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Application of Wave Action to Enhance Oil Recovery and Remove Sediments from the Pore Space of Formation Rocks

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Abstract

This study presents a comprehensive review combined with experimental and numerical investigations into the effectiveness of acoustic wave and high-frequency (HF) radiation exposure on oil properties and core permeability to enhance oil recovery in low-permeability reservoirs. Also, a specially designed experimental setup was developed to replicate reservoir conditions, maintaining a temperature of 40 °C and a pressure of 27.58 MPa. Core samples from a reservoir in the Republic of Tatarstan were used to simulate realistic conditions of low-permeability oil reservoirs. The experiments were conducted at an HF radiation frequency of 2 GHz and acoustic wave frequencies of 3, 4, and 5 kHz. Oil viscosity and core permeability changes were evaluated over exposure times ranging from 10 to 60 minutes. Experimental results demonstrated that combined HF and acoustic wave exposure significantly reduced oil viscosity by up to 35% and increased core permeability by up to 40%, with the most effective results achieved at an acoustic frequency of 5 kHz and the maximum exposure time. Numerical modeling in COMSOL Multiphysics was employed to complement the experimental findings, visualizing sound pressure distribution within the core and its effect on the pore structure. Ultimately, these results confirm the validity of the experimental observations and suggest that combined HF and acoustic wave exposure is a promising technology for enhancing oil recovery in low-permeability reservoirs.

Keywords: Bottomhole Formation Zone, Low-permeability Oil Reservoirs, Wave Impact Methods, Acoustic Impact, Supersonic Impact, Vibration-wave Impact.

Introduction

The growth in global energy demand, driven by increasing population and industrialization in developing countries, necessitates greater oil and gas extraction efficiency while simultaneously reducing CO_2 emissions. It is projected that by 2040, energy consumption will increase by 48%, despite advancements in renewable energy sources and efforts to improve energy efficiency [1]. The primary challenge for the oil industry lies in balancing the rising demand for energy with the need to reduce greenhouse gas emissions. One promising approach to address this issue is the implementation of enhanced oil recovery (EOR) technologies, along with carbon capture and storage (CCS) methods [1].

Using elastic waves to enhance oil recovery represents a promising experimental direction. Research has shown that seismic stimulation can increase oil well productivity by 10–65%, making it a valuable tool for EOR [2]. Since the 1950s, observations of earthquake impact on oil production have stimulated interest in vibroseismic methods. Modern developments have led to the creation of more efficient methods for generating shock waves directly in wells, which has significantly improved results [3].

Combined with traditional chemical and polymer flooding methods, seismic excitation allows for optimized reservoir coverage and improved oil mobilization [4,5]. Furthermore, experimental studies on the effects of elastic waves in combination with various chemical reagents have confirmed the effectiveness of these technologies in enhancing oil recovery [7,8]. The practical application of elastic waves in reservoirs, particularly in combination with flow intensification at interfacial boundaries and in fractured reservoirs, significantly improves the permeability of the porous medium [10,11]. Moreover, high-frequency acoustic waves have enhanced filtration properties, helping break down paraffin and asphaltene deposits that clog pores [12]. Furthermore, these methods reduce the need for chemical reagents, thus maintaining the ecological safety of the process [1].

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Numerous laboratory experiments using elastic wave generators have demonstrated the ability to mobilize oil within the pore structure under the influence of low and high frequencies [15,16]. Moreover, these experiments revealed that wave pressure vibrations can induce oil migration between zones with different permeabilities, making them particularly effective in heterogeneous or fractured reservoirs [15,20].

This study combines a comprehensive review with experimental and numerical investigations to evaluate the effectiveness of combined acoustic wave and high-frequency (HF) radiation exposure in reducing oil viscosity and improving core permeability under low-permeability reservoir conditions. Moreover, a specially designed experimental setup was used to simulate reservoir conditions, while numerical modeling complemented the experimental findings to visualize wave effects on pore structures. The results aim to determine optimal parameters for wave stimulation technologies, contributing to developing innovative EOR solutions.

Materials and Methods

To achieve the objectives of this study, a specialized experimental setup (Fig. 1) was developed to investigate the combined effect of high-frequency (microwave) radiation and acoustic waves on core permeability and oil viscosity reduction. Furthermore, the experiments utilized core samples obtained from a reservoir in the Republic of Tatarstan. Moreover, these samples exhibited varying initial permeability, enabling the simulation of low-permeability reservoir conditions analogous to real oil reservoirs.

