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Application of a Novel Ultrasonic Technology to Improve Oil Recovery with an Environmental Viewpoint

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Abstract

It is proven by recent studies that sonication has a positive influence over the oil flow within the porous media. Accordingly, the researchers in this paper evaluated the influence of sonication over the oil recovery by means of free fall gravity drainage. Furthermore, the influence of sonication on the oil permeability was assessed in three samples that had different bead size in average. By use of the Hagroot backward method and Matlab simulation, the optimal petrophysical situation for sonication was determined. The authors concluded that sonication positively affects the oil recovery for the non-asphaltenic samples, while it has a reverse effect on the asphaltenic samples because of increasing the viscosity in long-term. Furthermore, it was witnessed that gravity drainage was heightened by increase of beads' size in the non-asphaltenic sample. Accordingly, this mechanism can be useful in oil recovery by means of gravity drainage, specifically in fracture reservoirs.

Keywords: Improved oil recovery; Ultrasound; Gravity drainage; Hagroot method; viscosity; Matlab simulation; Relative permeability

Introduction

Oil extraction from the reservoirs is primarily initiated by the pressure gradient of the reservoir that brings about the fluid flow to the production wells and afterward to the surface [1]. When the reservoir pressure is not sufficient, down-hole pumps are implemented or gas lift methods are used to get the oil to the surface. Sole reliance on the characteristics of the rocks in the subsurface, the oil properties, and the extraction method, will contribute to recovering only 10 to 15 percent of the total oil in the reservoir in what is referred to as the primary recovery stage [2]. The methods used in the second stage- namely secondary recovery- includes injection of fluid into the reservoir in order to displace the fluid produced in the well, so that the pressure of the reservoir is maintained. These methods include water flooding and brine and gas reinjection, among which water flooding is the most commonly used. Up to 40 percent of the total oil in the reservoir can be extracted in this stage [3].

There is a variety of factors that negatively affect the oil extraction process in the primary and secondary recovery. These factors include capillary forces, high mobility ration, and finally heterogeneity of reservoir rocks. So far, up to 55 percent of the existing oil in the reservoir can be extracted. Hereby, the third stage in oil extraction appears, that is tertiary recovery [4]. This stage is commonly called Enhanced Oil Recovery (EOR). The common techniques used in the EOR are thermal recovery, gas injection, and chemical injection [5], and the goals of implementing the EOR methods are decreasing the oil-water interfacial tension, lowering capillary pressure, and finally, lowering the oil-water mobility ratio by means of increasing the viscosity of water [6].

However, researchers are looking for new techniques to reduce the related risks of the EOR process. One of these techniques is ultrasonic wave radiation which supports EOR while prevents imposing damages to the producing formation. The studies on the implementation of ultrasonic waves and their manner of influence started in 1950 with a study on the correlation between the water level and the stimulation caused by earthquakes [7]. In fact, the seismic waves emitted by the earthquake were identified as the causes of the increase in fluid's level and its pressure. The same result was achieved for the wells around highways and railways. As a result, the researchers came to conclusion that the behavior of the sound waves and the phenomenon of simulation by the sound waves must be understood better in order to safely use these waves. Since the 1970s, a great number of studies on ultrasonic waves have been conducted [8-11].

Implementation of ultrasound waves in EOR methods has a number of advantages including easy and quick application, protection of wellbore formation against damages, low operational costs and high profitability, high compatibility with other EOR methods, and finally having a wide range of applications [12,13].

The Enhanced Oil Recovery methods can be utilized in the following conditions [14]:

- When the drilling mud has been flowing for a long time, and the well is damaged due to overuse of the drilling mud.
- When injection of water and acid into the well is in vain, and does not increase the recovery rate.
- When the wells show a high potential for production, but the production rate is low.
- When the wells are producing heavy oil and paraffin.
- When the well is damaged by salt and sediments.

Literature Review

Application of electromagnetic methods or wave treatment requires the utilization of various physical fields instead of a substance to play

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the role of an agent. Since the other methods of enhancing oil recovery, including chemical flooding, polymer flooding, gas flooding, and steam flooding, have a number of disadvantages like being costly, requiring too many surface apparatus, being environmental-unfriendly, and having technical constraints, the advantage of acoustic treatment lies in the need for lower resources, lower energy, and lower expenses than the other methods of IOR currently being used [15]. The results of a number of studies revealed that acoustic treatment of the oil well, especially within the ultrasonic range, is among the best methods of boosting oil extraction from the wells [16-18]. The advancements in the efficient ultrasound generators, choice of appropriate wells, and finally physically modeling of the processes by means of mathematics has improved the performance of this method in the recent decades [19].

