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Effect of Distance Intermittent Ultrasonic Wave Source on the Surfactant-Polymer Flooding Recovery and its Displacement Pattern

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The ultimate recovery factor of primary and secondary recovery process can be up to approximately 40 % of oil in place. Technology development is required in order to improve and maximise the recovery and recover some of the oil left. Enhanced Oil Recovery (EOR) method been introduced to solve the main issues of poor recovery, and theoretically, Surfactant-Polymer (SP) flooding would be the EOR method that are able to maximise both, sweep and displacement efficiency. Application of ultrasonic waves and pulse vibrations in the reservoirs has been noticed to reduce the interfacial tension (IFT) between oil and water, resulting in reduction of capillary pressure in the pores and therefore, resulted to an improvement on oil recovery. Ultrasonic waves are longitudinal mechanical waves, which are generated by an infinitesimal compression of a medium. It is known that propagation of the sound waves depends on the elasticity, grain size and density of the rock. It is not certain how far an acoustic wave propagates into the reservoir, nor how such propagation occurs. 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). The main focus of this research is to initiate the use of intermittent ultrasonic radiation in assisting SP flooding process under microscopic visualisation and how it enhances oil recovery through the reduction of residual oil saturation. This work has been designed to understand the mechanics of intermittent ultrasonic vibration in influencing additional recovery of SP flooding. This research is important to know more on how intermittent vibration influences the wave propagations inside the porous media. To achieve this, series of experiments consisting of visualisation and displacement experiments were conducted by using micro-model and macro-model, respectively. SP flooding with aid of ultrasonic waves was compared with normal SP flooding process. Distance of ultrasonic energy source from porous media, d, also was changed to monitor their influence on the process. Snapshots of oil displacement of glass micro-model were taken for visualisation purposes. 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, and the distance of ultrasonic energy source highly affects the residual oil left in the porous medium after SP flooding.

1. Introduction

1.1 Enhanced Oil Recovery (EOR)

The remaining oil in the reservoir after the primary and secondary methods is the potential target of the third production stage, namely the tertiary recovery method, or often termed as Enhanced Oil Recovery (EOR). The main goal of the EOR methods is one or more of the following (Zhu et al., 2005): (1) Reduction of the interfacial tension (IFT) between oil and water, and reduce capillary pressure; (2) Decrease of the mobility ratio between oil and water by increasing water viscosity; and (3) Injection of chemical solvents.

This work will focus on surfactant-polymer (SP) chemical flooding as this slug accommodate both sweep and displacement efficiency. SP flooding can improve oil recovery by combining certain type of polymer and

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surfactant. Polymer can increase the viscosity of fluid, so as to enhance the sweep efficiency, while surfactant can improve the displacement efficiency by reducing the IFT between oil and water.

1.2 Ultrasound Waves

Investigation on the effect of uses of continuous vibration wave been initiated after the earthquake incident in 1950's which generated elastic wave that increase 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 MHz, 3.1 MHz, and 5.5 MHz). Results from these experiments showed that the ultrasonic energy improved the recovery of oil and displacement efficiency in cores. 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.
Ultrasound waves will create vibrations in the reservoir, which would facilitate the production by changing the capillary forces, adhesion between rocks and fluids and cause oil coalescence (Hamida and Babadagli, 2005). General principles of ultrasonic/vibration application are 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. In the presence of surfactant, ultrasonic energy helps the emulsification of oil.
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 believed that the bubbles collapsed and the liquid level within a capillary is raised up.
Simkin and Surguchev (1991) found that size of oil droplet increased when applying continuous ultrasound due to primary Bjerknes forces. Bjerknes forces can be attractive or repulsive depending on the droplet's location relative to the wave field. The magnitude of the forces is depending on the density of continuous phase and radius of the droplet. The coalescence can help to accelerate the gravity phase separation within the porous media and improve the relative permeability of oil.
Beresnev and Johnson (1994) indicated promising result in application of ultrasonic wave but the exact mechanism behind it is still poorly understood. This is because the problem is very complex, involving a superposition of several competing mechanisms. It is not certain how far an acoustic wave propagates into the reservoir, nor how such propagation occurs. 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.
Mohammadian et al. (2013) conducted an ultrasonic stimulated water-flooding experiment on unconsolidated sand pack. Kerosene, Vaseline and engine oil were used as the non-wet phase in the system. A 3 – 16 % increase in the recovery of water-flooding was observed. Emulsification and cavitation was identified as contributing mechanisms. These findings are expected to increase the insight into involving mechanisms which lead to improving the recovery of oil as a result of application of ultrasound waves (Mohammadian et al., 2013).