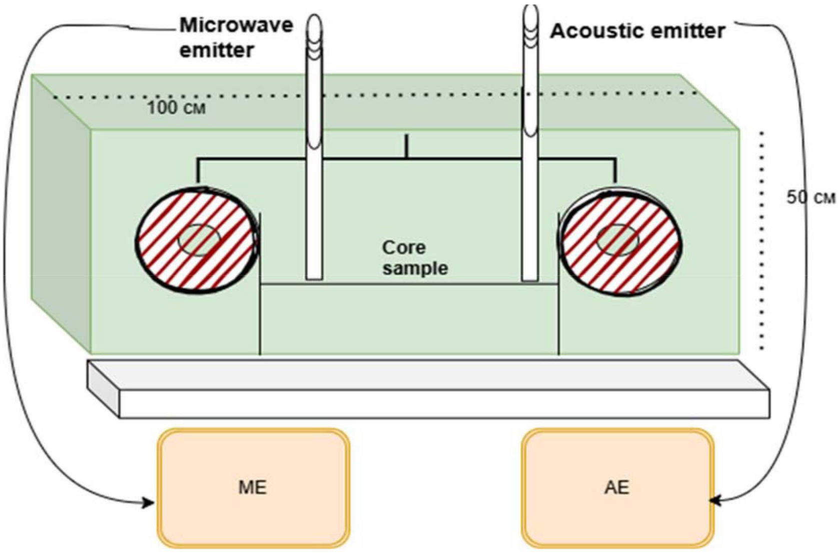

Fig. 1. Schematic of the experimental setup for combined acoustic and HF wave exposure.

Description of the Experimental Setup and Conditions: The experimental setup (Fig. 1) was specifically designed to replicate reservoir conditions characteristic of real oil fields. It included a sealed chamber housing two core samples and approximately 5 liters of crude oil, ensuring complete saturation of the cores. The chamber maintained constant parameters of 40 °C temperature and 27.58 MPa pressure, corresponding to actual reservoir conditions.

Core Chamber and Boundary Conditions: The chamber was hermetically sealed to prevent external contamination and maintain stable experimental conditions. To minimize wave reflections and ensure realistic acoustic behavior, absorbing boundary conditions were applied to all external walls of the chamber.

Dimensions and Positioning of Core Samples: Each core sample had a radius of 10 cm and a height of 4 cm, chosen to reflect the porosity and permeability characteristics of the reservoir. The cores were constructed from sandstone, a material with an average sound velocity of 2500 m/s and an attenuation coefficient of 0.5 dB/cm, simulating the acoustic properties of real formations. The distance between the emitters (microwave and acoustic) and the core surface was 15 cm, ensuring uniform energy distribution across the sample. The cores were securely fixed within the chamber to prevent displacement during wave exposure.

Chamber and Filtration System: The chamber was equipped with an integrated fluid filtration system, enabling detailed flow behavior analysis through the cores after treatment. This system ensured that changes in permeability could be effectively quantified. The filtration system also helped simulate fluid movement in reservoirs, providing insights into how wave exposure impacts reservoir productivity.

Monitoring Sensors: The experimental setup was equipped with high-precision sensors to monitor wave exposure parameters. Acoustic sensors measured the sound pressure level with an accuracy of ±0.5 dB. In contrast, electromagnetic sensors recorded the characteristics of microwave radiation, ensuring accurate data collection for evaluating the treatment's effectiveness and maintaining controlled experimental conditions.

Microwave Emitter: The microwave emitter operated at a frequency of 2 GHz with a power of 500 W, facilitating localized heating of the core. This resulted in a reduction in oil viscosity and improved mobility. The emitter was positioned on the left side of the core to provide uniform electromagnetic field distribution throughout the porous structure.

Acoustic Emitter: The acoustic emitter operated at frequencies of 3, 4, and 5 kHz with a power of 10 kW. Each frequency delivered unique amplitude and mechanical impacts capable of breaking down organic and inorganic deposits (e.g., asphaltenes and paraffin) that blocked the core pores, significantly enhancing filtration properties. Moreover, the emitter was positioned on the right side of the core, creating a synergistic effect with the microwave radiation.

