An extended model for ultrasonic-based enhanced oil recovery with experimental validation

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ABSTRACT

This paper suggests a new ultrasonic-based enhanced oil recovery (EOR) model for application in oil field reservoirs. The model is modular and consists of an acoustic module and a heat transfer module, where the heat distribution is updated when the temperature rise exceeds 1 °C. The model also considers the main EOR parameters which includes both the geophysical (i.e., porosity, permeability, temperature rise, and fluid viscosity) and acoustical (e.g., acoustic penetration and pressure distribution in various fluids and mediums) properties of the wells. Extended experiments were performed using powerful ultrasonic waves which were applied for different kind of oils & oil saturated core samples. The corresponding results showed a good matching with those obtained from simulations, validating the suggested model to some extent. Hence, a good recovery rate of around 88.2% of original oil in place (OOIP) was obtained after 30 min of continuous generation of ultrasonic waves. This leads to consider the ultrasonic-based EOR as another tangible solution for EOR. This claim is supported further by considering several injection wells where the simulation results indicate that with four (4) injection wells; the recovery rate may increase up to 96.7% of OOIP. This leads to claim the high potential of ultrasonic-based EOR as compared to the conventional methods. Following this study, the paper also proposes a large scale ultrasonic-based EOR hardware system for installation in oil fields.

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1. Introduction

Thermal-based EOR techniques including steam flooding, cyclic steam injection and in situ combustion have direct impact on the viscosity of crude oil. However the use of these conventional techniques for long term production of heavy oil, usually damages the formation mainly because of deposition of paraffin near the well bore and incursion of outside liquids and solids for various types of production operations. Paraffin deposition may also reduce the formation permeability. In addition, these techniques may also introduce the deposited paraffin into the formation resulting in pore throat plugging which may lead to production loss [1,2]. Microwave-based EOR is another attractive alternative with less power and energy requirements and does not require the injection of any fluid. However, its main drawback is the limited penetration depth of microwaves in conductive mediums (e.g., case of water-saturated fluid) [3]. Thus, with the presence of certain quantity of water lying over thick and heavy oil, microwaves will not be able to reach the oil content as they can only penetrate up to few millimeters in the water layer [4]. Under such scenario, ultrasonic-based EOR may be a good alternative since the energy it induces is not heavily altered during its propagation into the oil–water mixture (since oil and water phases have very close acoustic impedance) and thus can reduce the viscosity of heavy oil resulting in an improvement of its recovery [5]. The other advantage of ultrasonic-based EOR over conventional EOR techniques is that they do not require to inject chemical solvents such as acids and that they can be deployed while the oil production is in operation [6,7]. In addition, they allow precise positioning of wellbore stimulation and can be employed for any interval of interest.

Some works in this area have already been reported in the literature [4,6,8–11]. However, most of them are provided by researchers with petroleum engineering background. Hence, tackling the issue from the electrical engineering point of view was lacking. This may include the electrical design of the array of ultrasonic transducers and the associated power generator under the constraint to recover a specific quantity of oil from a given reservoir. This constitutes one of the main contributions of this paper which suggests a full design of the ultrasonic-based EOR system for actual oil reservoirs. This was done following the formulation of a new modular model which takes into consideration both the geophysical (e.g., porosity and permeability) and acoustical (e.g., acoustic
penetration in various fluids and mediums) properties of the reservoir with experimental validation. This is an improvement over previous models which only considered partially few of these properties.

2. Literature survey

Several studies have been reported for the use of ultrasonic waves for EOR [4,6,8–11]. Different papers have addressed different parameters of EOR e.g., change in viscosity, permeability, pressure, temperature and interfacial tension while considering different type of fluids and ultrasonic sources. However, to our knowledge, no literature has addressed all these parameters in one study, making it difficult to correctly model and solve the problem. In Addition, only few of them performed experiments to prove the effect of ultrasonic waves on capillary and viscous displacement of oil. Among these practical studies, it has been found that ultrasonic waves may increase the solubility of surfactants in oil which in turn will lead to a decrease of the interfacial tension [12,13]. Miscible experiments have also been conducted and found that ultrasonic waves enhance the molecular diffusion at low water injection rates leading to an adequate EOR [8]. In [14], researchers performed experimental studies of ultrasound application to oil saturated unconsolidated sand packs proving the improvement in cumulative oil recovery as well as oil production. Many field tests have also been performed with the application of ultrasonic waves to oil fields resulting in improved oil recovery in Texas, Siberia and California [15].