Later Hamida and Babadagli (2007) 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.
Most of the field application and laboratory experiments involved continuous radiation and it proved the successful of enhanced oil recovery. On the other hand, the cost to generate consistence continuous radiation is rather expensive. In terms of machinery, a large amount of money need to spend in order to carried out the maintenance. In this study, a series of micro-model experiments were performed to see how intermittent and continuous radiation combination can affect the oil recovery.

2. Experimental Procedure

2.1 Fluid Properties

There were three types of fluids been used throughout the experiment, which are kerosene oil as a non-wetting phase, 20,000 ppm NaCl brine as an artificial formation brine, and surfactant-polymer slug as chemical slug agent to displace the remaining oil after water flooding. Alpha Olefin Sulphonate (AOS-surfactant) and Hydrolysed Polyacrylamide (HPAM-polymer) were used to formularise the chemical slug. The complete formulation of SP slug used was comprised of 0.15 wt% AOS + 400 ppm HPAM + 20,000 ppm NaCl, with the viscosity of 6.96 cp. On the other hand, viscosity for kerosene oil and 20,000 NaCl brine was 0.4 cp and 0.74 cp, respectively. All of the viscosity measurements were done at 40 °C.

2.2 Displacement Test

Displacement test was conducted by using an artificial unconsolidated glass bead core as the porous medium. This artificial core was prescribed or termed as macro-model throughout this paper. This macro-model was made up from cylindrical hollow perspex with measurement of 3.4 cm of inner diameter, 42.5 cm of length, and 0.6 cm of wall thickness. Four different ranges of glass beads size (which are 90 µm – 150 µm, 150 µm – 250 µm, 250 µm – 425 µm, and 425 µm – 600 µm, following ratio of 2 : 1 : 1 : 1) were mixed and scattered to represent heterogeneity, and been filled in these Perspex holders. Formation inside this macro-model is 30 % porosity and 1 Darcy at its best due to belief that this artificial core is unconsolidated.
Displacement test was designed to evaluate the recovery factor and percent of residual oil left in the artificial core after surfactant-polymer (SP) flooding process. The core was first introduced to water flood, and then ultrasonic wave was applied simultaneously with SP flooding. Decrement of residual oil left in the core after applying SP flooding was recorded as a reference value to be compared with SP flooding with aid of ultrasonic later. There were two types of waves been applied, which are continuous vibration (CUS) and intermittent vibration (IUS). 40 kHz frequency and 300 W of ultrasonic intensity been used to assist SP flooding process. Ultrasonic wave source was placed 30 cm from the core during the displacement process. Figure 1 shows the experimental set up of SP flooding without aids of ultrasonic vibration. Figure 2 shows the SP flooding with aids of ultrasonic vibration.

2.3 Penetration Test

Penetration test was designed to study how the distance of wave source to porous media affect the recovery in term of residual oil saturation, S_{OR} after SP flooding. The setup of this penetration test would be the same as displacement test, which using the macro-model as well, but the distance of wave source, *d*, were changed and varied from 30 cm to 20 cm and 15 cm distance. Ultrasonic generator and transducer used to accommodate and transmit the wave throughout the medium.

