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Macro-Model and Micro-Model Observation on The Effect of Intermittent Ultrasonic Waves on Surfactant-Polymer Enhanced Oil Recovery

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ABSTRACT

In the early 50's, vibration has been noticed to have effects on improvement of oil recovery. Since then, vibration has been studied in this field. Application of high frequency sound waves to enhance the oil recovery has been point of interest for some decades. Many theoretical and experimental works have been done to describe use of continuous ultrasonic stimulation as a potential method for enhancement of oil recovery. The main focus of this research is to initiate the use of intermittent ultrasonic radiation in assisting Surfactant-Polymer (SP) flooding process under and also the influence of ultrasonic energy to enhance oil recovery through the reduction of residual oil saturation. Uses of intermittent energy can save the cost in term of energy generation, etc. instead of using continuous vibration. This work has been designed to understand the mechanics of intermittent ultrasonic vibration in influencing additional recovery of SP flooding. To achieve this, series of experimental programs consisting of visualization and displacement experiments were conducted by using micro-model and macro-model respectively. In each series of experiments, various parameters (ultrasonic frequency and oil viscosity) were changed to monitor their influence on the process. Snapshots of oil displacement of glass micro-model were taken for a fixed period of times for visualization purposes. While, reduction of residual oil saturation for displacement process by using macro-model porous media were recorded. The outcomes justified that intermittent vibrations can produce and enhance more additional oil recovery of SP flooding compared to the continuous vibration.

INTRODUCTION

Surfactant-Polymer (SP) Flooding:

In average, the oil recovery factor after primary and secondary operations is between 30%-50% of the original oil in place. Needed for Enhanced Oil Recovery (EOR) application is high as large percent of residual oil saturation still left in the reservoir that need to be recovered. Chemical Enhanced Oil Recovery (CEOR) is identified by the specific chemical that is injected. The most commonly used are polymers, surfactants, and alkalis, but chemicals are often combined. For example, surfactants act to reduce the IFT between oil and water and hence improve displacement efficiency. Alkali is used to create in-situ surfactant and also increases pH value. Polymer slugs usually follow surfactant or alkaline slugs to control the mobility of injected fluid and improve sweep efficiency, but not displacement efficiency (Zhou *et al*., 2003). Alkali-Surfactant-Polymer (ASP) can be treated as other solution to solve this efficiency cases, but it also can lead to scale. With the exception of alkaline, SP is one of the best solutions to solve both sweep efficiency and number of limitations.

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Sound Waves:

Sound waves are thus a series of compressions and expansions in the medium surrounding them. Basically, the principles of ultrasound are means acoustic signals in the frequency range from 10 kHz up to approximately 30 MHz.

When such sound waves propagate in a material, it forces particles to oscillate. They oscillate around their equilibrium positions with a frequency equal to that the ultrasonic wave.

Cavitations:

When the sound waves travel through a fluid medium, changing in hydrostatic pressure might happen. Pressure will be negative on stretching if those waves do have sufficient power, thus foams will be formed. This phenomenon is known as cavities.

The first theory had been concluded based on the surveyed to propeller that have low efficiency showed the big movement will produce pressure on the propeller surface, which can cause water separation and then produced small waves. The movement of sound waves in fluid medium was formed by stress and strain process that alternately happened.

Ultrasonic Vibration in Porous Media:

Investigation on the effect of uses of continuous vibration wave been initiated after the earthquake incident in 1950's which generated elastic wave that increased the water and oil production. After this scenario, quite a number of field application and laboratory observation had been carried out to investigate the effect of vibration on oil recovery and to observe principally on those effects and it does bring positive outcomes.

Duhon and Campbell (1965) initiated the investigation by carrying out an experiment on waterflood tests through cores under ultrasonic energy with three different frequencies set (1, 3.1, and 5.5MHz). Results from these experiments showed that the ultrasonic energy improved the recovery of oil and displacement efficiency in cores. Besides, ultrasonic excitation also resulted in the decreasing permeability of water to the ratio of oil. The permeability reduced greatly in the presence of ultrasound effect.