Studies of oil recovery by using vibration first began in the 1950s, at the time the researchers witnessed an increase in oil extraction after the cultural noises and occurrence of earthquakes. The first scholars who posed the possibility of using sound waves to increase oil production were Duhon and Campbell [20] who tested water flooding on the well cores while radiating ultrasonic waves with frequencies between 1 and 5.5 Megahertz. In their study, the water was injected to the center of the sandstone core of the well, while the ultrasound-generating probe was placed in the center of the core too. The receiver probe was located in the bottom of the core. The authors concluded that the usage of ultrasound waves enhanced the oil extraction and made the fluid displacement better. They also observed a negative correlation among the frequency, cavitation, and recovery- i.e., an increase in frequency of the waves brings about a decrease in cavitation as well as oil recovery.

The two studies of Chen, Fairbanks and Chen [21,22] showed that the usage of ultrasonic waves in porous media is capable of boosting the percolation rate, while the heat made by ultrasound waves plays a minor role in this increase. These researchers radiated ultrasound waves with the frequency of 20 Kilohertz and the power of 10 W/cm^2 to the oil and water that was flowing in the porous sandstone and the capillary. Moreover, the results of a research conducted by Cherskiy showed a notable boost in the permeability of the cores which were saturated with water while there was acoustic radiation [23]. The other two studies that approved the results of the previous studies were conducted by Neretin and Yudin and Pogosyan [24,25]. Neretin and Yudin [24] reported that displacement of oil by water in the well's loose sands increases while ultrasound waves are radiated. Pogosyan [25] concluded that ultrasound waves boost the gravitational separation of water and kerosene.

There was a shift of focus in 1990, and in the next three decades, the scholars paid attention on the simulation of elastic waves as well as seismic methods. In this regard, the systematic review of Beresnev and Johnson [26] collected and analyzed the studies on the methods that took advantage of elastic wave simulation in oil extraction- both ultrasound and seismic waves. This systematic review came to conclusion that both elastic waves and seismic waves are able to increase the rate of permeability as well as production within the porous media.

In another study, Beresnev [26] tried to analyze the mobility of the oil droplets within the porous media- through a capillary-oriented mechanism- afterward the ultrasound waves are radiated. Figure 1 displays a schematic view of the trapped oil. The scale of this research was a pore scale of an oil droplet which was not wet. The droplet was entrapped at the pore's opening in a channel. As shown in the Figure below, the right meniscus is smaller than the left one. The result will be the formation of an imbalanced capillary pressure (ΔP) inside the droplet. This imbalance stands against the pressure from outside, and

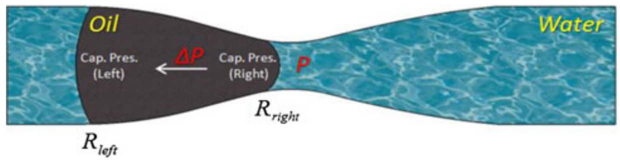

Figure 1: Trapped oil under ΔP (pressure gradient. R_{right} and R_{left} represent the droplet radii. Cap. Press stands for capillary.

increases as the droplet travels toward the pore's throat. The external pressure gradient is parallel with the internal pressure gradient (ΔP_S). As a result, (ΔP_S) must increase so that the droplet passes the pore's throat. Ultrasound waves are able to generate this extra pressure (P_U). In a mathematical way, the droplet passes through the pore's throat if we have $\Delta P_S + P_U > \Delta P$. It is obvious that the higher the power of the ultrasound wave, the higher the generated force will be.

Mobilization of the oil after radiation of ultrasonic waves was further analyzed in the study of Amro [27]. These researchers came to conclusion that ultrasound waves are able to improve the oil mobility, while changing its permeability. Moreover, they compared the oil extraction after ultrasound treatment in residual oil saturation and original oil in well. The results revealed that residual oil saturation brought about more oil recovery.

