ultrasonic generators were used for the experiments. For dynamic experiments, ultrasonic transducers were specially installed surrounding the test section. Crest ultrasonic generator with frequency of 40 kHz and power output of 100-500 W was used. Figure 1 shows a schematic of the displacement experiments. A centrifugal pump was used for the injection of the fluids; the rate of the injection was fixed on 3 ml/min in all flooding tests. Meanwhile for batch experiments, Branson ultrasonic cleaner with the frequency of 40 kHz and the power output of 110 W was used.

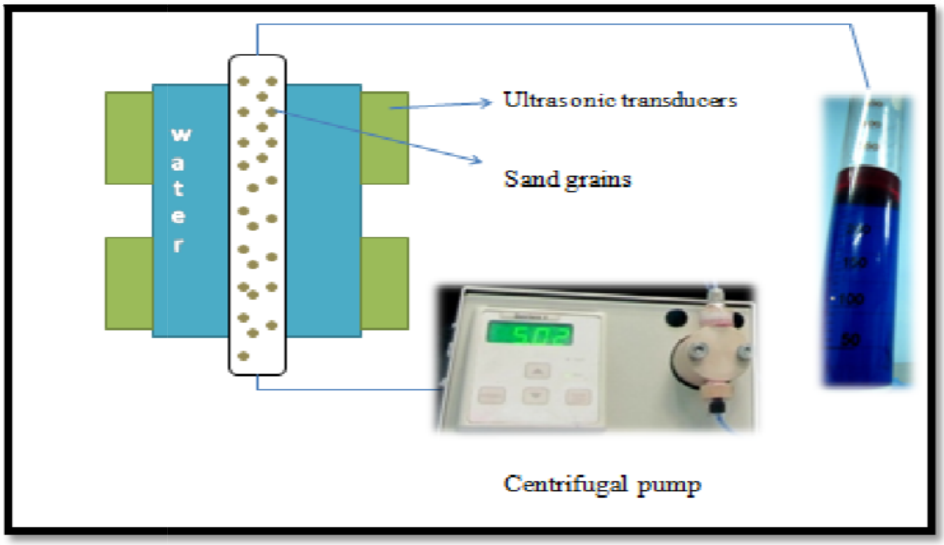

Figure 1 Flooding (displacement) experimental setup

2.2 Fluids

Two types of brine were used for the experiments, normal and de-aerated 3% NaCl brine (with the density of 1.05 g/cm^3). Kerosene, vaseline and engine oil were used as non wet phase in the experiments. Table 1 summarizes the properties of the fluids used. The viscosity of the fluids was measured using Cannon-Fenske Routine Viscometer-100 at 25 and 40˚C.

Table 1 Testing fluid properties

Name of fluid	Viscosity @ 40˚C (cp)	Viscosity @ 25˚C (cp)	Density @ 27˚C (g/cm^3)	°API	IFT with brine @ 27˚C ($dyne/cm^2$)	IFT with deaerated brine @ 27˚C ($dyne/cm^2$)
Kerosense	0.9	0.99	0.770	52	31	33
Vaseline	12	22.0	0.856	33	38	35
Engine oil	65	240	0.923	21	18	20
Normal brine	0.65	0.92	1.03	10	-	-
De-aerated brine	0.65	0.93	1.04	10	-	-

2.3 Porous Media

The quartz grains of 225-300 μm size fractions were packed in a stainless steel sample holder of 92 cm× 3.8 cm to represents the porous media. The porosity and permeability of the sand pack were 32±2% and 4 Darcy, respectively.

2.4 Displacement Test

Oil saturated sandpack was waterflooded until the residual oil saturation was obtained. Ultrasonic radiation (40 KHz and 250 Watts) began at this point simultaneous with water flooding. The same volumes of water (as in waterflooding) were injected and the recovery was calculated for each case. The graphs of recovery versus time were plotted for straight and ultrasonic stimulated waterflooding.

2.5 Supplementary Experiments

Two types of supplementary experiments were conducted, namely: one phase flow experiment and temperature experiments. One phase flow experiments conducted using the same setup of displacement tests. In this experiment the core was saturated with brine (normal and de-aerated) and exposed to ultrasonic waves and the pressure changes for the system were recorded.

