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REVIEW

Experimental application of ultrasound waves to improved oil recovery during waterflooding

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Abstract In oil reservoirs about 40% of the original oil in place is produced and the rest remains as residual oil after primary and secondary oil recovery due to geological and physical factors. Additional oil can be mobilized by applying some improved oil recovery methods. However, there is no universal IOR method to be implemented in any reservoir. Efforts are made to develop IOR methods with lower risk. One of these methods is the application of sound/ultrasound waves in the reservoirs to overcome the interfacial tension between oil and water, and reduce capillary pressure in the pores.

In this study, laboratory experiments on core samples were conducted to investigate the ability of ultrasound waves to mobilize additional oil. The core flooding was performed horizontally and vertically and the wave stimulation was applied at original oil in place and at residual oil saturation after performing initial waterflooding. Oil/water relative permeability was calculated to evaluate the flooding performance in the presence and the absence of wave stimulation and the rate of oil recovery was determined. In addition, water fractional flow curves were considered to determine the average water saturation after breakthrough in the presence and the absence of ultrasound waves. Moreover, the effect of wave stimulation on unconsolidated core samples was investigated.

Results show that the rate of oil displacement increases due to various identified mechanisms, and the interaction of the generated waves with the fluids in porous media causes changes in relative permeability and in water breakthrough. Wave stimulation at residual oil saturation was more effective than the case of original oil in place. Therefore, this method is advised to be used in depleted reservoirs. Moreover, wave stimulation on core sample with a compressive strength of <150 psi (unconsolidated) is not recommended due to sand production.

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Contents

1. Introduction

The world oil reserves can be increased by employing new oil production methods to recover most of the oil found in pores between rock particles. The production history of a petroleum reservoir goes through several production stages. The first stage is primary recovery process, in which the reservoir pressure causes the fluid to flow into production wells and then to the surface. If the reservoir pressure is not significant to maintain fluid flow to the surface, down hole pumps or gas lift is used to raise the oil to the surface. The average primary recovery rate is around 10–15% of the original oil in place, depending on the oil and rock properties as well as drive mechanism. The second production stage known as secondary recovery methods includes gas and brine reinjection or water flooding. The injection of fluids is implemented to replace the produced reservoir fluid, thus, the reservoir pressure can be maintained, or to displace the oil directly into the production wells and then to the surface. The most common method involves flooding the reservoir with water. The ultimate recovery factor can be increased to about 40% by employing the secondary recovery method (Roger Hite et al., 2004; Lake et al., 1994; Chierici, 1994; Laherrere, 2001).

The main causes of the poor recovery of the first two production stages are the existence of the interfacial tension between oil and water (capillary forces), high mobility ratio, and the heterogeneities in the reservoir rock. Therefore, 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 methods. The tertiary recovery method is often termed as Enhanced Oil Recovery (EOR). In order to recover some of the oil left in the reservoir, EOR-methods have to be applied to overcome the physical and geological effects.

The main goal of the EOR methods is one or more of the following (Lake et al., 1994; Littmann, 1997; Williams, 2003; Amro, 1994; Zhu et al., 2005; Gharabi, 2005):

- Reduction of the interfacial tension between oil and water, and reduce capillary pressure.
- Decrease of the mobility ratio between oil and water by increasing water viscosity.
- Injection of chemical solvents.

However, efforts are made to develop new techniques with lower application risk. One of these alternatives is the application of sound/ultrasound wave stimulation. This technique is promising as new well stimulation technology to enhance oil recovery and/or to remove formation damage around the wellbore. It is known that propagation of the applied waves depends on elasticity, grain size and density of the rock (Gharabi, 2005).

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 (Frederick, 1965; Kouznetsov, 1998; Hamida and Babadagli, 2005).

Generating elastic waves in the reservoir can cause an acceleration of gravitational segregation of gas, oil and water. International interest in developing elastic wave stimulation as an effective enhanced oil recovery technology is growing.