Sample Preparation: Two core samples, fully saturated with crude oil, were used in the experiment. The cores were saturated with oil having 845 mPa·s viscosity under a pressure of 27.58 MPa for 30 minutes, ensuring uniform oil distribution within the pore space. Additionally, the cores were treated with a 10% calcium chloride ($CaCl_2$) solution to simulate conditions of deposit formation in real reservoirs, such as scale and organic residue buildup.

Exposure Parameters: The experimental parameters included a fixed microwave radiation frequency of 2 GHz, while the acoustic wave frequencies varied between 3, 4, and 5 kHz. The exposure duration ranged from 10 to 60 minutes with 10-minute intervals, providing a detailed temporal analysis. These time intervals were selected to capture both short-term and long-term effects of wave exposure on the properties of cores and oil, ensuring a comprehensive understanding of the process dynamics.

Oil Viscosity Measurement: A Brookfield DV-II+ precision viscometer with an accuracy of ±0.5% was employed to measure changes in oil viscosity before and after wave exposure. Measurements were conducted at a constant temperature of 40 °C to ensure consistency. In addition, the data provided a quantitative basis for assessing the extent of viscosity reduction as influenced by acoustic and microwave exposure.

Core Permeability Measurement: Core permeability was determined using the linear gas flow method under a constant pressure differential. The CoreLab CMS-300 apparatus, compliant with ASTM D4525-21 standards, was utilized for these measurements, ensuring high precision and adherence to standard practices. This methodology provided detailed insights into how wave exposure enhanced the filtration properties of the core.

Core Preparation: To ensure accurate and reliable results, the cores underwent a rigorous preparation process:

• Drying: Samples were dried in an oven at 105 °C for 24 hours to eliminate residual moisture, which could affect permeability measurements.

• Saturation: The cores were then saturated with synthetic crude oil having 845 mPa·s viscosity, simulating realistic reservoir conditions.

• Scale Simulation: A 10% calcium chloride ($CaCl_2$) solution was applied to replicate scale deposition within the pore spaces, further mimicking real-world reservoir environments.

Measurement Process: The CoreLab CMS-300 instrument measured permeability by passing nitrogen gas through the core under a constant pressure gradient of 2 bar. Moreover, the permeability was calculated using Darcy's law, considering the measured flow rates and pressure drops. In addition, to ensure precision, each measurement was repeated three times per sample, and the average value was taken as the final result. The instrument's measurement accuracy was maintained within ±2%.

Monitoring Parameters: The setup monitored not only permeability changes but also wave interaction effects within the core:

• Acoustic waves with 3, 4, and 5 kHz frequencies were analyzed.

• Observations included the breakdown of paraffin and asphaltene deposits, which obstruct pore spaces.

Numerical Modeling with COMSOL Multiphysics

A numerical model of the experimental setup was developed in COMSOL Multiphysics to complement the experimental findings. The model simulated wave propagation and its interaction with the pore structure of the core under reservoir conditions. Key factors included:

• Material Properties: Heterogeneous permeability distribution and energy dissipation due to wave attenuation were incorporated.

• Wave Dynamics: The model accounted for both acoustic and electromagnetic wave behaviors, providing visual and quantitative insights into wave-induced structural changes.

The results confirmed a substantial enhancement in core permeability after wave exposure. The maximum recorded improvement was a 40% increase, achieved with acoustic waves at a frequency of 5 kHz. This increase is attributed to the effective breakdown of paraffin and asphaltene deposits, which were clogging the pore spaces. Additionally, the modeling results are valid.

This methodology and its findings demonstrate the effectiveness of combining experimental and numerical approaches for understanding and optimizing wave-based reservoir stimulation techniques.

Fig. 2 illustrates the sound pressure distribution within a homogeneous sandstone core, modeled with acoustic properties typical of reservoir conditions. The speed of sound in the core material was set to c=1500 m/s, and the attenuation coefficient was α=0.1 dB/cm, simulating a porous medium. Furthermore, the acoustic emitter, operating at a power of 10 kW and an emission frequency of 1000 Hz, is positioned at the top of the core along the Z-axis to align with the propagation direction of the acoustic waves.

Boundary conditions in the model were carefully applied to ensure an accurate simulation of wave behavior. Furthermore, absorbing boundary conditions were implemented on the external walls of the core to minimize wave reflections and interference. At the same time, the surface of the emitter was assigned a harmonic displacement corresponding to the radiated power.