General principles of ultrasonic/vibration application is wave travels through the porous media, and excites the fluids mechanically by delivering compressional waves into reservoirs. The vibration force introduced in the reservoir is thought to facilitate the movement of oil in one or more ways: by diminishing capillary forces, reducing adhesion between the rock and fluids and causing oil droplets to cluster into streams that flow with the waterflood. The vibration may lead to deformation of pore walls and also help removing fines, clays and asphaltenes from pores which will increase the permeability and porosity of rock. While, in the presence of surfactant, ultrasonic energy helps the emulsification of oil.

Fairbanks and Chen (1971) observed there was an increase in percolation rate under the influence of ultrasonic vibration. Nevertheless, it was not yet clear whether the improvement was due to the heat transfer or due to the vibrations of ultrasound. Gadiev (1977) observed a considerable increase in oil production rate and cumulative oil production of unconsolidated sand packs under ultrasonic effect. "Sono-capillary effect" has been proposed as the phenomenon contributed to this increase in oil production. During cavitation, it is believes that the bubbles collapsed and the liquid level within a capillary is raised up.

Snarskiy (1982) reported a 19% incremental of oil displacement for fine-grained quarts sand exposed to 9 – 40 Hz sound field, and observed the effect was frequency dependent. Ganiev at el. (1989) advocated that ultrasound would deform the pore walls and change the radius of the pore and leads to peristaltic transport. This maybe the reason supported the changed of permeability observed by Cherskiy *et al* (1977). Dyblenko *et al*. (1989) observed the enhancement of kerosene displacement by water in a reservoir core sample by applying sound at a frequency of 200 Hz. The mobility of residual oil increased and the permeability to water decreased during the excitation. Besides, Nikolaevskii (1989, 1992) developed a mathematical model in order to clarify the dominant vibration frequency. Based on the analysis conducted, elastic wave field may reduce the capillary forces by vibrating and then break the surface films.

However, the theory expects ultrasonic waves to be present in the reservoir because dispersion of low frequency waves within porous media forms high frequency harmonics (ultrasonic noise). Short wavelength of ultrasonic leads to a strong directional propagating ability. When propagating through liquid and solid, a small quantity of ultrasonic energy is absorbed and spoiled, therefore it has a strong penetrating capacity. The propagating characteristics of ultrasonic in medium, such as velocity, spoilage and absorption, are related to the media elastic modulus, density, temperature, component content, porosity and viscosity.

In addition, Nikolaevskii et. al (1996) did explained that wave generation and propagation in porous media are very much dependent on reservoir lithology, stratification and fluid saturation. Spanos *et al*. (2003) studied the use of pressure pulsing for IOR and the pulses are generated by using hydraulically operated tool. It is concluded that IOR process can be enhanced by applying pressure pulsing. Pulse removed the barriers which blocked the fluid flow and viscous fingering was reduced are the following mechanism involved.

Limited work had been done in micro scale to investigate ultrasonic in terms of displacement mechanism. Li *et al*. (2005) performed the study on pore scale on the mobilization of oil ganglia in a 2D glass micro-model under low frequency vibration. Increased in recovery were observed with higher amplitude and lower frequency. Beresnev *et al*. (2005) showed vibration can solve the entrapped residual oil problem because of existing capillary forces. They concluded that residual saturation of ganglia is proportional to the amplitude and inversely proportional to the frequency.

Later Hamida and Babadagli (2005a, 2007b, 2007c) showed rheological properties of polymer maybe changed and the surfactant solubility maybe increased under ultrasonic energy. They also performed Hele-Shaw experiments. Ultrasonic improve the molecules diffusion at low injection rates during miscible displacement. Besides, cavitation, viscosity reduction and emulsification are suggested to be the mechanism involved when ultrasonic waves were applied to water-flooding. He also showed that, temperature rises are not significant enough to reduce the IFT to a large extent.

Based on the previous researches been made, theoretically, ultrasonic vibration wave mechanism mechanically effect to reduce interfacial tension, meanwhile surfactant and polymer flooding effect chemically to reduce interfacial tension and viscosity. With combination of both methods, both mechanisms: mechanically and chemically could work mutually to enhance oil recovery.