In Russia, China, Canada, USA and Norway, laboratory investigations have focused on elastic-wave vibration, pressure pulsing, vibro-seismic technology as new EOR techniques, to study the effect of these technologies on improving oil recovery and reducing water oil ration (Frederick, 1965; Kouznetsov, 1998; Hamida, 2005). Sound waves are generally used in the oil industry for exploration and appraisal during seismic and logging surveys and they are used in many other industrial applications to remove contaminants from other parts (Hamida and Babadagli, 2005; Westermark et al., 2001; Nikolaevskiy et al., 1996; Al-Homadhi et al., 2001).

Erfan et al. 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 cavitations were 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).

Khosrow and Tayfun use oil saturated cylindrical sandstone cores placed into imbibition cells, then oil recovery performances were tested with and without ultrasonic radiation. The ultrasonic frequency was 22 and 40 kHz. An increase in recovery was observed with ultrasonic energy in all cases. This change was more remarkable for the oil-wet medium. But the additional recovery with ultrasonic energy became lower as the oil viscosity increased (Naderi and Babadagli, 2010).

Tarek and Tayfun investigated the effect of ultrasound on flow through a capillary using the pendant drop method. Water was injected into a capillary tube submersed into several mineral oils with different viscosity, and kerosene. The average drop rate per minute was measured at several ultrasonic intensities. Their semi-quantitative results reveal that the remarkable change in the interfacial forces between oil and water could be the explanation to the enhancement of oil recovery when the ultrasonic waves are applied (Hamida and Babadagli, 2008).

Vladimir et al. described a new method for ultrasonic enhancement of oil recovery from failing wells. The technology involves lowering a source of power ultrasound to the bottom of the well either for a short treatment before removal or as a permanent placement for intermittent use. They concluded that in wells where the permeability is above 20 mD and the porosity is greater than 15% ultrasonic treatment can increase oil production by up to 50% and in some cases even more. And for wells of lower permeability and porosity ultrasonic treatment alone is less successful, but high production rates can be achieved when ultrasound is applied in conjunction with chemicals (Abramov et al. in press).

These field results make this method a very promising enhanced oil recovery method in the near future.

The results of Erfan and Khosrow and the work of other scholars encouraged me to extend their research work by performing ultrasonic stimulated water-flooding experiments, but with a different approach:

- First: by using consolidated natural sandstone cores and crude oil as the displaced fluid, instead of unconsolidated pack and kerosene or mineral oil as Mohammadian et al., 2013 did.
- Second: by using core flooding process, instead of using imbibition cells as Naderi and Babadagli, 2010) did.
- Third: by using a higher ultrasonic frequency.

In this study, the potential of the sound and ultrasound waves to enhance oil recovery will be investigated as an alternative method to the conventional EOR.

The advantages of this method compared to other conventional recovery methods can be summarized as follows:

- It may replace or reduce the need for chemical stimulation (acid, solvents...), which is in some cases not compatible with the reservoir rock or fluid.
- It can be conducted at any defined interval allowing precise wellbore stimulation.
- It might be conducted to remove the filter cake especially in horizontal wells with long horizontal section, in which large amount of acid solution might be required. Coiled tubing attached with ultrasound wave generator can be run into the horizontal section to remove the filter cake.
- It might be carried out while the well is producing.

In this study, laboratory experiments on core samples have been conducted under reservoir conditions with the following objectives:

- To investigate the applicability of sound and ultrasound waves as an effective method to transport energy through the reservoir with the aim of oil mobilization.
- To determine the rate of oil displacement by water flooding in the presence of applied sound and ultrasound waves.
- To identify the main causes of the additional recovery.
- To compare this approach with other conventional methods.

To describe and interpret the data obtained from laboratory displacement tests in this study, determination of the relative permeability was essential for all flooding runs. Johnson, Bossler, Nauman (JBN) method is used to interpret the obtained data. The JBN method presents the calculation of relative permeability more accurately than other interpretation methods (Toth et al., 2001; Al-Fattah, 2004).

2. Experimental work

The purpose of ultrasound technology is to provide continuous energy to create hydrodynamic waves downhole for dislodging trapped oil at a distance from the source. To evaluate the effect of sound/ultrasound wave stimulation to enhance oil recovery, flooding tests on core samples were carried out. A specially designed flooding system was installed to conduct the required experiments (see Appendix A). The main components of the flooding apparatus are fluid storage vessels, displacement pumps, Hock cell (core holder), fraction collector and acoustic and ultrasound generator. The pressure drop across the core was measured using pressure transducers.