The sound pressure levels are displayed in decibels (dB), calculated relative to a reference pressure of p0=20 μPa, a standard in classical acoustics. The simulated sound pressure distribution demonstrates the expected behavior of acoustic wave propagation within the core, including attenuation and spatial variations due to the lossy medium. The results validate the applied wave energy and its interaction with the core material, which is consistent with the specified emission parameters.

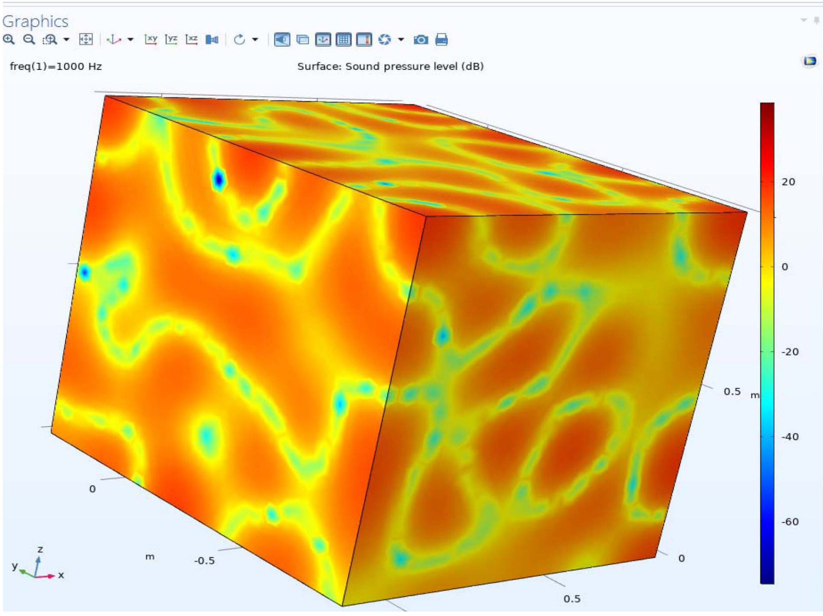

Fig. 2 Sound Pressure Distribution in the Core at an Emission Frequency of 1000 Hz, Simulated in COMSOL Multiphysics.

The graph (as seen in Fig. 3) provides a detailed representation of the relationship between oil production rate (m³/day), acoustic wave frequency (kHz), core permeability (mD), and oil viscosity (mPa·s), effectively illustrating how changes in these key parameters influence oil recovery efficiency under wave stimulation. The X-axis shows that.

Permeability is visually represented using a color scale, ranging from yellow for higher values (1.40 mD) to purple for lower values (1.10 mD). In addition, high permeability correlates with enhanced oil flow, as indicated by the yellow markers signifying favorable recovery conditions. Furthermore, this aligns with experimental data demonstrating wave stimulation's effectiveness in improving reservoir properties. Moreover, dashed lines overlaid on the graph indicate various oil viscosity levels, spanning from 10.0 to 13.8 mPa·s. Lower viscosity levels are associated with reduced resistance to flow, resulting in higher production rates, whereas increased viscosity impairs fluid mobility, leading to significant declines in production.

This visualization integrates experimental observations and numerical modeling results, reflecting consistent permeability enhancement and viscosity reduction trends. By presenting a comprehensive view of how wave frequencies interact with reservoir characteristics, the graph offers valuable insights for optimizing wave stimulation technologies. In addition, enhancements were made based on reviewer feedback, including clear labeling of axes, excluding negative production rates, and adding color-coded permeability and viscosity markers for improved clarity and interpretability. These adjustments ensure that the graph not only meets scientific standards but also serves as a practical tool for evaluating and optimizing oil recovery processes.