Experimental Setup And Procedure:

Equipment:

In order to investigate the enhanced oil recovery under intermittent ultrasound, an experimental setup included a syringe pump model NE-1000, *Crest* ultrasonic generator with immersible transducer, ultrasonic water bath, and porous media holder were needed. Injection rate was fixed constant at 0.5 ml/min and 1.0ml/h for macro-model and micro-model respectively. Two frequencies (25 kHz and 40 kHz) and a constant intensity (150W) were used in this study. De-aerated water is a medium that will carry fluid and allow wave to transmit to the micro-model. Figure 3 displays the schematic diagram of the displacement experiments.

Fluid Properties:

They were oil, brine and optimum SP solution been used throughout the experiments. Synthetic brine with 2 wt% of NaCl brine was used as displacement fluid. Two types of oil which are kerosene and paraffin were used as non-wetting phase fluid system. Paraffin and kerosene was used to represent heavy and light oil, respectively. An SP formulation been used throughout all experiments with 0.15 wt% AOS + 400 ppm HPAM + 20,000 ppm NaCl. Table 1 summarizes the properties of used studied fluids.

Porous Media:

There were two types of porous medium were used in this study. They were artificial unconsolidated heterogeneous core with packed glass beads inside the Perspex holder (macro-model) for displacement experiments, and two-dimensional glass-etched (micro-model) for visualization tests.

Diameter, length and wall thickness of the macro-model was 34 mm, 42.5 cm and 6 mm respectively. Four different ranges of glass bead sizes were used which are 90µm – 150µm, 150µm - 250µm, 250µm - 425µm, and 425µm - 600µm, following ratio of 2:1:1:1. The glass beads were scattered to represent heterogeneity. Formation inside the artificial core is 30% Φ and 1 Darcy at its best using this method due to belief that this artificial core is unconsolidated. The general schematic diagram of macro-model is shown in Figure 1 (a).

Glass micro-model was first designed by using computer program, and glass been etched according to that design. It consisted of two sheets of glass (one side pattern etched, and the other side is plain glass). These two sheets of glasses were stacked over together and prepared to be put in high temperature furnace for several hours to undergo melting and stacking process. The general schematic of the 2D glass micro-model was designed to study on the interface of oil and water under ultrasound is shown in Figure 1 (b). The specification of the micro-model is given in Table 2.

Displacement Test and Visualization Experiment:

Displacement test were carried out by using macro-model to compare the recovery of SP flooding with and without the assistance of intermittent waves. Besides, these tests were carried out to study the influence of ultrasonic energy in enhancing additional oil recovery of SP flooding. The effect of oil viscosity, ultrasonic frequency (25 kHz and 40 kHz), and ultrasonic wave pattern (intermittent and continuous) on the recovery of SP flooding through the reduction of S_{OR} were investigated. The intensity of ultrasonic wave and injection rate was set constant at 150W and 0.5ml/min for all displacement tests by using macro-model.

While, the glass micro-model was used for visualization experiment. Snapshots were taken at a period of times during the displacement process took place. The injection rate used for displacement of micro-model was 1.0 ml/h. Ultrasonic vibration was applied to the porous media once the SP flooding process started. Intermittent radiation been applied by manually switch on and off the ultrasonic generator (20 minutes cycle). For the continuous radiation, the ultrasonic generator was continuing to on. The experimental runs in this study are presented in Table 3. Figure 2 and Figure 3 illustrate the setup of SP flooding without and with aid of ultrasonic vibration, respectively.

RESULTS AND DISCUSSION

SP Flooding Process assisted by Ultrasonic Vibration:

Figure 4 shows the residual oil saturation (S_{OR}) of SP flooding with and without assisting of ultrasonic wave. Pattern of wave used was continuous vibration with 25 kHz frequency and 150W intensity. Based on Figure 4, the S_{OR} of SP flooding under ultrasonic wave is lower compared to SP flooding without ultrasonic wave. The S_{OR} decreased for about 6% when ultrasonic wave been applied. While, the % of oil recovered for non-ultrasonic (NUS) and continuous ultrasonic (CUS) was 48.8% and 56.6% respectively. Results from the displacement tests showed that significant improvement on oil recovery of SP flooding and reduction of residual oil saturation had been achieved with the application of ultrasonic.