Temperature experiments were conducted using both ultrasonic transducers and ultrasonic bath. Using ultrasonic transducer, the saturated sample (with oil and brine) was exposed to ultrasonic waves of different power outputs and temperature rises for the system were measured via a thermometer installed in the sand pack. Temperature experiment was also conducted in an ultrasonic bath as well. The sand was packed and saturated with kerosene, vaseline and engine oil. The temperature rises of the system were recorded regularly.

3.0 RESULTS AND DISCUSSION

3.1 Temperature Experiments

Temperature rises during stimulation with ultrasonic were reported by some authors. However the methods they used were sometimes too simplistic to show the real changes of temperature in the system, therefore the magnitude of the effect is not sufficiently discussed. The temperature rises of the system (normal brine-saturated sand pack) were 4°C, 12°C and 16°C for the respective power outputs of 100, 250 and 400 Watts (Figure 2). In the second part of the experiment temperature rises for vaseline, kerosene and engine oil was measured in the ultrasonic bath. Due to the same conductivity coefficient in three of the cases the temperature rise was almost the same as expected. Figure 3 illustrates the temperature rise for different fluids.

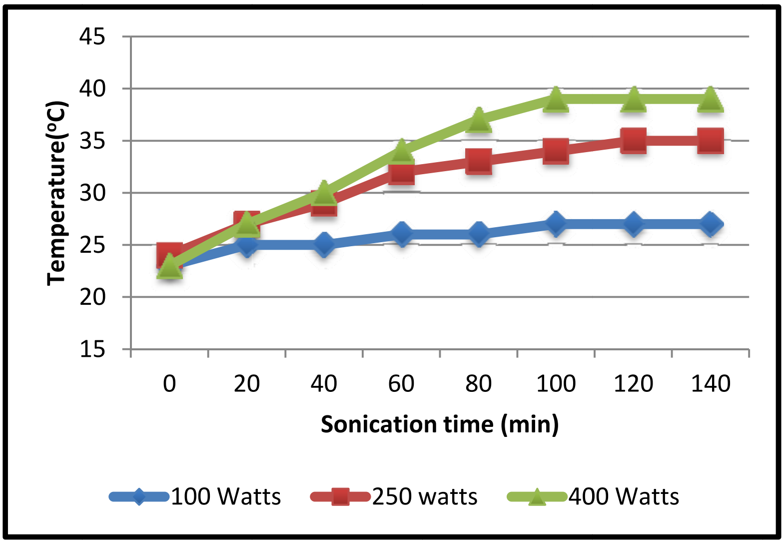

Figure 2 Temperature versus time at different intensities

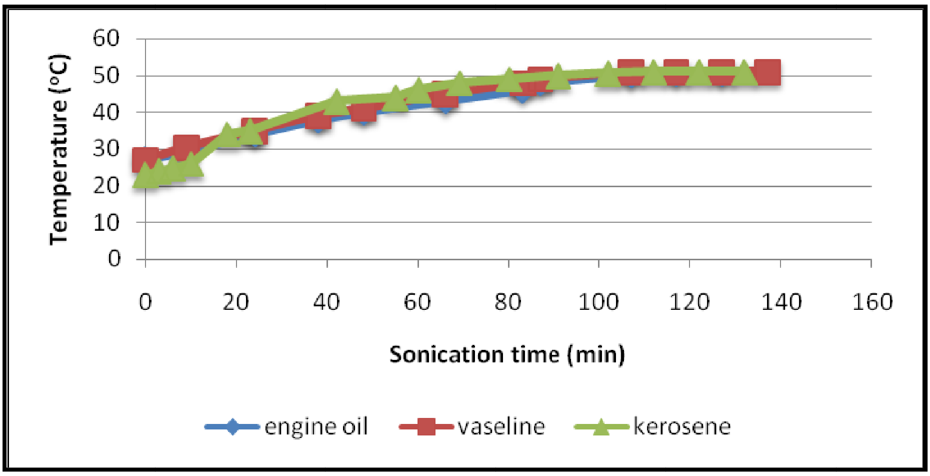

Figure 3 Temperature rises for different fluids

The temperature rise can affect fluid properties i.e. viscosity and interfacial tension. Interfacial tension between oil and brine is a function of temperature. Table 2 shows IFT reduction of different fluids versus time calculated by Firoozabadi's equation. Although the IFT decreased in all the cases, the reduction is not high enough to have significant effects on the capillary number; therefore it is not able to contribute in reduction of residual oil saturation. It should be noted that above mentioned discussion is only related to IFT reduction as a consequence of temperature rises and the direct effect of ultrasonic waves on reduction of IFT is excluded in this section. Hence it can be concluded that, if the waves have any effects on reduction of IFT, it cannot be related to temperature rises of the system.