On application of ultrasonic waves, movement of pore walls of porous media have been reported to help mobilize the oil droplets trapped inside pore spaces [16]. This is because ultrasonic waves change the contact angle between fluid and the porous wall. In addition, the ultrasonic energy is usually dissipated at the location of cracks & defects causing temperature distributions at these locations which in turn significantly contribute in oil recovery. Furthermore, it has been demonstrated that small oil droplets, which usually are found in the reservoir after primary recovery, may coalesce to form larger ones leading to the flow of oil which results in oil recovery [17,18]. In terms of ultrasonic frequencies, some practical experiments done in [19] showed that high ultrasonic frequency is better as compared to low ultrasonic frequency as long as the velocity of waves and their thermo sonic effects are concerned. Finally, in terms of ultrasonic intensity, it has been experimentally demonstrated in [4] that oil recovery increases proportionally with the increase of amplitude of the ultrasonic waves.

Oil reservoirs contain crude oils of different rheology which is a critical parameter to be taken care of during oil recovery. Hence, some experiments have also been conducted to verify that ultrasonic waves have no effect on the rheology of crude oil with different asphaltene levels proving that they can be safely used for enhanced oil recovery [20].

In summary, from these studies, it has been concluded that ultrasonic-based EOR can be applied to any type of oil reservoir and may also be useful in heterogeneous environment [21–23]. However, to our knowledge, no literature has addressed simultaneously both the experimental and simulation studies with a detailed mathematical modeling. In addition, none of them has addressed the case of multiple injection wells which is very typical with traditional enhanced oil recovery techniques. Another not less important point missed in these studies is the lack of design considerations for the electronic part of the system under the constraint of the geometrical constraints of the oil reservoir.

This paper suggests a new design of a feasible power ultrasonic device which takes into consideration the geometrical parameters of the reservoir (e.g., diameter and depth of the well). In addition, it investigates the effect of increasing the number of injection wells on the oil recovery.

3. Technical background & hardware description

One aim of this paper is to suggest a design of an ultrasonic-based hardware system for EOR. The system is expected to be deployed onto one or several injection wells surrounding a production well (Fig. 1). Without loss of generality, Fig. 1 shows a two dimensional (2D)-top view of an oil reservoir which comprises four (4) injection wells surrounding one producing well. Usually the diameters of the wells are standardized and range between 50 and 90 cm. As for the depth, it can reach up to 4 km. This constitutes one major constraint for application of large diameter ultrasonic transducers. Powerful ultrasonic devices are sought to be inserted inside the injection wells to create vibrations of a predefined frequency in the reservoir which would lead to an increased pressure. This would lead the oil to move towards the producing well. Among the typically used frequencies, it has been reported that ultrasonic waves with a resonant frequency of 20 kHz can only penetrate up to 2–10 cm depth. Increasing this value beyond 20 kHz will further reduce the penetration depth [8]. Nevertheless, the effect of ultrasonic waves for wider areas gradually takes place after a specific amount of time.

3.1. Overall hardware

Fig. 2 shows a detailed schematic of the suggested ultrasonic device which is immersed inside one injection well. It consists of an array of ultrasonic piezoelectric transducers which are placed at different heights of the well. Each element of the array is exited in a time multiplexed manner through the control circuit which controls an associated switch that connects the actuators to the shared high voltage line generated by the high frequency inverter. The ultrasonic waves are generated continuously using a built-in 20 kHz signal generator. This latest comprises a fine tuned band pass filter with lower and upper cut off frequencies at half power (3 dB) points, a rectifier to provide regulated high voltage DC for ultrasonic generation and low voltage DC to different electronic circuits, and a power amplifier to generate high frequency and high power electrical signal. This latest consists of a class B analog switch type transistor amplifier with an efficiency of almost 80% and a power level ranging from 0 to 3000 W. The narrow band pass filter is of 5th order with Quality factor of 20 and upper and lower cutoff frequencies at 20.5 and 19.5 kHz. These aforementioned modules are placed at the surface of the well and hence do not require to sustain high temperature. They are connected to the array of the piezoelectric sensors trough a shared watertight coaxial cable of type (TWS 900 DB) which has the capacity to keep 90% of the power of the transmitted signal over a distance of 4 km, which is enough in our application. This cable has the lowest losses
and is completely waterproof. The piezoelectric sensor induces periodical vibrations, the frequency of which is equal to the one of the electrical signal applied across its two terminals [24].

