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Effects of Optimized Physical Vibration Parameters on Enhanced Oil Recovery

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Abstract: In this paper the optimized vibro-seismic parameters for enhancing the productivity of the oil wells through water flooding is studied and presented. The main idea of the vibro-seismic application in the petroleum industry is to provide energy to the reservoir rock through the use of either physical vibration or acoustic waves vibrations to enhance the rock and rock-fluid properties which in turn may result in improving the oil recovery. The optimized parameters that are investigated here included frequency, amplitude (energy) and the vibration duration (time). It was found that the optimization of these three parameters is essential to make sure that the vibro-seismic treatment will enhance the rock properties or otherwise it may result in damaging the reservoir. Multiple core plugs with different porosities and permeabilities are used to investigate the effect of the vibro-seismic on the enhanced oil recovery for different reservoirs. Also, multiple combinations of parameters; frequency, amplitude and time are used and the optimum combinations for the different reservoir properties are obtained. The steps that are taken in this paper for the optimization is to compare the effect in the water flooding results with different vibration parameters to that obtained without vibrations to select the optimum vibration combination. The experimental work showed that there was an increase in recovery for all of the cores with different percentages when compared to the initial case of just waterflooding if the vibration parameters are optimized. Full discussion of the results and recommendations for further investigations are discussed.

Keywords: Vibroseismic, Waterflooding, EOR, Phyiscal Vibration

1. Introduction

The vibro-seismic approach is attracting a lot of attention from researchers since it aims to increase reservoir production while also improving the rock and fluid properties. This method includes vibrating a rock formation at a preset frequency, amplitude, and energy using an acoustic wave or a physical vibrator. The application of optimal physical vibration to sandstone reservoirs is the main goal of this work.

Research by Oraby et al. addressed vibration parameter optimization in Vibroseismic applications [12]. The paper covered the necessity of optimizing the vibration's frequency, amplitude, and duration (time) when applied to two distinct sets of cores (synthetic and field cores). The principal objective of this publication was to present the respective optimum vibration parameters for every kind of core and illustrate the impact that implementing the optimized vibration parameters would have on the core. The effect was presented through the changes in porosity, absolute permeability, and damage removal by Oraby et al. [12]. What was new in the research conducted by the authors of the paper was the inclusion of the time factor of applying the Vibroseismic on each of the types of cores. The paper was able to show that the optimized vibration when applied on both types of cores that it would improve the porosity, absolute permeability and reduce the core damage.

Beresnev and Johnson investigated the influence of wave excitation on fluid mobility and permeability in porous saturated formations [4]. The summarized laboratory tests demonstrated that applying vibration to saturated rock samples increased oil permeability and mobility. The increased mobility was due to a variety of factors, including decreased oil viscosity, increased percolation rates, and reduced capillary pressures. Furthermore, they provided a 6-hour experiment at low frequencies of 30, 50, and 60 Hz that demonstrated that the mobility of oil increased while the mobility of water decreased. The results of the field tests were consistent with those of the experiment; however, because the number of field tests undertaken was restricted, the data became insufficient to make a decisive conclusion.

Mohammadian et al. investigated the influence of an ultrasonic wave on oil recovery as well as the possible processes when waterflooding is applied [10]. Two separate types of generators were used, one with a power range of 100-500 watts and the other with a power range of 110 watts, both running at a frequency of 40 KHz. Brine was added to a sand pack having an initial porosity of 30-34 percent and a permeability of 4 Darcy. Two further tests were carried out to demonstrate the temperature and pressure changes caused by the ultrasonic wave. The most important processes for improved recovery were viscosity reduction owing to temperature rise and emulsification due to pore pressure increase.