The effect of ultrasound waves on oil recovery was investigated using Berea sandstone saturated with Saudi crude oil. The core was placed in the core holder with confining pressure up to 1500 psi applied with hand pump. Then it was evacuated using a vacuum pump and saturated with 5% brine. The pore volume was measured and porosity was calculated. Then Brine was flooded with 5 pore volume (PV) and the core permeability was calculated at a constant injection flow rate. The core samples were then flooded with the crude oil until no Brine was produced.

Then oil was displaced with brine at a constant flow rate until the residual oil saturation was reached and the original oil in place (OOIP) was determined. Continuous recording of the pressure drop to determine the relative permeability was performed. This first step of the experiment will represent the waterflooding without applying ultrasound waves and will be used as a reference.

In the second step of the experiment wave stimulation was applied on these cores at the residual oil saturation using an ultrasound wave generator with a special design to mobilize additional oil.

Other displacement tests on core samples were conducted at the original oil in place (OOIP) to investigate the effect of the ultrasonic waves under initial reservoir oil saturations (at the start of oil production), and the oil/water relative permeability was evaluated.

Another set of experiment was performed using unconsolidated core samples to examine the influence of the generated waves on poorly consolidated sandstone formations.

The experiments were conducted using the Arabian light crude oil with a viscosity of 13 to 16 cp and API gravity of 31.2° measured at ambient conditions.

Synthetic brines at 5 wt.% concentration were applied in all runs, consisting of 83% wt sodium chloride (NaCl) and 17% wt calcium chloride ($CaCl_2$).

Two different types of core samples were used through this study. Berea sandstone core samples with a compressive

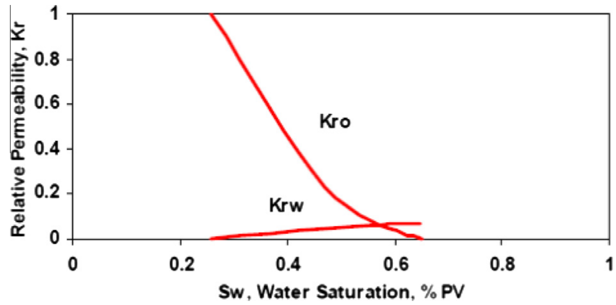


Figure 1 Relative permeability curves to water and oil in the absence of wave stimulation as a reference experiment.

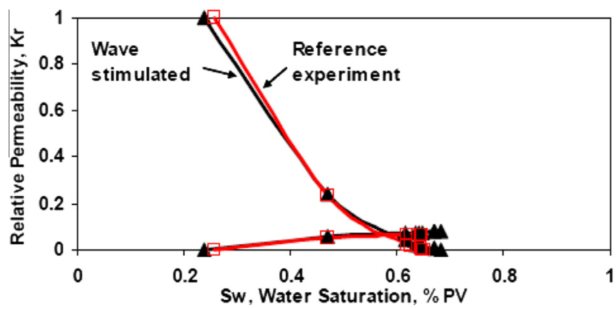


Figure 2 Behavior of water/oil relative permeability in absence and presence of wave stimulation at OOIP.

strength of 5000 psi were selected. The other type of core samples was cut from an outcrop of sandstone rock as unconsolidated with a compressive strength of almost 150 psi. The core samples were washed and dried in an oven at 120 °C for 24 h. The dimension of the core plugs range between 9.0 and 10.45 cm in length and 5.2 cm in diameter.

The high-frequency ultrasonic source is a Clifton ultrasonic bath MU-22. It generates high-frequency waves at 50 kHz with a power output of 300 watts. The bath is filled with water as a carrying fluid to allow transmitting the waves to the core sample. The dimension of the ultrasonic bath allowed the experiments to be carried out in vertical and in horizontal positions. The samples were exposed to ultrasonic stimulation using two treatment procedures, for several cycles of short time (few minutes), and for continuous wave stimulation treatment. Ultrasonic energy is used in this application to perform some kind of mechanical work and the power required is the main important factor for this method to be economical. However, the power may range from just few watts to several kilowatts depending on the frequency.