Intermittent (IUS) and Continuous (CUS) Ultrasonic Vibration:

Figure 5 shows the results comparison of residual oil left in the porous medium after exposing to intermittent and continuous ultrasonic waves. Frequency of wave used was 25 kHz with 150W of intensity. SP flooding assisted by intermittent radiation has lesser residual oil left in the porous media than the continuous radiation. SP flooding assisted by IUS left 39.6% of oil inside the porous media compared to CUS which is 41.7%.

Effect of Viscosity on SP Flooding Recovery:

Figure 6 shows the displacement experiments results on the effect of viscosity. It showed that, heavy oil which underwent 25 kHz and 150W intermittent vibration resulted in a significant reduction of S_{OR} to 43.5% compared to continuous vibration which is 53.9%. On the other hands, there are only a slight different in S_{OR} of kerosene in porous media between assisted by IUS and CUS which are 39.6% and 41.7% respectively.

Overall, heavy oil with intermittent vibration shows conducive in producing more oil which is about 70%. Intermittent vibration work compatible with high viscosity than low viscosity. Heavy oil contains different high molecules and it starts to break up after ultrasonic vibration is applied. Due to its relative movements of the molecules and difference in their acceleration leads to reduction in the oil viscosity and producing more oil. When oil viscosity is reduced, mobility ratio will be decreased. These experiments concluded that intermittent vibration work well in high viscosity than low viscosity.

Effect of Ultrasonic Frequency on SP Flooding Recovery:

Figure 7 (a) and Figure 7 (b) shows the effect of ultrasonic frequency (25 kHz and 40 kHz) on the S_{OR} of light oil and heavy oil, respectively. For CUS vibration, there were very small decreases recorded in S_{OR} when increasing the frequency from 25 kHz to 40 kHz, both for light IUS ultrasonic wave for both light and heavy oil application. The S_{OR} reduced 5.5% from 43.5% to 38.0%, for heavy oil application under IUS wave when increasing the frequency (25 kHz to 40 kHz). While, S_{OR} reduced from 39.6% (25 kHz) to 38.0% (40 kHz), for light oil application under IUS wave. Results showed that oil recovery and reduction of S_{OR} in porous media is greatly affected by frequency dependent.

Mechanism involved here is the coalescence of 2 or more oil droplets into the larger droplets having higher mobility then become part of the flow stream due to the Bjerknes forces (attractive forces acting between the vibrating droplets). Interfacial tension had been reduced and will affect the capillary number. Capillary number will be increased and residual will be decreased. This mean more oil can be extracted from the pore.

Shorter distance will lead to less attenuation. Vibration and energy which travel for long distance will lose their energy through the medium. Energy loss not only happens in distance but also energy loss in molecules (in water) which continue to vibrate. These can be proved in the experiments that intermittent vibration show better improvement than continuous vibration.

Visualization Experiments:

For the visualization experiments, snapshots were taken during the process of SP flooding. Figure 8 (a) and Figure 8 (b) show the comparison of micro-model displacement experiment between IUS and CUS for heavy and light oil, respectively. Red color represents oil while white color represents water. On the application of IUS, there was lesser oil was observed at the end of the process compared to CUS for heavy oil application. By changing paraffin to kerosene, snapshot observation in Figure 9 (a) and Figure 9 (b) showed that, again intermittent vibration can increase the oil recovery. Less residual oil remains in the micro-model than the continuous. It was observed the enhancement of kerosene displacement by SP flooding in micro-model sample at frequency of 40 kHz as the displacement efficiency is dependent on the ultrasonic frequency. It shows that oil less trap in the micro-model compared to the continuous vibration. Results from these experiments showed that intermittent ultrasonic energy improved the recovery of oil and increased rate of oil displacement. In addition, ultrasonic radiation enhanced the movement of oil in porous media and hence, reduced the residual oil saturation, S_{OR}.

Results showed intermittent vibration can solve the entrapped residual oil problem during SP flooding process more effectively than continuous vibration.