Temperature rises as much as 24°C will largely affect viscosity of fluids. Viscosity of water and oil will be reduced as a result of temperature rise. Since the viscosity of fluid at different temperatures was needed it was calculated via proper formulas i.e. Meehan and Glaso's relations. The measured values of viscosity (using Cannon-Fenske viscometer as shown in Table 1) have 5% variance from calculated values using Glaso's formula. Figures 4, 5, and 6 illustrate viscosity reduction for each case together with a third degree polynomial trend line drawn for each fluid to facilitate the comparison between slopes of the graphs.

Table 2 IFT reduction for different fluids versus time

T(°C)	Kerosene (dyne/cm^2)	Vaseline (dyne/cm^2)	Engine Oil (dyne/cm^2)
23	31.0	38.0	18.0
27	30.5	37.4	17.7
31	30.0	36.8	17.4
35	29.5	36.2	17.1
39	29.0	35.6	16.8
43	28.6	35.0	16.6
47	28.1	34.5	16.3
51	27.7	33.9	16.1
55	27.3	33.4	15.8

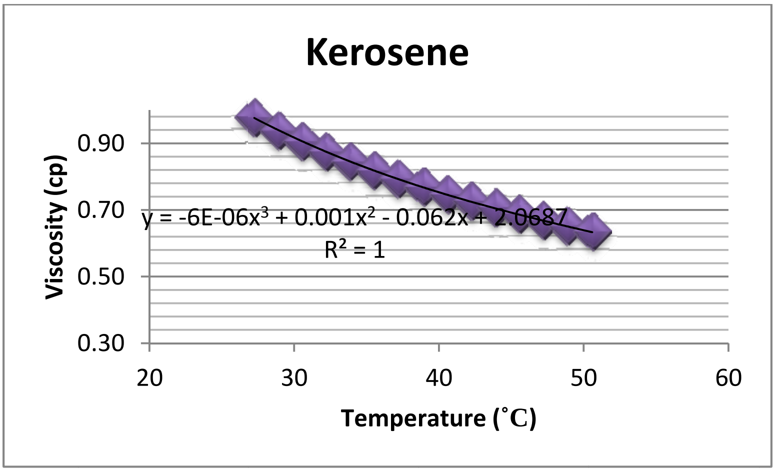

Figure 4 Reduction in viscosity of kerosene

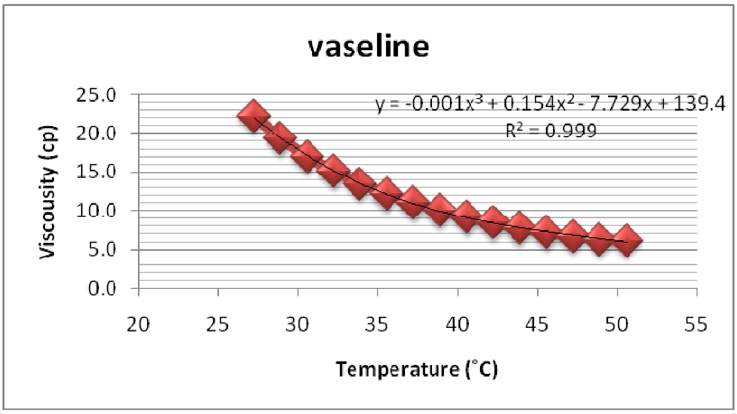

Figure 5 Reduction in viscosity of vaseline

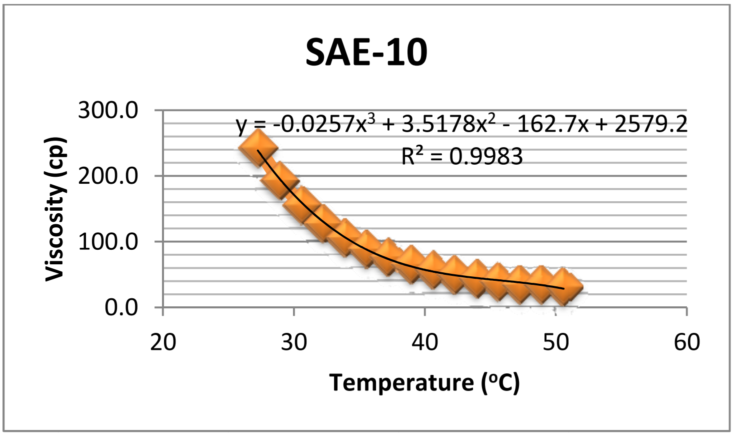

Figure 6 Reduction in viscosity of engine oil (SAE-10)

3.2 One Phase Flow Experiments

In these series of experiments nearly in all the cases, pressure reaches a peak initially then decreased to lower values according to the intensity of waves (Figure 7). The increase in the pressure may be attributed to the cavitation phenomena; however more comprehensive experiments are needed to show this effect precisely. The decrease in the pressure drop could be attributed to increase in absolute permeability only if the viscosity of water remains the same. This