In a recent study by Keshavarzi [28], the influence of ultrasonic waves on free gravity drainage of the oil was analyzed. The researchers in this study utilized a glass bead pack porous medium for conducting the free fall gravity drainage tests under the conditions of ultrasound radiation and non-radiation. Moreover, the permeability of the wetting phase was obtained in this research. The results of this study revealed that radiation of ultrasound waves notably boosts the recovery factor in the process of free gravity drainage. Furthermore, the permeability of the wetting phase as well as the non-wetting phase increased by radiation of ultrasound waves.

Research Methodology

As mentioned in the previous section, Keshavarzi [28], conducted a study on the role of ultrasonic wave on two-phase relative permeability in a free gravity drainage process. This recent study analyzed the relative permeability of merely one sample (one glass bead pack). As a result, the researchers in the present study decided to conduct a series of similar experiments on three samples to confirm or refute the findings of this study. Consequently, the same methodology as the Keshavarz's was used in this research:

The test setup included a Plexiglas cylinder whose length was 30 centimeters. The diameter of the cylinder was 4 cm, while its inner diameter was 3 cm. Moreover, a graduated cylinder was used for measuring the amount of the extracted liquid. The ultrasonic generator had an average effective output of 80 Watts, and a frequency of 22 KHz. Figure 2 depicts a schematic view of the apparatus [28]. There were three samples used in this research with an average bead size of 80-100 µm, 170-200 µm, and 240-270 µm. In order to calculate the medium porosity, the volume of the entering fluid to the cylinder was measured; and, the calculated amount for medium porosity was 40 ± 0.3% for the first sample, 52 ± 0.48% for the second sample, and finally 63 ± 0.52% for the third sample. By means of fluid injection into the cell with a certain pressure gradient and calculation of the flow rate, the bead pack's absolute permeability was measured to be 30 ± 1 Darcy for the first sample, 38 ± 1.4 Darcy for the second sample, and finally 43 ± 1.2 Darcy for the third sample.

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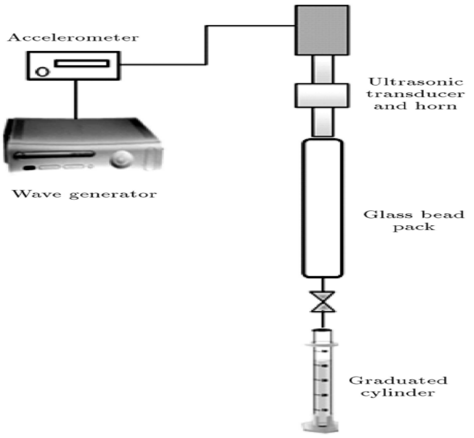

Figure 2: A schematic of the apparatus used for conducting the experiments.

Fluid	Density $\left(\frac{kg}{m^3}\right)$	Viscosity (cp)	Asp. content
Crude oil A	920	5.39	0.23%
Crude oil B	984	74	4.2%

Table 1: Physical characteristics of the used wetting fluids in this study (in a standard condition).

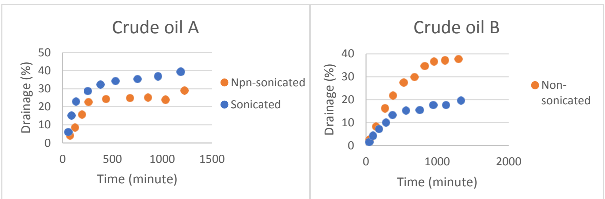

Figure 3: The effects of ultrasound radiation on ultimate drainage recovery of the sample with an average bead size of 80-100 µm.

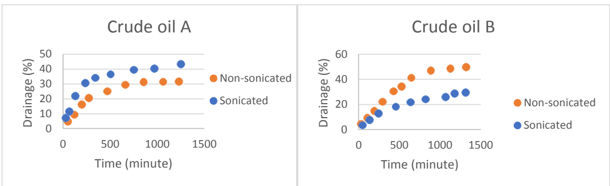

Figure 4: The effects of ultrasound radiation on ultimate drainage recovery of the sample with an average bead size of 170-200 µm.

The researchers used air in the non-wetting phase, and such materials as crude oil A and crude oil B (asphaltenic) in the wetting phase. Table 1 displays the characteristics of the wetting fluids used in the study.