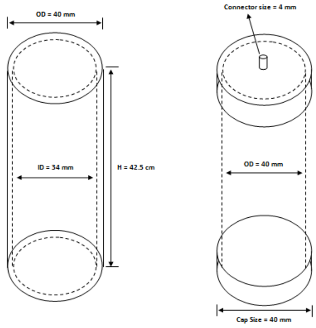

Fig. 1(a): Schematic diagram of macro-model

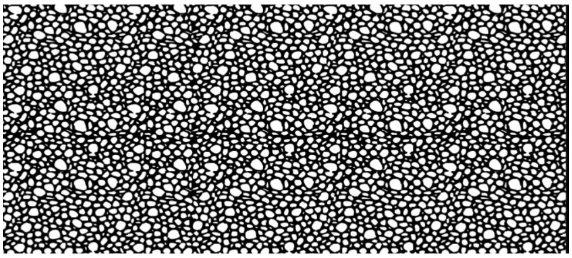

Fig. 1(b): Schematic diagram of 2D glass micro-model

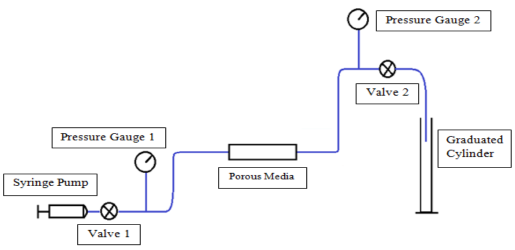

Fig. 2: Setup of SP flooding without aids of ultrasonic vibration

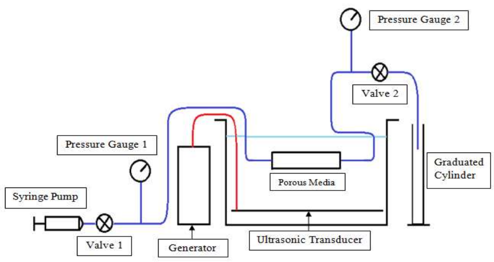

Fig. 3: Setup of SP flooding with aids of ultrasonic vibration (displacement experiments)

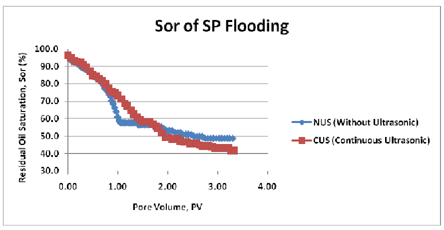

Fig. 4: Sor of SP flooding with and without assisting of ultrasonic wave

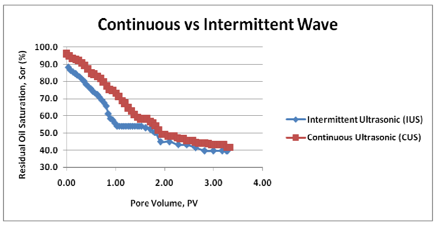

Fig. 5: Results comparison of residual oil left in the porous medium after exposing to intermittent and continuous ultrasonic waves

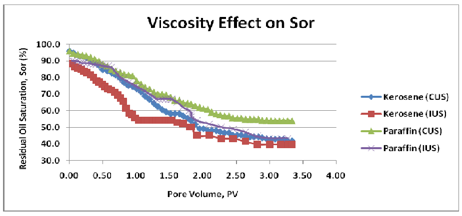

Fig. 6: Displacement experiments results on the effect of viscosity

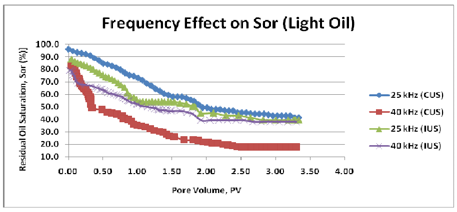

Fig. 7(a): Effect of ultrasonic frequency on the residual oil recovery of light oil (kerosene)

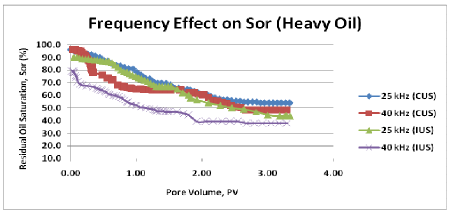

Fig. 7(b): Effect of ultrasonic frequency on the residual oil recovery of heavy oil (paraffin)