3. Results and discussion

Flooding experiments on core samples were conducted horizontally and vertically. The wave stimulation was carried out in the first set of experiments at residual oil saturation after waterflooding, and in the second set of experiments at the original oil in place. Oil/water relative permeabilities were determined in the presence and the absence of ultrasonic waves, the additional oil recovery due to wave stimulation was measured and water fractional flow was calculated.

The displacement runs were applied on Berea cores and other cores to investigate the effect of wave stimulation on the relative permeability at the original oil in place (OOIP) and at the residual oil saturation after waterflooding (SOR).

3.1. Effect of wave stimulation on oil recovery with waterflooding at original oil in place

The experiments were conducted in two series, horizontally and vertically, to describe the flow of oil and water in the porous media. The relative permeability of each phase is plotted against water saturation to identify the performance of wave stimulation. It is also worth mentioning that a reference-flooding test was conducted each time in case of any modification of flooding and/or rock parameter. Moreover, the excitation time, at which the core was exposed to the wave stimulation, did not exceed 45 min. as per manufacturer's recommendation. Several repeat runs were made to ensure the reproducibility of the results obtained.

3.1.1. Horizontal core floods

Fig. 1 presents a typical behavior of relative permeability curves to water and oil as a function of water saturation. It was generated in the absence of wave stimulation as a reference experiment for the horizontal flooding tests.

As shown in the figure, the recoverable oil by waterflooding after water breakthrough lies between the irreducible water saturation (S_{wi} = 25.7% PV) and the water saturation at residual oil saturation, which is $Sw_{or} = 1 - S_{or}$ = 65.9% PV. The relative permeability to oil is close to one at S_{wi} and decreases rapidly as oil is displaced by water while the relative permeability to water rises gradually.

Another flooding experiment was run in the presence of wave stimulation at the original oil in place (OOIP) to compare the water/oil relative permeability with that presented in the previous run.

The rate of oil recovery by water in the presence of wave stimulation, which started at OOIP, increases considerably. In the presence of wave stimulation, the oil recovery is at a level of about 59% of the OOIP, while in the absence of wave stimulation oil recovery was at 54% of the OOIP.

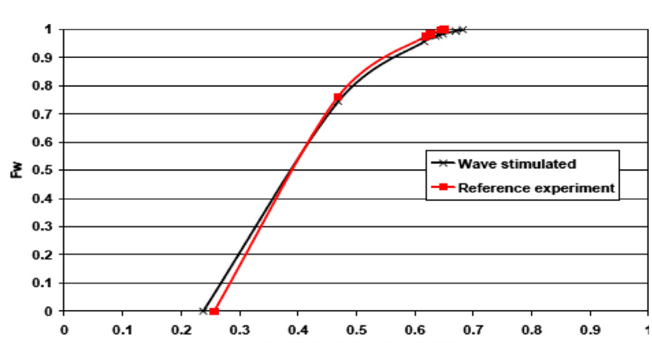


Figure 3 Fractional flow curves of reference and wave stimulated experiments.

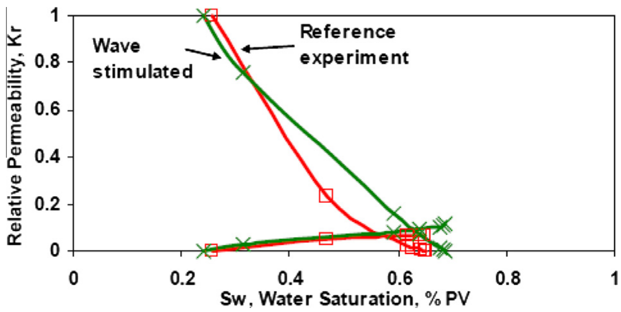


Figure 4 Effect of wave stimulation on the water/oil relative permeability in high permeable core sample.