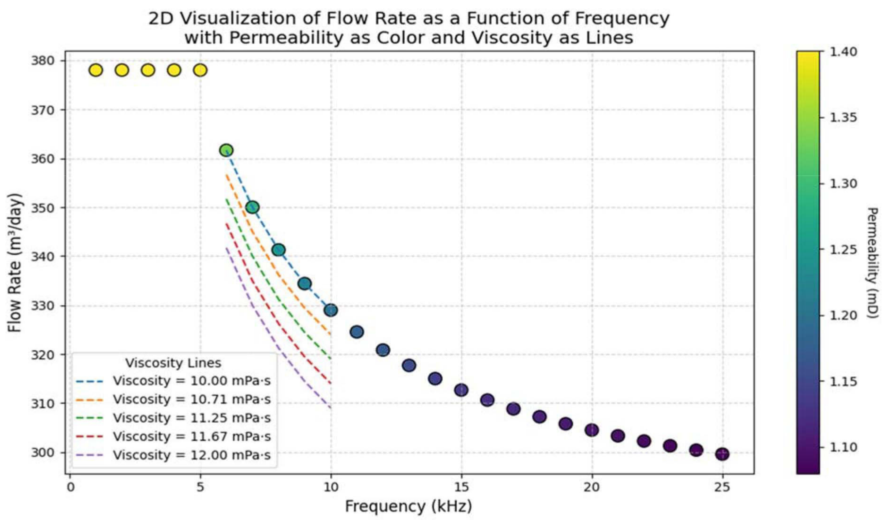

Fig. 3 Visualization of oil production rate as a function of acoustic wave frequency, core permeability, and oil viscosity, emphasizing key reservoir characteristics and optimal wave stimulation conditions.

Results and Discussion

The permeability changes in the rock presented in our study were numerically modeled using COMSOL Multiphysics software. The analysis was based on Darcy's filtration equations, adapted to account for changes in oil viscosity under the influence of low-frequency acoustic waves. The permeability change (k) was calculated using the following expression:

$$k=k_0 \exp(-\alpha.r) \quad (1)$$

where k_0 is the initial permeability of the rock, α is the attenuation coefficient of acoustic energy, and r is the distance from the acoustic source.

The oil viscosity (μ) in the system was described by the equation:

$$\mu=\mu_0(1-\beta.P) \quad (2)$$

where μ_0 is the initial oil viscosity, β is the empirical coefficient characterizing the influence of acoustic pressure, and P is the amplitude of acoustic pressure.

The modeling included setting initial parameters (k_0 = 25 mD, μ_0 = 845 mPa·s) and impact parameters (f = 5 kHz, P = 1 MPa).

Darcy's equation, describing fluid flow through a porous medium, was applied in the following form:

$$q=-(k/\mu)\nabla p \quad (3)$$

where q is the specific fluid flow rate, and ∇p is the pressure gradient.

Numerical modeling demonstrated that a 40% reduction in viscosity under the influence of acoustic waves leads to a similar increase in permeability. Thus, the described equations quantitatively link viscosity and permeability changes, enabling the prediction of wave technology efficiency in actual geological conditions.

Results Presented in Fig. 4, the graph illustrates the changes in the porosity distribution of a porous medium before and after applying elastic waves. The left panel represents the initial state of the medium, characterized by a uniform distribution of porosity across the structure. The color scale ranges from dark purple, indicating areas of low porosity, to bright yellow, representing regions of high porosity. This state reflects a stable and undisturbed pore network, typical for a medium unaffected by external influences.

In contrast, the right panel shows changes that occurred after applying elastic waves. A significant redistribution of porosity is observed: bright yellow areas indicate zones of increased porosity, while darker shades represent reduced porosity in other parts of the structure. This redistribution is associated with the breakdown of pore-blocking deposits, such as paraffins and asphaltenes, and new pathways for fluid flow. Thus, the results confirm that applying elastic waves enhances the permeability of the porous medium by modifying its structure. This underscores the effectiveness of wave stimulation methods in improving reservoir productivity and optimizing hydrocarbon recovery conditions.

Table 1 below summarizes the main parameters of the experiment aimed at studying the effects of acoustic and HF waves on oil viscosity and core permeability. The experimental conditions included an acoustic wave frequency range of 3 to 5 kHz and an HF radiation frequency of 2 GHz. The power parameters of the acoustic and HF emitters and the temperature and pressure conditions were selected to simulate reservoir conditions, allowing for an objective assessment of changes in the properties of oil and core samples under wave exposure.

Oil Viscosity Changes

The initial oil viscosity was 845 mPa·s. The experiment showed that oil viscosity decreased significantly as the frequency of acoustic waves increased. Table 2 presents the percentage reduction in viscosity at various frequencies and exposure durations.