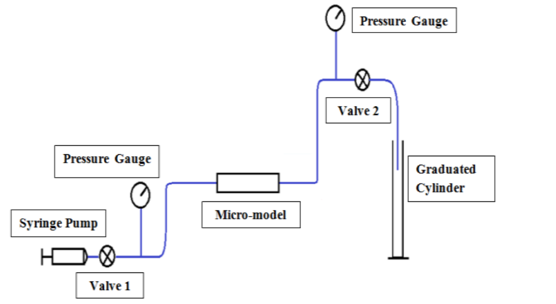
2.4 Visualisation Experiment

Visualisation experiment was design in order to observe the displacement of oil during SP flooding process under the assistance of ultrasonic wave. Two-dimensional (2D) glass-etched micro-model was used as the porous medium. It is designed to study on the interface of oil and water under ultrasound wave. The specification of 2D glass micro-model was shown in Table 1. Experimental setup for visualization experiment can be referred as in Figure 2. Pictures were taken for every 15 min once the SP flooding and ultrasonic vibration were started. Table 2 indicates the summary of all experimental runs to complete the objective of this work.

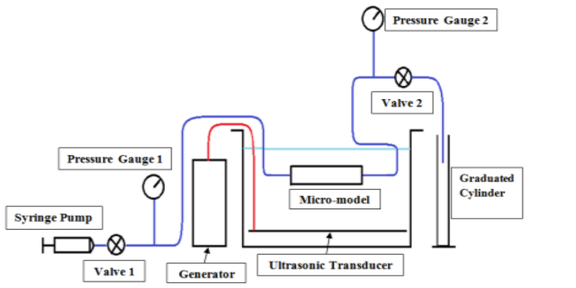
3. Results Analysis

3.1 Surfactant-Polymer (SP) Flooding with and without Assistant of Ultrasound

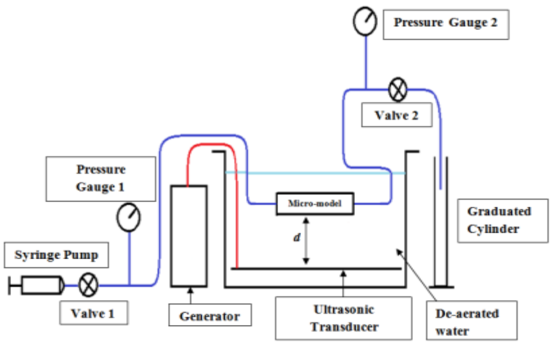
Displacement test was first conducted by running the surfactant-polymer flooding alone, without applying any vibration energy. This result was considered as benchmark and reference in comparing with the flooding under the assistance of ultrasonic vibration, later. This experiment was conducted to highlight on the improvements of reduction in residual oil saturation (S_{OR}) in porous media, once vibration was applied. S_{OR} recorded for the benchmark experiment, SP flooding without aid of ultrasonic vibration, was 48.7 %.
As to emphasise the effect of ultrasonic vibration in assisting the SP flooding, continuous vibration (CUS) with 25 kHz frequency, 300 W intensity, and 30 cm distance of porous medium from wave source, was applied. As can be referred in Figure 3(a), there was 7.7 % of SOR reduction recorded as the SP flooding and ultrasonic vibration stop. It showed that significant improvement on S_{OR} after SP flooding had been achieved when applying vibration to assist the process.