It is worth noting here that the design suggested in Fig. 2 covers the limitations of injection well tubing size by suggesting placement of both the ultrasonic generator and power amplifier on the surface of earth while the piezoelectric actuators, boosters, horns and associated control switches are installed within the injection well tubing.

Prior to finalize this design, several type of ultrasonic setup designs for injection wells were considered and analyzed. This includes consideration of a long ultrasonic probe dipped inside the formation liquid instead of having multiple probes and sensors at different altitudes. Among the main advantages of this design, one can cite the reduced cost, in addition to not having any limitation on the length of the probe with respect to the injection well diameter. Nevertheless, its main disadvantage is that longitudinal ultrasonic waves emitted by the probe will just be focusing in downward direction having very less effect on the liquid found in the surroundings. As a result the efficiency of the setup is heavily reduced.

In contrast, the proposed design in Fig. 2 is efficient in terms of sending powerful longitudinal ultrasonic waves radially away from the injection well. In this way, it stimulates the areas of reservoir liquid located radially at a distance from injection well and hence pushes them towards the production well.

3.2. The booster and horn

The mechanical vibrations generated by the piezoelectric transducer are relatively very low in amplitude and therefore needs to be amplified for practical use. This is achieved by the coupling the piezoelectric sensor to the pair booster–horn. These latest are a sort of mechanical resonant elements operating in the compression mode and are usually half wave length long. Aluminum is found as the best candidate for horns because of its easy machining capability, high fatigue strength and low acoustic loss [25]. Fig. 3 illustrates this module in more detail. The power amplifier, the booster, and the horn have actually the same function of amplification of the original signal received. The only difference is the type of signal being dealt: the power amplifier is responsible for electrical signal amplification while the booster amplifies the mechanical vibration generated by the piezoelectric transducer. For large distance between the piezoelectric transducer and the target, several half wave length long boosters are cascaded to cover the distance. However, as was previously mentioned, our assessment of the device for large scale reservoir (see Section 5) took into consideration the maximum diameter of the well bore since the pair booster–horn is put along its cross section.

3.3. The feedback module

The built-in feedback module is used to maintain both the control frequency and the output power to a target value. The output frequencies of both the electrical signal from the power amplifier and the mechanical signal from the horn are constantly monitored and whenever a loss of synchronism or resonance is detected, the output frequency of the inverter is adjusted using a built-in PID controller. Hence, the resonant frequency generated by the transducer has odd overtones with less amplitude associated with it but the even overtones are suppressed. This is because of 180° phase shift between the mass controlled region of lower resonant frequency and stiffness controlled region of upper resonance. This suppression of even harmonics can be removed by insertion of a
new resonant frequency. As a result coupling coefficient will be distributed over a band of frequencies and the power factor of the transducer will be improved leading to a wide band ultrasonic wave comprising of multiple frequencies [26,27]. Achieving the proper thickness to diameter ratio of ultrasonic sensor, fine tuned resonant frequency can be generated offering more precise control over ultrasonic frequency generation. This is because of Poisson's effect and the coupled vibrations in radial and longitudinal dimensions. In this case a critical value always exists for the thickness to diameter ratio and when the actual thickness to diameter ratio matches this critical value, the resulting coupled vibration incorporating longitudinal and radial vibrations is very intense [28,29].

4. Mathematical modeling

Fig. 4 shows the flow chart of the overall suggested ultrasonic-based EOR model. It is modular and comprise mainly an acoustic pressure module and a heat transfer or temperature module. The key idea is that with the application of ultrasonic waves in the injection well, the surrounding pressure will increase depending on the fluid density, as well as on the reservoir’s permeability and porosity. This leads to an increase of the overall temperature in the reservoir which leads to a reduction of the liquid viscosity and eventually to oil recovery.