is however only possible if the temperature increase within the system could be considered negligible. In none of the experiments during the sonication, temperature remains constant. Since all the dynamic experiments were conducted on unconsolidated sand pack and only certain size of sand grains were used without any cementing materials, it can be assumed that the changes in absolute permeability did not occurred.

The reduction in pressure is caused by the reduction in viscosity of water. As an example, during sonication using 2.4 Watts/cm^2 pressure increased to 2.3 psi from initial value of 2.1 psi; at the end of the experiment pressure was constant at 1.8 psi which is 0.1 psi less than its initial value. It could be attributed to the reduction in the viscosity of water.

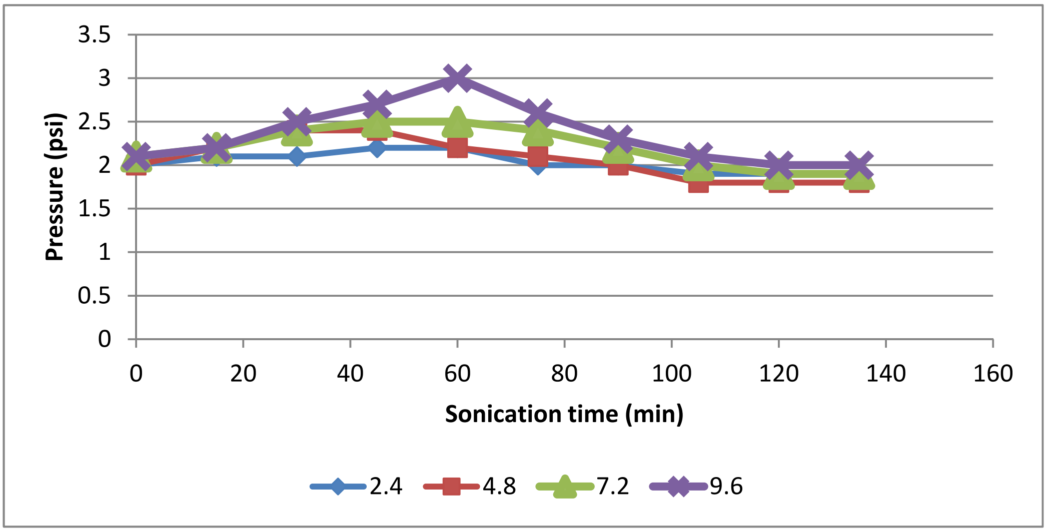

Figure 7 Pressure gradient versus time for various intensities (watts/cm²) of waves for one phase flow using normal brine

Rearranging Darcy formula, as in Eq. 1 below;

$$\Delta P = \frac{Q\mu L}{KA} \tag{1}$$

Terms Q, L, A, K and φ are considered constant. As there is only one phase flowing in the system, the term μ stands for viscosity of water. The increase in temperature leads to viscosity reduction; since ΔP is proportional to μ_w, any reduction in the viscosity decreases the pressure drops by the same magnitude. Due to existence of cavitation as a result of using aerated water, quantification of the effect becomes difficult. But as in all of the one phase flow experiment the pressure reaches to a value lower than its initial value, it could be concluded that the reduction of pressure is due to reduction in viscosity of water (Mohammadian, 2010).