(a) Set up of SP flooding without aid of ultrasonic vibration



(b) Set up of SP flooding with aids of ultrasonic vibration



(c) Set up of penetration experiment

Figure 1: Type of set up of SP flooding

Table 1: Specification of 2D glass micro-model

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

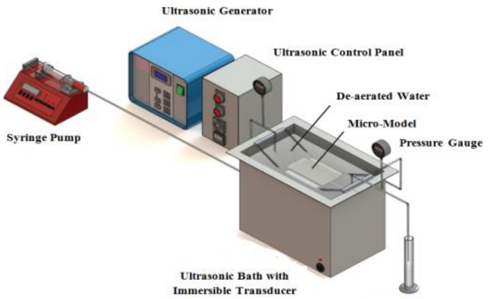


Figure 2: Set up of visualization experiment by using micro-model

Table 2: Summary of experimental runs

No.	Test	Wave Type	F (kHz)	I (W)	*d* (cm)	No.	Test	Wave Type	F (kHz)	I (W)	*d* (cm)
1	Displacement	-	-	-	-	8	Visualisation	CUS	25	300	30
2	Displacement	CUS	25	300	30	9	Visualisation	IUS	25	300	30
3	Displacement	IUS	25	300	30	10	Visualisation	CUS	25	300	30
4	Displacement	CUS	25	300	20	11	Visualisation	IUS	25	300	30
5	Displacement	IUS	25	300	20	12	Visualisation	CUS	25	300	30
6	Displacement	CUS	25	300	10	213	Visualisation	IUS	25	300	30
7	Displacement	CUS	25	300	10						

3.2 SP Flooding Assisted by Intermittent (IUS) and Continuous (CUS) Ultrasound Radiation

In order to compare the effectiveness of IUS with CUS in assisting SP flooding, another displacement test was carried out by using 25 kHz frequency, 150 W intensity of intermittent ultrasonic vibration, and 30 cm distance of wave source from porous medium. Figure 3(b) shows there is a decrement of S_{OR} value as by using IUS (38.0 %) compared to CUS (41.0 %).

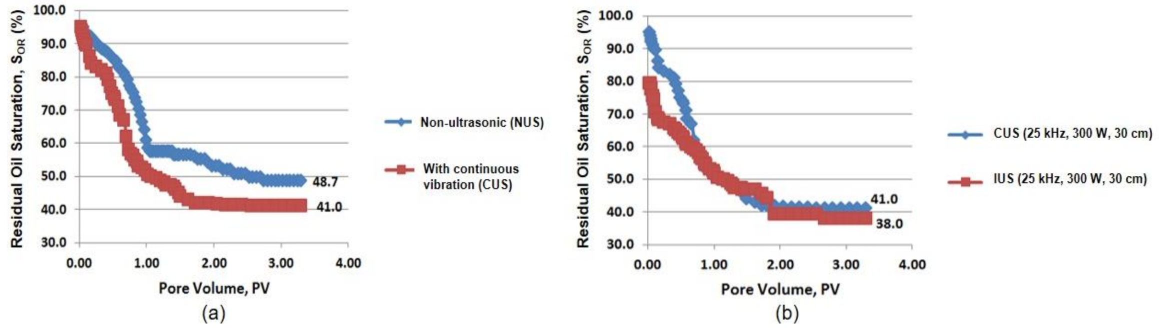


Figure 3: Residual oil saturation, S_{OR} after (a) SP flooding with and without assistance of ultrasonic wave, (b) exposing to intermittent (IUS) and continuous (CUS) ultrasonic waves

The intermittent vibration gives more ample time for the droplets to coalescence compare to the continuous energy. 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) by Bjerknes, V.F.K.. Interfacial tension had been reduced and will affect the capillary number. Capillary number will be increase and residual will be decreased. This mean more oil can be extracted from the pore. By applying suitable vibration and intensity, it can reduce the S_{OR} and also saving the cost of production.

3.3 Effect of Wave Distance to Porous Media on Residual Oil Saturation After SP Flooding

Another displacement experiments (penetration test) were conducted by changing the distance of source of wave from the porous medium, *d*, to evaluate the performance of ultrasonic wave travel in long and shorter distance. Porous medium was placed at three different distance from the ultrasonic transducer (where the ultrasonic energy been transmitted from), which were 30 cm, 20 cm and 10 cm. Figure 4(a) and 4(b) shows the S_{OR} after applying CUS and IUS, at respective distances. Both CUS and IUS exhibit the same trend, where the closer the source of wave located, the higher improvement in S_{OR} recorded. Result in Figure 4(c) indicates that IUS exhibit significant reduction in S_{OR} compared to CUS and SP flooding without non-vibration (NUS). 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 shorter distance of wave source from porous medium, and intermittent vibration as well, shows better improvement.