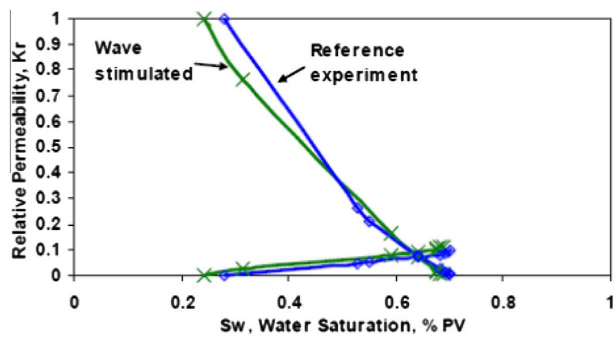


Figure 5 Water/oil relative permeability in cores with higher initial permeability.

Fig. 2 shows that the relative permeability to oil and water of the wave stimulated experiment is very close to that obtained in the reference experiment (this could be due to the intrinsic differences in core sample properties). However, the improvement of relative permeability to oil in wave stimulated run appears at water saturation higher than 60% of PV. This is an indication that the wave stimulation might be beneficial in the reservoirs at advanced stage and not at early stage.

Fig. 3 presents the fractional flow curves of the core samples given in Fig. 2. The intercept of the tangent line drawn from the initial water saturation with the line, $f_w = 1$, is the actual value of average water saturation after breakthrough. The fractional flow for water (f_w) varies between zero (which means 100% oil is leaving the core sample) and one (which means that 100% water is leaving the core sample). The average water saturation after breakthrough in the wave stimulated core was higher than the average water saturation in the reference experiment core.

To clarify the result of the previous runs, a series of corefloods were conducted using core samples having higher initial permeability (around 3000 mD). Fig. 4 presents the relative permeability curves in core samples having high initial permeability.

The oil recovery in the presence of wave stimulation is at a level of 59.3% of OOIP and was higher than that obtained in the reference experiment (54.1% of OOIP). Although the final oil recovery of the wave stimulated sample is higher than that of the reference sample, an early water breakthrough was observed in the stimulated core.

Moreover, similar results concerning the early water breakthrough were obtained in the runs as presented in Fig. 5.

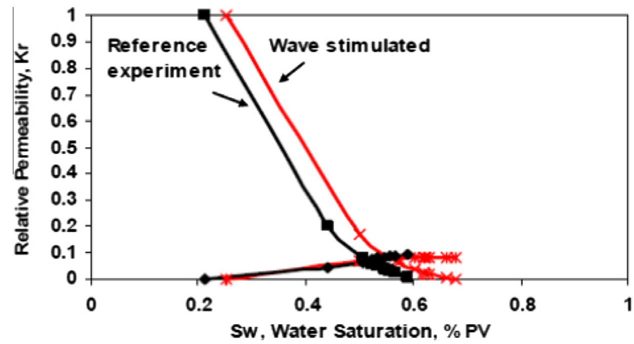


Figure 6 Effect of wave stimulation on the water/oil relative permeability in vertical corefloods.

Although the presence of wave stimulation leads to higher cumulative oil recovery, it accelerates the water breakthrough in core samples having high permeability.

The observation of early water breakthrough, especially in the experiments of high permeability corefloods in the presence of wave stimulation, guided us to study the effect of gravitational separation, which might be the reason behind this phenomenon. Therefore, a series of core floods in vertical positions were performed.

3.1.2. Vertical core floods

A series of corefloods were conducted vertically with the same flooding parameters and conditions used in horizontal corefloods to evaluate the effect of wave stimulation on the oil/water segregation. The wave stimulation was applied at original oil in place (OOIP) and at residual oil saturation after water flooding (SOR). Also, reference experiments were necessary to compare the recovery performance in the presence and the absence of wave stimulation. The flow was directed upward.

Fig. 6 shows the flood performance in the presence and the absence of wave stimulation. The figure exhibits a difference in the relative permeability and in the recovery performance between the reference and stimulated cores. The presence of wave stimulation causes an improvement of relative permeability to oil at any water saturation, and higher oil recovery occurred. In the presence of wave stimulation 58% of OOIP was obtained, while it was about 49.9% of OOIP in the absence of wave stimulation.

On the other hand, the water breakthrough in the stimulated core appears later than that in the reference core. Fractional flow curves of water for the same cores were calculated and presented in Fig. 7.