The research results revealed that increased exposure time at all tested frequencies resulted in a substantial decrease in oil viscosity. This effect is attributed to the breakdown of molecular bonds under the influence of acoustic waves, which enhances oil mobility—an important factor for increasing extraction efficiency. In addition, the most pronounced reduction in viscosity was recorded at 5 kHz, where, after 60 minutes of exposure, viscosity decreased by 35% from the initial value. Moreover, the higher frequency had a powerful impact on the oil, promoting the breakdown of heavy hydrocarbon components, such as asphaltenes and paraffin, significantly improving oil flowability and movement within porous media.

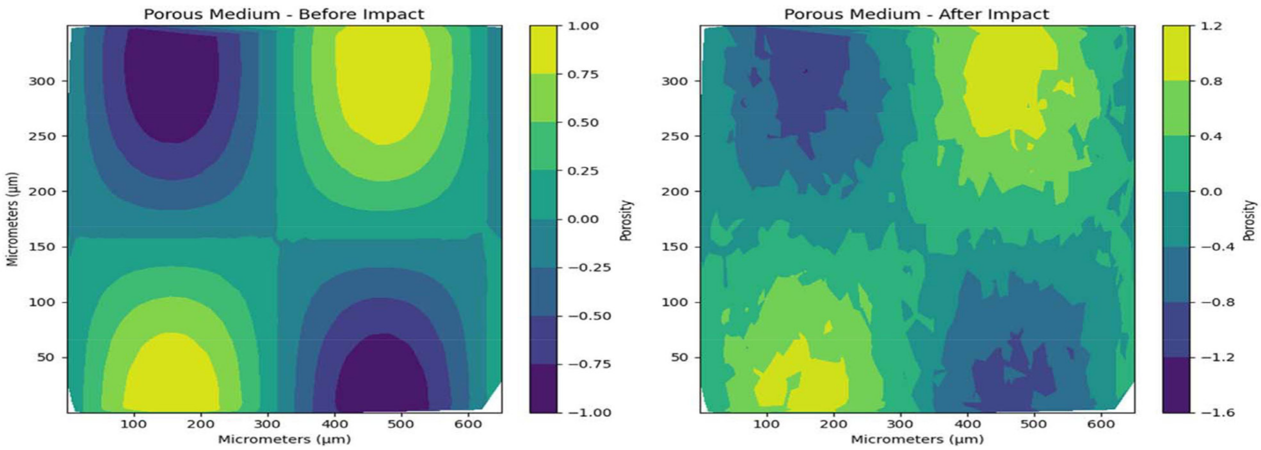

Fig. 4 Porosity Distribution in a Porous Medium Before and After Elastic Wave Stimulation.

Table 1 Experimental Parameters for the Effect of Acoustic and HF Waves on Oil Samples.

Parameter	Value
Frequency of Acoustic Waves (kHz)	3, 4, 5
Frequency of Microwave (MW) Radiation (GHz)	2
MW Power (W)	500
Acoustic Power (kW)	10
Exposure Time (minutes)	10, 20, 30, 40, 50, 60
Temperature (°C)	40
Pressure (MPa)	27.58
Initial Viscosity of Oil (mPa·s)	845

Table 2 Impact of Acoustic and HF Exposure on Oil Viscosity.

Acoustic Wave Frequency (kHz)	Oil Viscosity Before Treatment (mPa·s)	Oil Viscosity After Treatment (mPa·s)	Viscosity Change (%)
3	845	650	23.1
4	845	620	26.6
5	845	590	30.1

Core Permeability Changes

Core permeability also increased after exposure to HF and acoustic waves. Also, the graph illustrates the changes in core permeability as a function of exposure time and acoustic wave frequency. Moreover, impacts of Acoustic and HF Exposure on Core Permeability are shown in Table 3.

Table 3 Impact of Acoustic and HF Exposure on Core Permeability.

Acoustic Wave Frequency (kHz)	Initial Permeability (mD)	Permeability After Treatment (mD)	Permeability Change (%)
3	25	30	20
4	25	32	28
5	25	35	40

The results demonstrate that with increased exposure time at all tested frequencies, there was a notable increase in core permeability, indicating improvements in the pore structure. Prolonged exposure to acoustic waves helps break down deposits that clog the pores, such as asphaltenes and paraffin, thus enhancing the filtration properties of the core. The maximum permeability increase was recorded at a frequency of 5 kHz, where a 40% improvement was achieved. This confirms the hypothesis that higher frequencies generate intense vibrations that exert a powerful effect on the pore structure, improving permeability and creating more favorable conditions for oil movement.