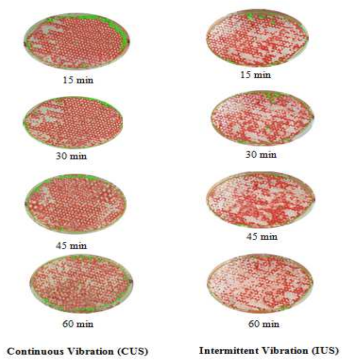

Fig. 8(a): Comparison of micro-model displacement experiment between IUS and CUS for heavy oil

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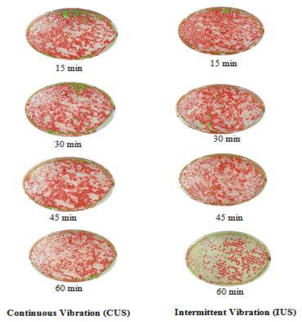

Fig. 8(b): Comparison of micro-model displacement experiment between IUS and CUS for light oil

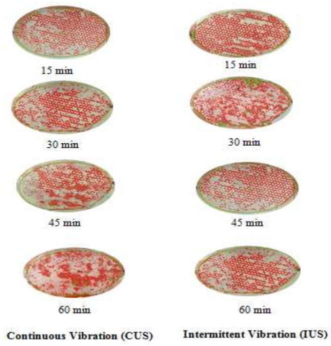

Fig. 9(a): Effect of 25 kHz frequency on displacement of light oil (Kerosene) assisted by SP flooding process

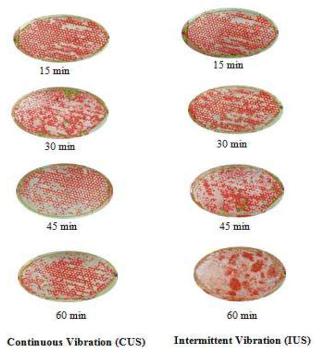

Fig. 9(b): Effect of 40 kHz frequency on displacement of light oil (Kerosene) assisted by SP flooding process

Table 1: Properties of used studied fluids in displacement experiments

Name of Fluid	Viscosity @ 40°C (cp)
Kerosene	0.4
Paraffin	21
De-aerated NaCl Brine	0.74
SP Slug (0.15 wt% AOS + 400 ppm HPAM + 20,000 ppm NaCl)	6.96

Table 2: Specification of the micro-model

Parameter	Specification
Pore volume	37.688 mm^3
Dimension	60mm x 60mm
Throat diameter	0.15mm
Porosity	34%
Permeability	1.94 Darcy

Table 3: Summary of experimental runs

No.	Test	Oil Type	Wave Type	F (kHz)	I (W)
1	Displacement	Kerosene	None	None	None
2	Displacement	Kerosene	CUS	25	150
3	Displacement	Kerosene	IUS	25	150
4	Displacement	Paraffin	CUS	25	150
5	Displacement	Paraffin	IUS	25	150
6	Displacement	Kerosene	CUS	25	150

7	Displacement	Kerosene	IUS	40	150
8	Displacement	Paraffin	CUS	40	150
9	Displacement	Paraffin	IUS	40	150
10	Visualization	Paraffin	CUS	25	150
11	Visualization	Paraffin	IUS	25	150
12	Visualization	Kerosene	CUS	25	150
13	Visualization	Kerosene	IUS	25	150
14	Visualization	Paraffin	CUS	25	150
15	Visualization	Paraffin	IUS	25	150
16	Visualization	Paraffin	CUS	40	150
17	Visualization	Paraffin	CUS	40	150

Conclusion:

Series of displacement experiments were conducted in this study and the following conclusions were made, (1) Ultrasonic vibration proved to enhance a significant value of additional oil recovery on Surfactant-Polymer flooding, (2) Intermittent vibration managed to produce more oil recovery compared to continuous vibration, (3) Intermittent vibration together with high viscosity and high frequency of ultrasonic gives the best recovery and reduced the residual oil saturation at the very best value, and (4) Residual oil saturation in ganglia is inversely proportional to the frequency.

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