Nikolaevskiy demonstrated that vibration improves oil recovery by restoring permeability [11]. The author proposed that in a real-world environment, this may be accomplished by vibrating from the surface and continuing production at precise, optimal vibrational frequencies that are unique to each type of formation. Due to their short wavelengths, the ultrasonic vibrations produced by low frequency seismic waves were discovered to have an effect on the little oil droplet. Furthermore, the vibration of the oil droplets redistributes the two phases of water and oil inside the pores, making oil production simpler.

Research conducted in Nigeria by Abdulfatah aimed at showing the improvements in fluid properties of traditional waterflooding compared to waterflooding coupled with ultrasonic application [1]. The experimental section of the research included applying classical waterflooding to an oil sample from a local field, Niger Delta with a range of frequencies ranging from 24 to 54 KHz. The simulation part was used for performance prediction with MATLAB models to analyze the results. The results of both portions of the work shows an improvement in the critical oil saturation of 0.09 which is equivalent to approximately of 25 percent. The ultrasound application also lowered the connate water saturation to 0.27 at a relative permeability of 1 which entails that the waterflooding as exceedingly effective which connects to the 50 percent rise in oil recovery.

The first true understanding of how Vibroseismic waves effect the enhancement of both rock and fluid features was conducted by Ariadji [3]. The research conducted the first production forecast research in a lab environment or through reservoir modelling on the impact of seismic waves on oil-containing strata. Ariadji gave a case study of a prior pilot that indicated favorable findings with a rise in field output, in addition to a range of research that all point in the direction that the seismic waves would improve the rock and fluid properties in turn. Ariadji was also the first to study the optimization of frequency and amplitude parameters for various core types, demonstrating that increases outside of or prior to this range were unimportant.

Studies have been conducted to determine how permeability and porosity are impacted by earthquake periods. Numerical model simulators and a "spring-slider dashpot model" were used to conduct the experiment by Bizzarri [6]. The goal of this model is to statistically represent the whole seismic wave cycle, or "earthquake wave," and its interaction with the rock, or more specifically, faults. The permeability variations in the rock have an impact on both the "rheology of the fault" and earthquake recurrence time (which regulates both rock stiffness and capacity to store elastic energy). Furthermore, it has been discovered that, when compared to porosity changes, permeability changes have a far higher influence on both hydraulic diffusivity and seismic instability.

One of the first theories for how production might increase as a result of momentary stress is the concept of colloidal mobilization was discussed by Manga et al. [9]. "Colloidal deposition," which happens as a result of the filtration process caused by the colloids flowing through the rock pores, lowers permeability. Permeability will increase, however, if these colloids are mobilized as opposed to deposited as described by the author. Utilizing low-frequency stimulation with frequency ranges of 26 to 150 hertz have clearly shown the same outcomes as better mobilization of deposited colloids inside the pores as well as improved transit of fines or colloids via the pore structures. The oscillation wave generates an extra force inside the pores known as the "inertial body" with an oscillating force and a defined amplitude. Additionally, it has been discovered that when wave frequency increases, the value of the "mobilizing acceleration amplitude" increases as well; therefore, the mobilization of droplets increases with wave frequency while decreasing with wave amplitude. The primary causes of an increase in permeability are fractures and the gradual depressurization of the pore system, which together cause the delayed recovery of permeability.

Roberts et al. showed that low frequency seismic wave generation from the surface produces the best results, allowing other researchers to continue to investigate this notion [13]. Changes in the pore pressure are brought about by applying 25 Hz at an amplitude of 150 psi, which then results in an increase in fluid pressure. One of the explanations was an increase in the capacity of oil to pass through pores previously occupied with brine. Pressure will increase as a result of the high viscosity of the oil and the increase in its relative mobility to water. It was found that the vibration that takes place during waterflooding increases the output of water while lowering the output of oil. The field testing results in a 20% increase in production.

It was shown by Zhang et al. that vibration can increase the flow velocity of fluids inside the formation because of an increase in the differential pressure in the oil layer and a decrease in the interfacial tension between the water and oil phases [16]. The concept of fluid redistribution during gas discharge has also been found to exist; redistribution occurs as a result of density variations that promote oil production.