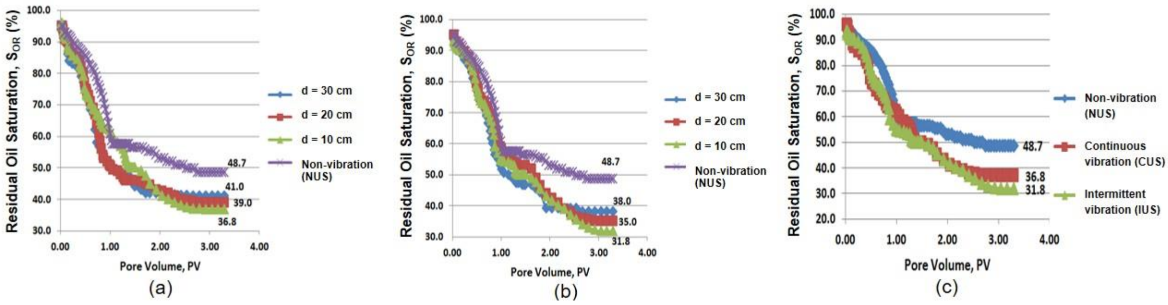


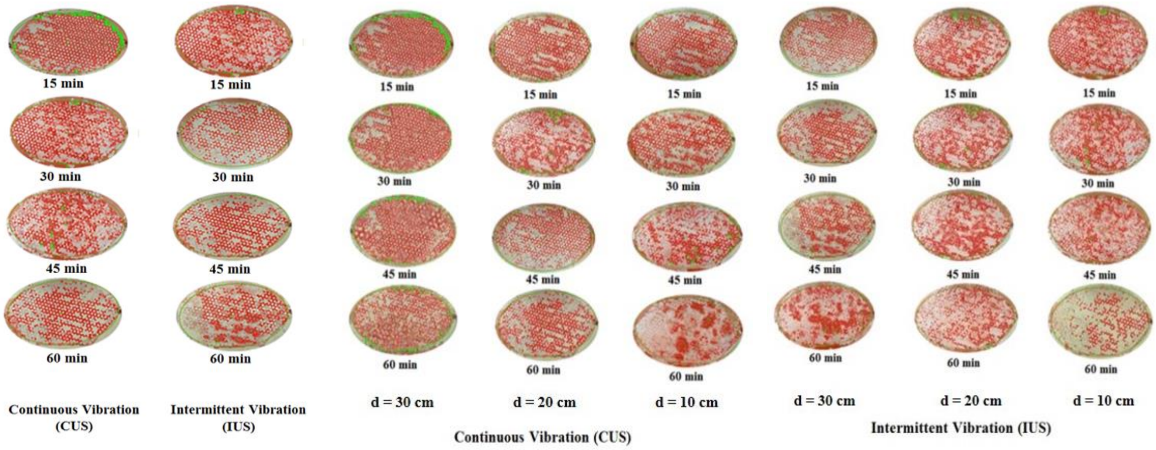
Figure 4: Effect of (a) wave distance under continuous wave (CUS), (b) wave distance under intermittent wave (IUS), (c)10 cm wave distance on S_{OR}

3.4 Visualisation Experiment

For the visualisation experiment, snapshots were taken during the process of SP flooding. Results in Figure 5(a) shows that intermittent ultrasonic (IUS) energy improved the recovery of oil and increase rate of oil displacement. IUS 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. Figure 5(b) and Figure 5(c) shows the displacement of oil at the specific period of time, under CUS and IUS, respectively. For both energy, lesser oil left in porous media been observed when the source of wave located closer (at d = 10 cm). It proves that energy less attenuate as the distance gets closer.

4. Conclusions

Results obtained from this study concluded that intermittent vibration managed to produce more oil and reduce residual oil left in porous media significantly compared to continuous vibration. Besides, intermittent energy also allowed significant reduction in residual oil saturation when the source of wave was placed closer to the micro-model. It can be visualised that oil can be displaced efficiently when intermittent ultrasonic wave was applied.



(a) (b) (c)

Figure 5: Visualisation of (a) oil displacement pattern under continuous and intermittent vibration, (b) effect of wave distance under continuous vibration (CUS), (c) effect of wave distance under intermittent vibration (IUS)

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