The second series of one phase flow experiments were conducted using de-aerated brine to remove effects of cavitation. The same procedure was performed and the pressure responses were recorded. Once the ultrasonic radiation started, the pressure started to decline and finally stabilized to a value at the end of each experiment. Figure 8 shows pressure response versus time for various power outputs. Considering the results from temperature effect experiment and one phase flow experiment, it is concluded that, reduction in viscosity of water could be the main reason behind pressure drop observed in one phase flow experiment. This result is in agreement with that of Poesio *et al.* (2002); they concluded that the reduction in pressure is due to decrease in the viscosity of fluids. However they did not conduct any other experiment to confirm their theory.

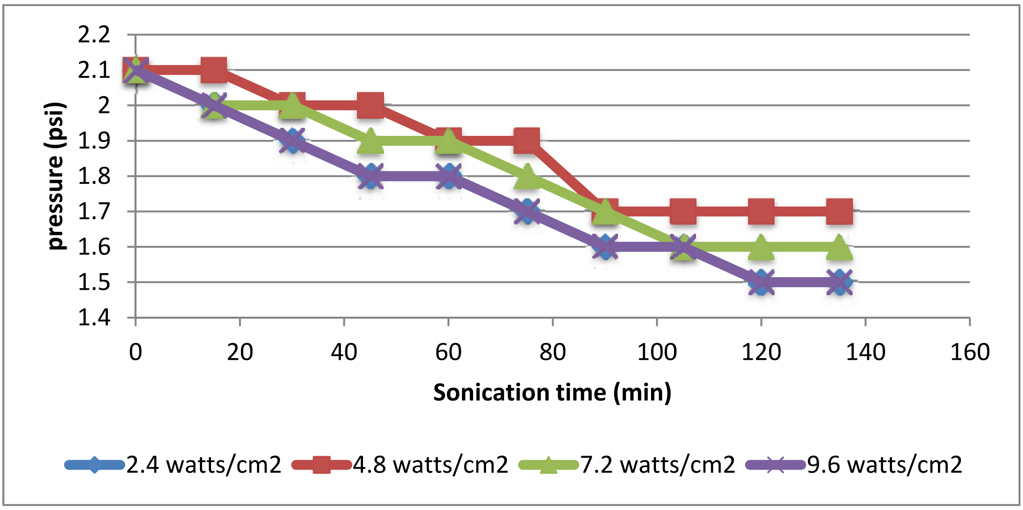

Figure 8 Pressure gradient versus time for various intensities (watts/cm^2) of waves for one phase flow using normal de-aerated brine

3.3 Displacement Tests

3.3.1 Effects of Ultrasonic Radiation on Oil Recovery

Recovery for waterflooding was 67%; sonication improved the recovery by 16%. Kerosene is a low viscosity high °API (0.98 cp and 52 °API) fluid, therefore the recovery of both sonication and waterflooding is high due to low mobility ratio and consequently, high sweep efficiency. Assuming relative permeability of non-wet and wetting phase at their end points, at ambient temperature (27 °C) the mobility ratio for kerosene and water may be calculated as (Eq. 2):

$$M = \frac{krw}{kro} \times \frac{\mu o}{\mu w} . = . \frac{0.3}{0.7} \times \frac{0.98}{0.95} = 0.44 \qquad (2)$$

The above mentioned mobility ratio is only valid for the ultrasonic stimulated waterflooding if viscosity remains the same throughout the experiment. In this study, the point of interest is the viscosity ratio of fluids and not the relative permeability of fluids. During ultrasonic stimulation, temperature rises was observed for the system. 10°C increase in the temperature reduces viscosity of water to 0.79 cp (17% decrease) and viscosity of kerosene to 0.79 (20% decrease). Therefore the viscosity ratio of the system becomes 1.