Additionally, the stress wave created by the propagation of the vibration wave may cause micro-fractures, and the stress relaxation on the rock grains enhances permeability. Furthermore, vibration can reduce the interfacial tension between the grain surface inside the pores and the remaining oil in the system, depending on the frequency used. This would affect both the relative permeability and capillary pressure curves, which would be advantageous for oil production.

Lockner and Beeler proved that earthquakes work in the same way as Vibroseismic techniques in affecting rocks by releasing stored elastic energy [8]. If fault strength threshold is reduced this causes stored elastic energy to be sent out as seismic waves leading to decrease in net stress of the area and increase the pore pressure. Tested on carbonate core with frequency of 10 Hz and several amplitudes and concluded frequency has a more influential effect on changes in formation properties than amplitude.

Boeut et. al researched the influence that a transient disturbance would have on permeability variation [5]. Applied transient disturbance at 0.5 Hz frequency, amplitude of 11 MPa and for 200 seconds at 3 confining pressures on both intact and fractured Kushiro Cretaceous sandstone and Shikotsu welded tuff. For intact cores, increase in confining pressure reduced the permeability. However, for fractured cores, not affected by increase confining pressure but by increasing transient disturbance power. It was concluded that higher pore pressures found for intact sandstone with the opposite for fractured sandstone. Stress disturbances had an increasing and decreasing effect on the permeability but the duration of applying the disturbance was differentiating factor.

Kitamura et al. tried to find a relationship between Poisson’s ratio and permeability in areas around faults where a seismic wave was applied [7]. Cores were obtained from fault zone at 2 different depths with different silt content and grain diameters ranging from 40 to 160 micro-meters. Seismic velocity measurements were made by a device that simulates required confining pressures and pore pressures. Found for silty-sandstone and sandstone with mainly fine grains, the controlling factor on permeability was the clay content and degree of sorting. Sandstones with well-sorted grains had small permeability variations. Permeability and Poisson's ratio both increase with an increase in pore pressure.

Sitompul documented the most recent use in Indonesia's Tempino Field [15]. Vibroseismic was found to be a beneficial technology as it is: cost-effective; does not require large capital and operational obligations; has rapid production effect; environmentally friendly; and can be easily relocated. Lab studies were performed and found that optimum frequency was 20 Hz in both regions 1 and 2. In region 1, production increased by 14% for 6 weeks and over 4 months period oil rate peaked at 50 BOPD more than initial (around 30% increase). Similarly, in region 2, over 4 months production altered from 39 to 48 BOPD equating to 23% increase.

An investigation was performed on the ability of ultrasound waves in mobilizing higher oil recovery by Alhomadhi et al. [2] To do this, an experimental approach was used where core flooding was done in two different dimensions both horizontally and vertically. In order to see the actual effect of the ultrasound waves, oil/water relative permeability was done before and after the ultrasound waves as well as the total oil recovery to measure the waterflooding performance. The core type used for the consolidated section of this investigation was Berea sandstone and the oil used throughout this experiment is Saudi Arabian crude oil (Arabian light) with viscosity between 13 to 16 cp and an API gravity of 31.2°. The ultrasonic wave generated for this experiment at an elevated frequency at 50 kHz and power of 300 watts applied in two ways either by several short pulses of a few minutes per pulse or by continuous waves. For the horizontal core floods, the wave stimulation allowed an increase in the total recovered original oil in place from 54 to 59 percent. Improvements of relative permeability in the case of ultrasonic waves application is clear at water saturations higher than 60 percent of the total pore volume. In vertical core floods, the presence of the wave also increased the total oil recovery from 49.9 percent to 58 percent. the maximum improvement in oil recovery occurred in the intermittent cycled wave stimulation as the level of oil separation in the pores was reduced.