The oil recovery at breakthrough is higher in the presence of wave stimulation. Therefore, wave stimulation would be more encouraging in horizontal wells, which are placed in the upper layers of the reservoir to benefit from the gravitational separation.

Additional vertical coreflood tests were conducted on core samples having lower initial permeability (176 mD) and results are presented in Fig. 8. The flooding performance in both core samples shows a uniform displacement, which may be an indication that more excitation time of wave stimulation should be applied in cores of lower permeability to mobilize additional oil from the core samples. However, taking again the fractional flow curves of both core samples into consideration, the water

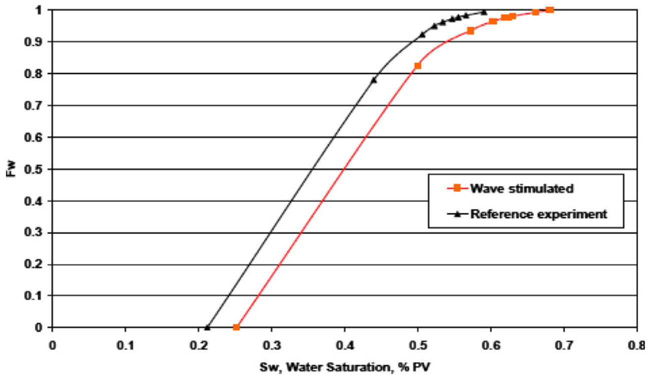


Figure 7 Comparison of fractional flow curves for water in the presence and the absence of wave stimulation in vertical corefloods.

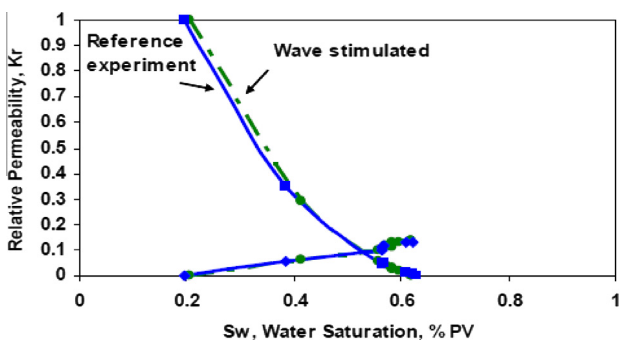


Figure 8 Effect of wave stimulation on water/oil relative permeability on low permeable core samples.

breakthrough in the reference run occurred slightly earlier than that in the stimulated experiment.

3.2. Effect of wave stimulation on oil recovery at residual oil saturation (SOR)

To evaluate the effect of wave stimulation on oil recovery at residual oil saturation, core samples were water-flooded until the residual oil saturation was reached. Generally about 4 PV of brine was injected before the residual oil saturation was reached. The cores were further water-flooded in the presence of wave stimulation. The effluents were collected using a fraction collector and the oil recovery was calculated. Different values were used to calculate the oil recovery; at the end of initial waterflooding in percent of pore volume (PV), at the end of wave stimulation (So_{rs}) in percent of the residual oil saturation, and in percent of original oil in place. All core samples stimulated at residual oil saturation showed additional oil recovery varying between 2.5% and 5% of OOIP or 5–10% of residual oil saturation, respectively. However, the additional oil recovery occurs in all runs after an excitation time of 15–20 min. However, two procedures of wave stimulation were applied namely; intermittent and continuous wave stimulation.

Fig. 9 presents the oil recovery performance of two core samples with different initial permeabilities of 300 and 1500 mD as a function of the cumulative volume injected.

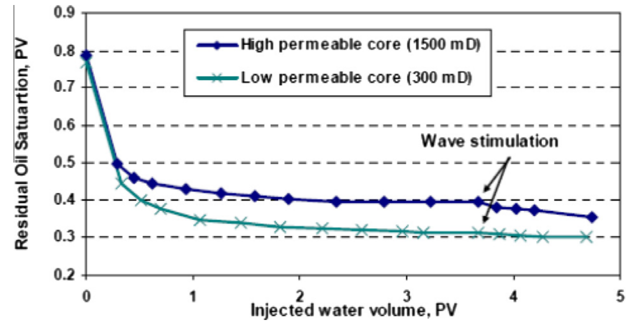


Figure 9 Effect of wave stimulation on the oil recovery in high and low permeable core tests.