The depth of penetration of elastic and electromagnetic waves into a reservoir formation is a critical factor in determining the efficiency of wave stimulation technologies. Elastic waves, particularly those in the low-frequency range (3-5 kHz), typically exhibit deeper penetration due to lower attenuation in porous media. Based on theoretical models and experimental studies, elastic waves used in this study are estimated to penetrate up to 50-100 meters in typical sandstone formations. This depth ensures the stimulation of near-wellbore zones, which are often clogged by deposits, improving permeability and enhancing oil flow.

Electromagnetic waves, operating at 2 GHz in this study, penetrate significantly less due to higher attenuation in conductive media, such as oil-saturated formations. The skin depth of electromagnetic waves is estimated to be 2-3 meters, depending on the electrical conductivity of the reservoir. Despite their shallow penetration, the localized heating effect of electromagnetic waves contributes to viscosity reduction by breaking heavy hydrocarbon bonds, such as asphaltenes and paraffin, near the wellbore.

Penetration through the steel casing is achieved due to the microwave emitter's design. The electromagnetic waves interact with the steel casing, creating eddy currents and heating effects, which subsequently transfer energy to the surrounding formation. This mechanism ensures that the impact is not limited by the presence of the casing, as confirmed by previous studies in wave propagation through metallic barriers. The process is enhanced using electromagnetic frequencies tailored to minimize reflection and maximize absorption within the targeted zone.

Fig.s 4a and 4b show the results of changes in oil viscosity and core permeability under the influence of acoustic waves at frequencies of 3, 4, and 5 kHz, with exposure durations varying from 10 to 60 minutes. These graphs allow a visual assessment of how exposure parameters, such as frequency and time, affect the properties of oil and the porous structure of the core, which is essential for optimizing the conditions for applying this technology on an industrial scale.

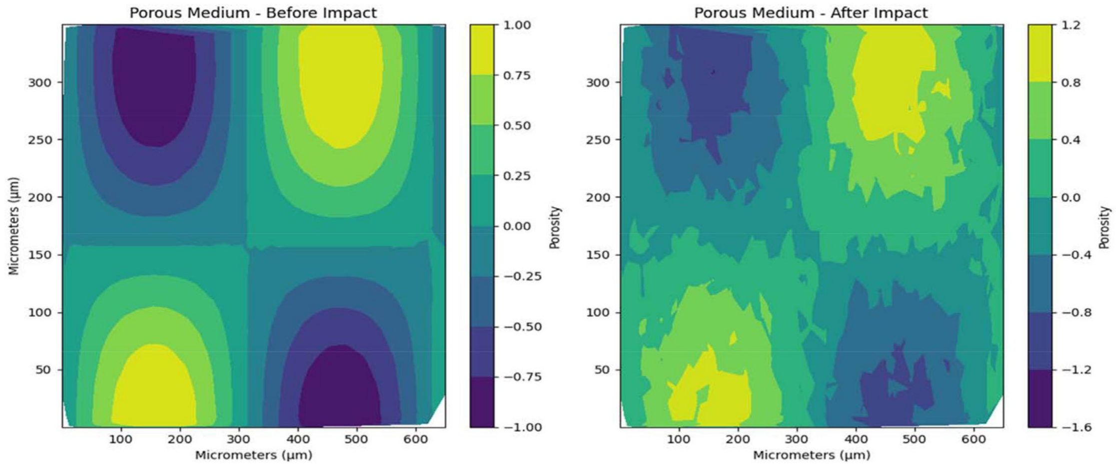

Fig. 4 Porosity Distribution in a Porous Medium Before and After Elastic Wave Stimulation.

Fig. 5a illustrates changes in oil viscosity. The X-axis represents exposure time, starting at 10 minutes and extending to 60 minutes, enabling analysis of how prolonged exposure to acoustic waves contributes to viscosity reduction. The Y-axis represents oil viscosity, with an initial value of 845 mPa·s, serving as a baseline for quantifying the changes induced by acoustic waves. Moreover, the lines on the graph for frequencies of 3, 4, and 5 kHz indicate that higher frequencies have a more significant impact, causing a substantial reduction in viscosity. The greatest reduction was achieved at 5 kHz, where viscosity decreased by 35% after 60 minutes of exposure.