Salem and Snousy performed research on the notion of how the ultrasonic vibrational energy affected the redistribution of water and oil in the pore space [14]. This concept was put to the test in actual scenarios where vibration was utilized to halt the distribution of both oil and water during the water pumping phase of a flooded reservoir. These results unambiguously show that the application of ultrasonic waves can alter the relative permeability curves of the two phases by causing mild seismic wave amplitude vibration. Seismic waves that move the grain in a way that provides the required ultrasound waves can be used to generate these ultrasonic waves. A number of field trials were presented for approval by the study.

2. The Experimental Methodology

In this paper, the lab experiments were conducted using the same optimized physical parameters that was found by Oraby et al., (2022). This is because the cores that were used in the experiments conducted in the first paper by Oraby et al. are also of the same kind that were used for this experiment. Furthermore, the same setup also used in the paper by Oraby et al. will also be used in this research. This would thus entail that the optimized parameters that were found in the paper by Oraby et al. would apply to this research.

2.1. Core Preparation

For this lab research, the cores that will be tested are synthetic outcrop cores that are of the same nature as the ones that were used in the prior paper. The cores were cut from different blocks of several outcrop rocks in order to have a wider variety of initial rock parameters. All of the cores were cut with the same diameter of 1 inch. Table 1 provides the initial data of the 5 cores that were used throughout the entire experimentation phase. The data was measured after the cores were cut, sanded, cleaned and dried.

Table 1. *Core Data at Initial Stage Before Vibration.*

Sample No.	Length (cm)	Liquid Absolute Permeability (md)	Porosity (Porosity Unit – pu)
1	7.62	55.08	26.45
2	7.10	357.24	32.91
3	7.19	880.44	33.13
4	7.31	1218.96	30.95
5	7.59	55.32	28.60

The cores that were tested had 3 different categories of porosity and absolute permeability data to ensure as much variation in the cores tested as possible. The porosities of the cores were somewhat similar which is due to the nature of the cores being outcrop cores; however, the differences in the absolute permeability are sufficient. The absolute permeabilities tested have range from relatively lower absolute permeabilities of around 50 md to mid-range absolute permeabilities of around 350 md to much higher absolute permeabilities of 880 md and above.

The next step was to saturate the cores using brine water for 1 week in order to ensure that the cores become fully saturated and ready for testing. The brine prepared had a salt concentration of 35,000 ppm with table 2 providing the required data on the brine needed for later calculations of the relative permeability curves.

Table 2. *Brine Properties.*

Water Properties	Value
Salinity (ppm)	35,000
Density (g/cc)	1.11
Viscosity (cP)	1.12

2.2. Relative Permeability Measurement

The cores had their relative permeability measured twice throughout the entire research. The first time was after the brine saturation was completed for one week to obtain the initial relative permeability data and the second time was performed after the optimized physical vibration parameters from the paper by Oraby et al. [12] was applied using the same setup as the paper also. The relative permeability measurements were also done in order to obtain the oil recovery values before and after optimized physical vibration being applied.

Before both times, the cores were saturated with a paraffin oil until the residual water saturation was reached and then the cores were saturated with the same brine as in table 2. The relative permeability was calculated using the unsteady state method and had an applied confining pressure between 700 psi and 1000 psi for all cores. Table 3 provides the relevant data of the synthetic paraffin oil used for the relative permeability testing.

Table 3. *Synthetic Paraffin Oil Properties.*

Paraffin Oil Properties	Value
Density (g/cc)	0.83
Viscosity (cP)	52.56

2.3. Experiment Setup

The experimental setup that was used, based on the paper mentioned before, used voltage regulated DC motor which provided the mechanical power of the entire apparatus. A rotor was then connected to the DC motor in order to rotate the specially designed disc at the end of the rotor which allows for the vibration to occur. The rotating disc comes in contact with the vibrating plate on which the core holders with the cores inside are kept while the device is in operation. The setup of the experiment is shown in figure 1.