The wave stimulation was applied after waterflooding at residual oil saturation as indicated.

The performance of the initial waterflooding of the high permeability core shows lower oil recovery than that obtained from the low permeability core and therefore the residual oil saturation, which is exposed to the wave stimulation, is 39% PV (50% OOIP) and 31% PV (41% OOIP), respectively. Thus, the wave stimulation in the high permeable core leads to higher oil recovery than that of low permeable core. Nevertheless, the potential of additional oil recovery is available in both cores if they are exposed to a longer excitation time.

The figure exhibits a clear difference in the recovery performance of both core samples. The remaining oil saturation in the case of a high permeable core dropped from 39% to 35% PV (50% to 45% OOIP) and in the case of a low permeable core from 31% to 30% PV (41% to 39% OOIP). However, the low recovery is mainly due to the time limitation of the manufacturer on operation of a ultrasonic wave generator. It was not recommended to exceed a running time of 45 min. The ultimate recovery would increase in the case of increasing the excitation time.

Moreover, it must be emphasized that the maximum increase in the oil recovery was associated with the cycled intermittent excitation. This is probably due to the fact that water/oil separation did not take place within the porous media during the very short period of excitation. In contrast, the continuous wave stimulation of 30–45 min. contributes to additional oil recovery but at the same time water/oil separation would occur resulting in low recovery and early water breakthrough.

However, based on the results obtained in this study, the main factors leading to additional oil recovery are: oil droplets that are stuck in nooks and crannies of the medium can be dislodged by vibration and subsequently carried along by water flow. Also, the wave stimulation can improve the oil recovery by the intensity of coalescence of water droplets and their sticking to the solid surface. Langnes (1972) describes the effect of coalescence of water droplets on the attachment of water to the solid surface, which can cause an alteration of wettability. Additionally, the formulation of emulsion was observed in all runs involving the wave stimulation, which is also one of the factors leading to additional oil recovery. But emulsions are usually more viscous than oil, which again may reduce recovery. Hence, these two factors may cancel each other.

Fig. 10 shows an image of the formulated emulsion in the glass tube. This emulsion was generated due to the ultrasonic vibrations. However, it has been found that this emulsion is

Figure 10 Generated emulsion with low stability observed in the effluent.

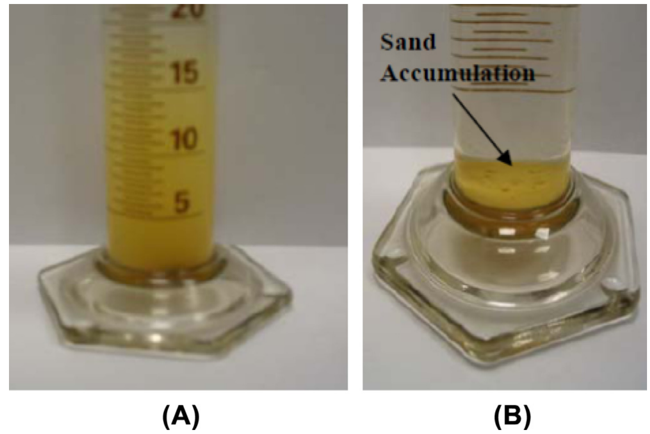


Figure 11 Images showing the sand production: (A) while waterflooding and (B) after sand grains have settled at the bottom of the glass cylinder.

instable, since both phases (Oil and Water) were separated after a short time (20–30 min.).

However, in some cases, where droplets were isolated, the glass cylinder was carefully shaken to liberate those oil droplets that remained attached to the glass wall.

3.3. Unconsolidated corefloods

Artificial unconsolidated core samples were prepared with a compressive strength ranging from 50 to 150 psi to study the effect of generated waves on the stability of the consolidation during the wave stimulation.

The unconsolidated samples were flooded with brine (oil flooding was not performed) and the pressure drop was observed and recorded. The measurement showed stabilized pressure drop at constant flow rates. Then waterflooding was applied in the presence of wave stimulation, which resulted in sand production and the flow resistance of brine in porous media increases gradually, which is indicated by the increase of pressure drop across the core. This phenomenon is due to the motion of the grains within the porous media caused by the mechanical energy created by ultrasonic generators.