The viscosity ratio decreases to 1 from an initial value of 1.2. Having IFT of 32 for brine and kerosene, the capillary number for the water is 1.58×10^{-7}. Having capillary numbers in the order of 10^{-7} showing that no more trapped oil could be produced by water flooding alone; capillary number in the orders of 10^{-5} to10^{-4} are needed to decrease residual oil saturations. Formation of emulsion was observed in the case of kerosene. After three hours the two phases were completely separated and the interface between the two phases could be easily seen. These results are in agreement with those of Amro *et al.* (2007). Figure 9 shows total recovery of kerosine as a result of straight and ultrasonic stimulated waterflooding.

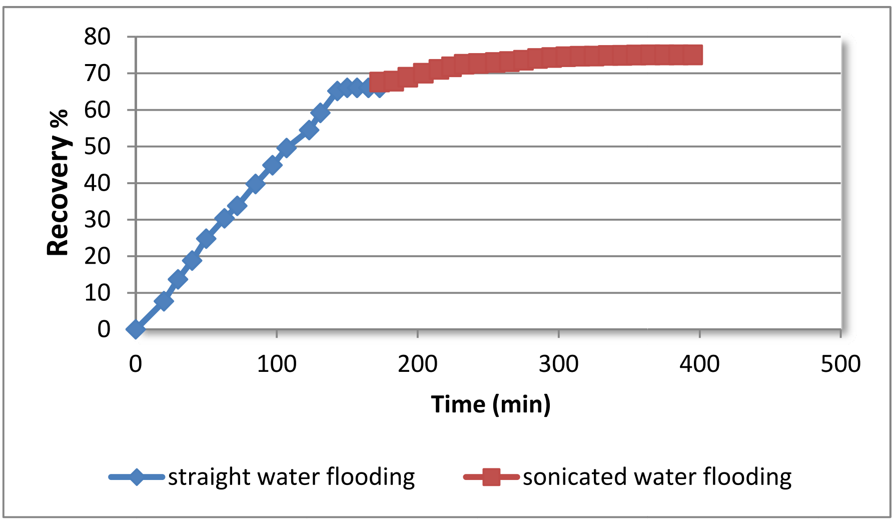

Figure 9 Recovery of kerosene as result of straight and sonicated waterflooding

In the case of vaseline, the viscosity ratio at 27 °C is 23.9. The recovery for normal water flooding is 56% ultrasonic stimulated waterflooding added 11% to the recovery. Figure 10 shows total recovery of vaseline. Viscosity reduction is known as one of the significant mechanisms in case of vaseline as viscosity ratio reduces to 13.9 from initial value of 23.9 as result of 10 °C temperature rise. Therefore, it can be concluded that ultrasonic stimulation increases the recovery by reducing mobility ratio and improving sweep efficiency. In the case of vaseline also, formation of emulsion was observed. Assuming the IFT value of 38 dyne/cm^2 for vaseline and brine, the capillary number for waterflooding is in orders of 10^{-7}. It can be concluded that increase in the oil recovery cannot be attributed to reduction of IFT from temperature rise.