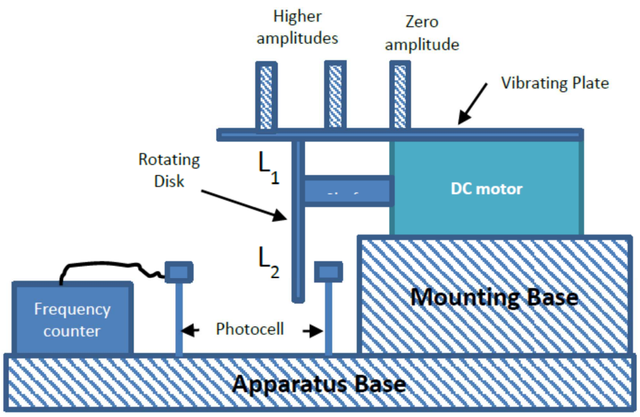

Figure 1. *Schematic of Vibration Tool.*

The voltage regulated DC motor controls the frequency at which the specially designed rotating disc applies the vibration to the vibrating plate. The photocells provide the number of rotations from which the frequency at each voltage of the voltage regulator can be found.

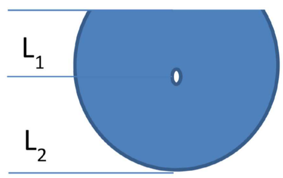

Figure 2. *Schematic of Rotating Disk.*

The special design of the rotating disc is the idea of the chopped section of the disc as can be seen in figure 2. The chopped section causes the vibrating plate to suddenly drop which causes the vibration of the vibrating plate. The amplitude of the vibrating plate is controlled by the difference in distance between end of the vibrating plate and the middle of the rotor with no chopped section (L2) and the end of the vibrating plate and the middle of the rotor with chopped section (L1). The difference in amplitudes can be seen in figure 3.

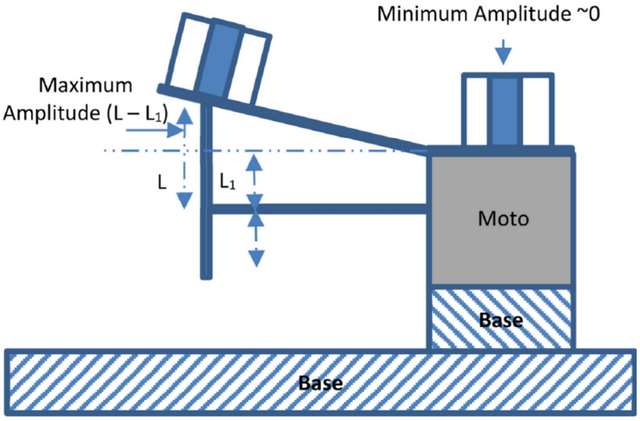

Figure 3. *Schematic of Amplitude Difference Along Vibrating Plate.*

Vibration Parameters and Experimental Steps

The optimized parameters for the types of cores that are used in this research and according to the paper done by Oraby et al. (2022) are as follows

1) Frequency of 10 Hz (which equates to 600 rotation per minute by the DC motor)
2) Amplitude of 4 mm
3) Duration of 15 minutes

The experimental procedures for this experimental research are as follows

1) Cut, sand, clean, and dry samples
2) Measure sample dimensions and dry weight
3) Measure sample porosity
4) Saturate all cores using prepared brine for 1 week
5) Measure liquid absolute permeability
6) Saturate cores using synthetic paraffin oil until residual water saturation is reached
7) Measure relative permeability before vibration by injecting prepared brine until residual oil saturation is reached
8) Clean and dry core
9) Re-saturate core with prepared brine for 1 week
10) Re-measure liquid absolute permeability
11) Perform vibration on each core using optimized vibration parameters
12) Saturate cores using synthetic paraffin oil until residual water saturation is reached
13) Measure relative permeability after vibration by injecting prepared brine until residual oil saturation is reached
14) Re-measure sample porosity

3. Results

3.1. Changes in Rock Properties

The application of the Vibroseismic application on the enhancement of the oil production starts with the improvement of the rock properties. The rock properties that were measured for this research is the absolute permeability and the effective porosity. Table 4 will present the percentage change of each parameter due to the application of the optimized Vibroseismic parameters.