The researchers decanted the glass beads into the Plexiglas cylinder and assembled the apparatus before conducting each experiment. In order to avoid mistakes in calculations, the researchers used first-hand dry glass beads in every experiment. The cell was completely saturated with the liquid sample after vacuuming the cell to a favorable pressure. Then, the researchers positioned the cell in a vertical standing, while its faces were open. After that, the liquid produced against the time was determined. The temperature in the experiment environment was the ambient laboratory temperature of 25°C, and the experiments were conducted under the radiation and non-radiation of ultrasonic waves [28].

In order to measure the relative permeability of the samples, the authors took advantage of Hagroot [29] backward method. According to this method, the value of normalized oil production, after the time of breakthrough, is measured by the following formula:

$$Np = 1 - \left(1 - \frac{1}{n}\right)\left(\frac{1}{nk_{r0}^{0} t_D}\right)^{\frac{1}{n-1}} \qquad (1)$$

In the above equation, n is the exponent of Corey equation and k_{r0}^{0} is the Corey constant.

The curves of relative permeability in the wetting phase were measured by comparing the recovery data with time. Afterward, these results along with the production data were utilized for drawing the relative permeability curves in the non-wetting phase. This process included the history matching of the wetting phase data with the production data [28].

Results

Figure 3 displays the results achieved from the free fall gravity drainage tests. The relative error in calculation of oil recovery rate was measured to be 3 to 6 percent for all three samples.

As can be seen in Figure 3, it can be mentioned that in general, ultrasonic radiation boosted the rate of oil recovery, the same as drainage recovery for the first sample with an average bead size of 80-100 µm. The crude oil A showed an increase of 38 percent from the initial recovery of 29% to 40% after ultrasound radiation. However, the crude oil B sample reflected a reduction of ultimate recovery rate after sonication. This sample showed a reduction of 50% in its ultimate oil recovery rate after sonication, and its recovery rate decreased from 38% before sonication to 19% after sonication. This reduction was related to the asphaltenic nature of the sample. Najafi [30] explained the reason of this phenomenon in their study on Quantifying the role of ultrasonic wave radiation on kinetics of asphaltene aggregation in a toluene–pentane mixture. The researchers concluded that disintegration of asphaltene micelle structures of the oil and its dissolution in the fluid leads to an increment in the oil viscosity after being exposed to ultrasound waves for extended periods for time. Finally, an increase in the viscosity of a liquid means a reduction in the drainage recovery.

The effects of radiating ultrasonic waves on the sample with average bead size of 170-200 µm are reflected in Figure 4.

In general, it was observed that ultrasound waves' radiation to crude oil A increased the ultimate rate of drainage recovery. However, this increase was almost 2% higher than the increase in the sample with the average bead size of 80-100 µm. As observed in Figure 4, the ultimate recovery rate of Crude oil A reflected an increase of 40 %, that is from the drainage recovery rate of 32% to drainage recovery rate of 44.8% in its final recovery. Similar to the previous sample, there was a decrease in the ultimate recovery rate of the crude oil B sample from 49% to 29.4%, that is a general decrease of 40%.

Figure 5 depicts the influence of sonication on ultimate drainage recovery of the sample with the average bead size of 240-270 µm. There was a congruity between the achieved results for this sample and the results achieved for the two previous samples- i.e., an increase in the ultimate recovery rate of crude oil A, and a decrease in the final recovery rate of the crude oil B. In general, it was observed that the increase in the recovery rate of the material in this sample was approximately 5% higher than the second sample, and 7% higher than the first sample. The acquired results for this sample showed an increase of 45% in the

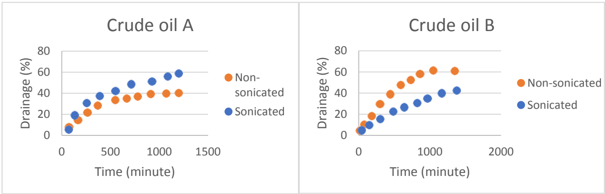

Figure 5: The effects of ultrasound radiation on ultimate drainage recovery of the sample with an average bead size of 240-270 µm.