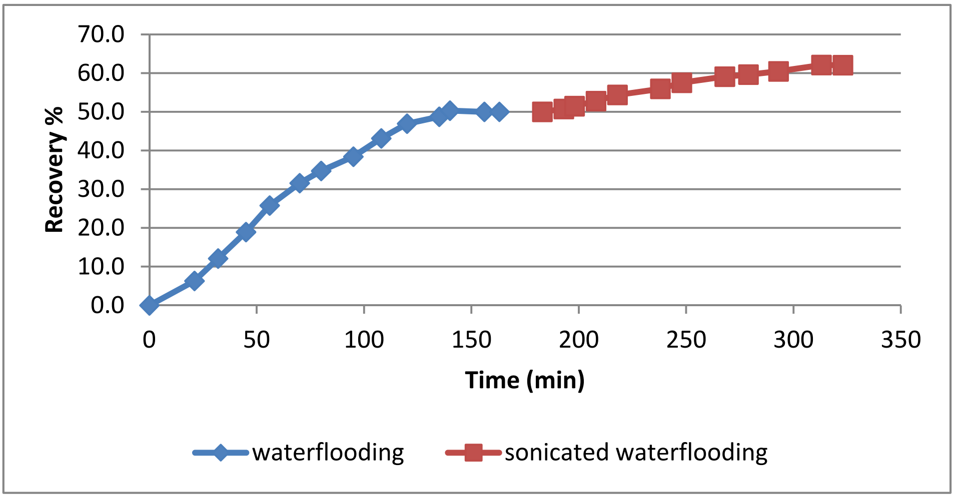

Figure 10 Recovery of vaseline as result of straight and sonicated waterflooding

Engine oil was chosen due to its high viscosity (243 cp at 23°C). The amount of oil produced by waterflooding was 38%. The sonication added 2% to the recovery (Figure 11). 10 °C increase in the temperature (around 23 °C increase in the temperature was observed by temperature experiment), is changing viscosity of fluids to a large extent. Viscosity ratio reduces to 97.1 from initial value of 255.0. Therefore one of the effective mechanisms in improving the recovery is viscosity reduction. One may expect higher recoveries considering huge reduction in viscosity ratio. But an unexpected result was deposition of paraffin as results of sonication. It was observed during emulsification experiment which was part author's previous work (Mohammadian, 2010). In this case also the IFT reduction from temperature increase is not large enough to reduce capillary number effectively and reduce the residual oil saturation.

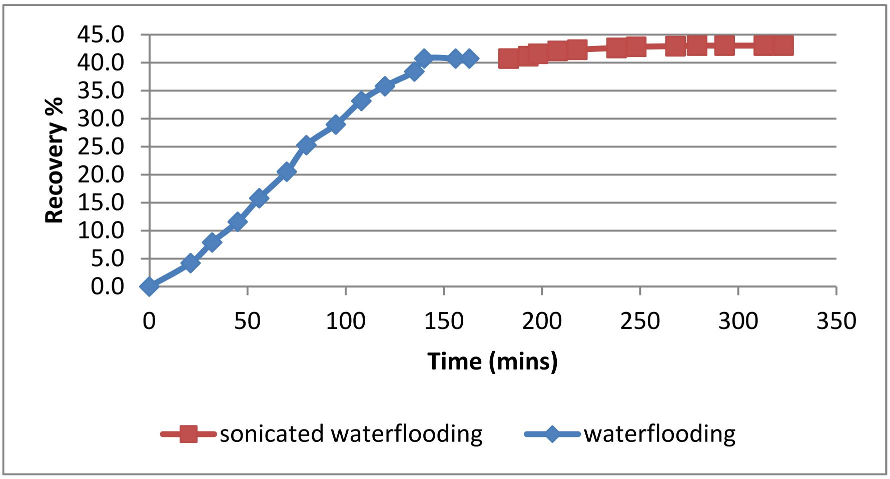

Figure 11 Recovery of engine oil by straight and sonicated waterflooding

4.0 CONCLUSIONS

A series of displacement and supplementary experiments were conducted in this study and following conclusions were made:

(1) The recovery of waterflooding increases as a result of sonication for all the cases (from 2-16%). The recovery of ultrasonic assisted waterflooding was higher for less viscous fluid being kerosene. Where normal brine was used the recovery was higher in comparison with the cases where de-aerated brine was used. This could be explained through the existence of cavitation in the system when using normal brine instead of de-aerated brine.

(2) Severe temperature rises was observed in the experiments. This leads to reduction in viscosity of fluids as well as reduction in the interfacial tension. The reduction in viscosity of fluid is detected as one of the contributing mechanisms of

production. On the other hand, the temperature rises is not high enough to reduce the IFT to a large extent, in other word IFT reduction from temperature rises is so small that cannot contribute in improving the recovery.

(3) The one phase flow experiments were conducted using normal and de-aerated brine. The initial increase in the pressure in one phase flow experiments (using normal brine) can be attributed to cavitation. Conducting one phase flow experiments with de-aerated brine proved that the reduction in pressure is cause by reduction in viscosity of water as a result of ultrasonic stimulation.

(4) Formation of emulsion was observed during displacement experiments for vaseline and kerosene. The generated emulsion was unstable and the phases were completely separated after 3 hours. It could be concluded that viscosity reduction and emulsification are contributing mechanisms in the application of ultrasonic waves to waterflooding.

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