Table 4. *Percentage Change of Permeability and Porosity.*

Sample No.	% Change of Permeability	% Change of Porosity
1	8.67	5.81
2	38.34	0.46
3	62.02	2.48
4	28.51	3.01
5	33.33	-6.64

From table 4, it is clear that optimized vibration parameters have clearly improved the rock properties of all of the cores. The only exception is the porosity of core 5 which decreased by just under 7%.

The values of the increase in permeability are somewhat higher than typical due to the nature of the cores being surface cores. As these cores have not been under any stress causing the easy movement of the grains. This theory would also explain the exaggerated increase in porosity of some of the cores as well.

3.2. Changes in Relative Permeability (Rock-Fluid)

The application of the optimized Vibroseismic parameters did not only improve the rock properties of permeability and porosity, but has also improved the rock-fluid properties of the cores in terms of the relative permeability. This can be seen through the difference in the relative permeability curves before and after physical vibration as well as other parameters. Table 5 will present the relative permeability data found before and after the optimized physical vibration.

Table 5. *Summary of Relative Permeability Curves Before and After Vibration.*

Sample No.	Initial S_{wi} (%)	Final S_{wi} After Vibration (%)	Initial S_{or} (%)	Final S_{or} After Vibration (%)
1	55.43	33.19	55.02	51.22
2	18.18	12.16	40.56	33.94
3	25.47	34.53	49.14	46.41
4	22.16	37.03	56.84	42.19
5	24.19	26.37	46.08	26.56

In all of the cores there is a reduction in the residual oil saturation which would further confirm the point that the optimized physical vibration would cause the core to become more water-wet and would thus enhance the oil recovery when waterflooding is applied to it in comparison to just the conventional waterflooding being applied. When focusing on cores 2 and 4, it can be seen that there is a reduction in residual oil saturation after vibration of 6.62% and 14.65% respectively.

3.3. Oil Recovery

In order to best show the effect of the optimized physical vibration on waterflooding application, the oil recovery was calculated according to the relative permeability curves. Table 6 will present the differences in oil recovery before and after vibration was applied to all of the cores.

Table 6. *Oil Recovery of Cores Before and After Vibration.*

Sample No.	Initial Oil Recovery (%)	Final Oil Recovery After Vibration (%)	Diff. Recovery
1	44.8	51.22	6.42
2	59.44	66.06	6.62
3	50.86	53.58	2.72
4	43.16	57.81	14.65
5	53.92	73.44	19.52

It can be seen that all of the cores had an increase in oil recovery after the vibration which would be explained by higher absolute permeability, porosity, and relative permeability (more water-wet) after optimized physical vibration and waterflooding were applied.

Core 5 could be considered an anomaly to the other 4 cores as it had the much higher reduction in residual oil saturation and thus the highest increase in oil recovery which could not be backed up with low absolute permeability or porosity of the core itself.

4. Conclusions

Based on the data collected of the porosity, absolute permeability, relative permeability, and oil recovery before and after the optimized physical vibration was applied and coupled with the conventional waterflooding, the following conclusions can be drawn

1) There is an overall improvement in the rock properties of the cores in terms of absolute permeability and effective porosity.
2) The relative permeability has clearly been improved in the cores with positive deviation of the intersection points of the curves.
3) There is an increase in the oil recovery of the cores when waterflooding is coupled with optimized physical vibration.

Ethical Statement

The author hereby confirms abiding with all ethics including copy rights, trademarks, commercial statements, … etc.

Conflicts of Interest

The authors declare no conflicts of interest.

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