Fig. 11 shows sand grains produced by waterflooding in the presence of ultrasonic stimulation.

Several attempts were made on other core samples with higher compressive strengths. Difficulties were still experienced in applying wave stimulation simultaneously with water flooding in all runs on porous media below a compressive strength of 150 psi.

Fig. 12 shows the general texture of core sample having a compressive strength higher than 150 psi. The SEM photo shows that the texture of the core was not affected by the wave stimulation.

From the above two observations, it is concluded that the application of wave stimulation is not recommended in oil reservoirs with rock compressive strength lower than 150 psi (weak consolidation rocks).

Finally, it is worth mentioning, that among the several features observed through this study, no negative impact on the rock and fluid properties was noticed due to the wave stimulation. Therefore, this method can be applied in wide ranges of types of reservoirs. This makes the wave stimulation more attractive than the other conventional EOR processes. In the conventional EOR methods, there is no universal method which can be implemented in any reservoir. The selection of an EOR process is based on different reservoir parameters, such as; temperature, salinity, types of formation, depth, permeability, etc. However, a selected EOR method, which is not suitable for the given reservoir, would have a negative impact on the reservoir associated with high restoration cost.

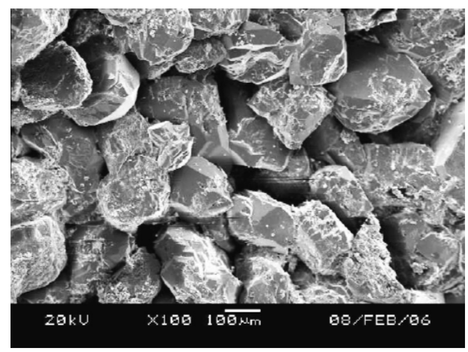


Figure 12 SEM photo showing the general texture of the core sample having a compressive strength of higher than 150 psi after wave stimulation.

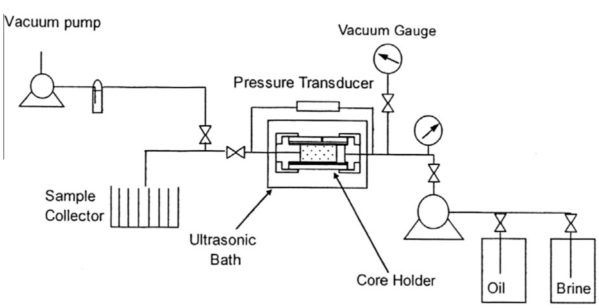
4. Conclusions and recommendations

It should be emphasized that the ultimate aims of this research are to investigate the effect of wave stimulation as a newly proposed method to improve oil recovery, and to identify the recovery mechanisms. Thus, extensive coreflood tests were conducted horizontally and vertically. The wave excitation was carried out at OOIP and at residual oil saturation. Relative permeability curves were created to evaluate the flooding performance in the presence and the absence of wave stimulation.

Based on this research the following conclusions can be drawn:

1- Wave stimulation shows an increase in the oil recovery in the case of vertical and horizontal corefloods. Every increase even 1% can make a huge difference in the amount of oil production and in the estimated oil reserve.
2- The interaction of the generated waves with the fluids in pores causes changes in relative permeabilities of the rock to oil and water, and improves the rate of oil production.
3- Gravitational separation leads to later water breakthrough in vertical corefloods.
4- Due to gravitational separation, horizontal wells especially can benefit much by using this method.
5- Wave stimulation at residual oil saturation shows higher results in the oil recovery rate and therefore, this method can be recommended in reservoirs having high water saturation or in depleted oil reservoirs.
6- In vertical wells with cased holes and selective perforation, wave stimulation is recommended in reservoirs at which the permeability decreases with an increase in depth.
7- Wave stimulation is not recommended in unconsolidated formations with a compressive strength of lower than 150 psi due to sand production.
8- The effect of oil API on ultrasonic water flood recovery should be taken into account in the future research.

Appendix A.



The experimental set used in this research.

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