Fig. 5b illustrates changes in core permeability. The X-axis represents exposure time, allowing for an analysis of how exposure duration affects the filtration properties of the core. The Y-axis shows core permeability in millidarcys, and the changes depicted on the graph enable an assessment of the effectiveness of acoustic waves in enhancing the permeability of the porous medium. The lines on the graph for frequencies of 3, 4, and 5 kHz demonstrate that a frequency of 5 kHz has the greatest effect, increasing core permeability by 40% at maximum exposure time. This effect confirms that higher frequencies create intense vibrations that help break down deposits blocking the pores and improve the core's filtration properties.

Together, both graphs confirm that increasing the frequency and duration of acoustic wave exposure has a positive effect on reducing oil viscosity and enhancing core permeability.

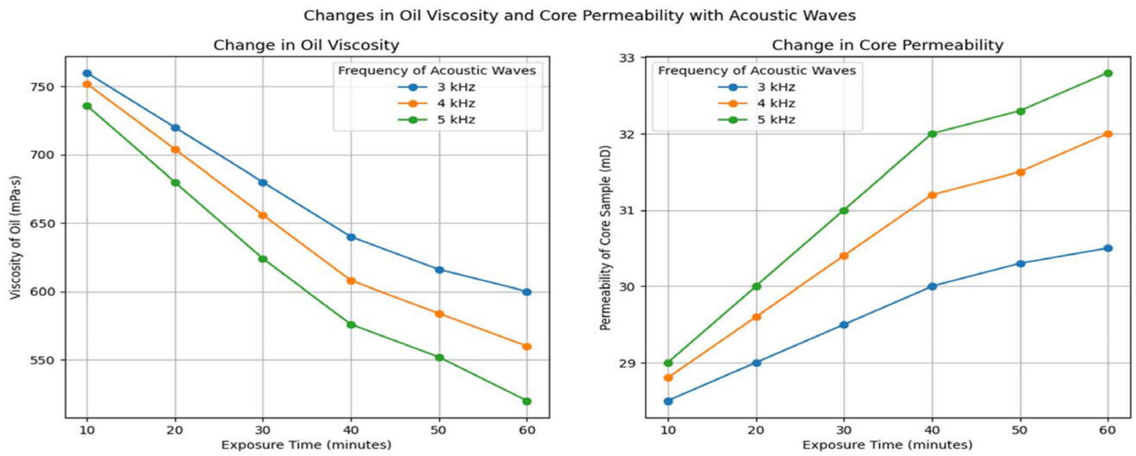

Fig. 5a) Change in oil viscosity depending on acoustic wave frequency and exposure time, b) Change in core permeability depending on acoustic wave frequency and exposure time.

The graph confirms that higher frequencies and longer exposure times of acoustic waves positively impact core permeability. This finding opens up opportunities for applying acoustic waves in enhanced oil recovery (EOR) methods, particularly in challenging low-permeability reservoirs where traditional methods may be insufficiently effective.

Conclusions

This study combines a comprehensive review with experimental and numerical investigations to evaluate the effectiveness of combined high-frequency (HF) radiation and acoustic waves in improving core permeability and reducing oil viscosity—critical parameters for enhancing oil recovery in low-permeability reservoir conditions. Moreover, a specially designed experimental setup allowed us to replicate reservoir conditions, enabling a detailed analysis of the effects of acoustic wave frequencies (3, 4, and 5 kHz) and exposure durations (10 to 60 minutes) on the properties of oil-saturated core samples. Experimental results showed that the maximum reduction in oil viscosity (35%) and the highest increase in core permeability (40%) were achieved at an acoustic wave frequency of 5 kHz with the longest exposure time. Numerical modeling conducted in COMSOL Multiphysics complemented these experimental findings by visualizing sound pressure distribution within the porous structure and revealing its role in structural changes and permeability enhancement. This integrated approach of reviewing, experimenting, and modeling provides a robust framework for understanding the mechanisms of wave stimulation.

The data obtained confirm that combined HF and acoustic wave stimulation is a promising technology for enhancing oil recovery in complex geological conditions. Ultimately, these findings are particularly valuable for developing and optimizing enhanced oil recovery (EOR) methods in mature fields with low-permeability reservoirs, where traditional approaches are often less effective. Also, the results of this study pave the way for further research aimed at refining wave stimulation parameters to maximize efficiency and applicability in industrial settings.

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