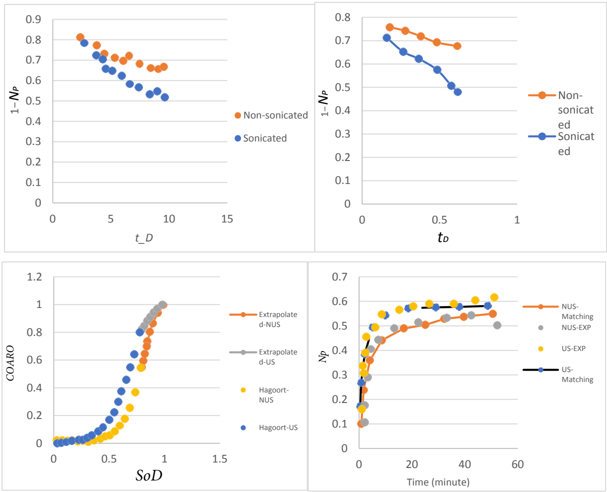

Figure 6: Steps of measuring the constants of Corey type equation for relative permeability of crude oil A-wetted sample.

final recovery rate of crude oil sample A from 40% to 58%. The decrease in the final recovery rate of the crude oil B-wetted sample was 30%, i.e., from primary 62% to 43.4% after radiation.

Due to the fact that Hagroot method cannot be used for samples which have alterations in their physical characteristics, this method was not applicable for crude oil B sample with asphaltenic nature. Consequently, the relative permeability of wetting as well as non-wetting phases was calculated for the samples wetted with crude oil A. As an example, the procedure of relative permeability calculation for crude oil A-wetted sample with the average bead size of 170-200 µm is depicted in Figure 6a. The breakthrough takes place in $t_{D=0.18}$ for non-radiation of ultrasound waves, and in $t_{D=0.16}$ for ultrasound radiation. As observed, breakthrough under ultrasound radiation condition took place earlier. For evaluation of n, the exponential data after the time of breakthrough must be utilized. As a result, a crossing line is drawn through the data (Figure 6b). By using the following equation, the value of n was calculated to be 5.80 for non-radiation of ultrasound waves, and 3.97 for the radiation of ultrasound waves.

$$\frac{d\ln(1-Np)}{d\ln t_D} = -\left(\frac{1}{n-1}\right) \qquad (2)$$

In order to calculate the amount of k_{r0}^{0} through Eq. 1, the value of N_p acquired from drawing a straight line at t_D=1 was used, and the value of k_{r0}^{0} was calculated to be 1.79 for non-radiation of ultrasound condition and 1.87 for radiation of ultrasound waves. Figure 6c displays the results achieved for the relative permeability of crude oil A-wetted sample by use of backward Hagroot method. At the end, it was observed that ultrasound radiation reduced the value of n for crude oil A, while increased the value of $CO\ A_{r0}^{0}$ for this material.

With regard to the calculation of relative permeability in the non-wetting phase, the history matching of the results acquired from Eq. 3 and the experimental data of production was done (Figure 6d).

$$\frac{dNp}{dt} = \frac{k_g\left(-\frac{pc}{H} + \Delta\rho g\left(1-Np\right)\right)}{H\phi\mu_g\left[Np\left(1-M\right)+\right]M} \qquad (3)$$

The results revealed a boost in the relative permeability of all the three samples in the non-wetting phase. Figure 6 displays the relative permeability of the crude oil A-wetted samples in both phases. As can be seen in the Figure 6, radiation of ultrasound waves increased the relative permeability of the gas and oil. Moreover, the relative permeability of gas end point improved, while there was a decrease in the amount of critical gas saturation.

Conclusion

The researchers in this study analyzed the influence of ultrasound radiation on the free fall gravity drainage and relative permeability of three different samples of sand pack beads with different sizes, and with different wetting and non-wetting conditions. Following up the methods used in the study of Keshavarzi [28], it was concluded that ultrasound waves are able to improve the recovery in the gravity drainage process, which is the main recovery parameter in the fracture reservoirs, for crude oil A (non-asphaltenic), while these waves increase the viscosity of the oil in asphaltenic samples, and, as a result, reduce its recovery in long exposure time. Furthermore, it was concluded that the increase in the size of the beads in the samples led to an increase of oil recovery in non-asphaltenic samples by the help of ultrasound waves; and, decreased the amount of gravity drainage in the asphaltenic samples.

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