4.1. Acoustic module

Assuming the medium as slightly lossy, the steady state element field equation also called as Helmholtz equation is given as [30]:

$$\nabla^2 P + K'^2 P = 0$$

where $|P|$ is the complex amplitude of pressure and $K'$ is the complex wave number given as:

$$K' = K \sqrt{1 + j \frac{\sigma}{\omega}}$$

Where $c$ is the speed of sound in the particular medium, $\omega$ the angular frequency in rad./sec, and $\sigma$ the damping factor of the material ($\sigma = 0.5$ [31]). Since an inhomogeneous medium representing a mixture of oil and water is the main concern, the compatibility conditions are defined at the boundary of two domains indicating the consistency of the pressure and continuity of velocity across the boundary.

$$P_1 = P_2$$

$$\nu_1 + \nu_2 = 0 \rightarrow \frac{1}{\rho_1} \frac{\partial P_1}{\partial n} + \frac{1}{\rho_2} \frac{\partial P_2}{\partial n} = 0$$

The pressure has a very less effect on the viscosity of liquid having a direct relationship as opposed to temperature. The viscosity is modeled as [32]:

$$\mu = A P^{1/2} \exp \left( \frac{(P + \rho^2) \sigma}{T} \right)$$

Here $P$ stands for pressure, $T$ the temperature, $\rho$ the density of liquid while $A$, $r$ and $s$ are constants. The change in density of fluids with the change in temperature and pressure is modeled as [33]:

$$\rho_1 = \frac{\rho_0}{1 - \frac{\rho_1 - \rho_0}{\rho_0}}$$

![Fig. 4. Block diagram of the suggested model for ultrasonic-based EOR.](image-url)
where $T_1$ and $T_0$ represent the final and initial temperature in the above expression. Similarly $P_1$ and $P_0$ represent the final and initial pressure values. $\rho_1$ is the final density, $\rho_2$ the initial density, $\beta$ the volumetric thermal coefficient of expansion in ($\text{m}^3/\text{m}^3$ $\cdot ^\circ\text{C}$) and $E$ the bulk modulus of fluid elasticity in $\text{N/m}^2$.

The change in the density is monitored to reduce the computational complexity and enhance the efficiency of the algorithm. The value of density is constantly updated until a significant change of about 0.1 g/ml is noticed. The pressure distribution is only calculated after seeing a meaningful change of the fluid density, $\rho$ (using Eq. (5)).

4.2. Heat transfer module

The temperature distribution is achieved as a result of the mechanical stimulations (pressure) and deals with the heat transfer through fluids given as:

$$K \left( \nabla^2 T - \gamma T \right) + W = 0$$

(6)

where $T$ is the temperature, $\gamma$ the cooling factor, $k$ is the thermal conductivity of the material and $W$ is the heating power density. The power dissipation resulting from ultrasonic absorption in the liquid is the main cause of temperature distribution. Hence, the heating power density $W$ is given as follows:

$$W = \frac{\alpha}{\rho c} |p|^2$$

(7)

where $\alpha$ is the attenuation coefficient of the medium for ultrasonic waves which results in heat dissipation inside the material and it can be calculated using the following equation:

$$\alpha = k \sqrt{\frac{1}{2} \left( \sqrt{1 + \frac{\sigma^2}{\alpha^2}} - 1 \right)}$$

Again at the boundaries’ domains (i.e., water–oil boundaries), the compatibility conditions need to be defined to ensure the consistency of temperature across the boundary and continuity of heat flow as:

$$T_1 = T_2$$

$$K_1 \frac{\partial T_1}{\partial n} + K_2 \frac{\partial T_2}{\partial n} = 0$$

(8)

In porous media, the fluid flow is calculated by using the Darcy’s law [34]:

$$V = \frac{k}{\mu} \frac{dP}{dL}$$

(9)

where $\mu$ is the viscosity, $k$ the permeability of the reservoir, while $dP$ and $dL$ are the differential pressure and length, respectively.

Hence, in the heat transfer module, the attenuation coefficient is constantly updated and the resulting temperature rise is also monitored. On the other hand, the heat distribution is only calculated when a temperature rise of around 1 $^\circ\text{C}$ is noticed.

5. Experimental results, numerical simulation and validation

5.1. Experimental setup

To validate the model, an experimental setup was developed in the Laboratory (Fig. 5). It consists of an ultrasonic generator, an amplifier, and a built-in booster and horn. The transducer is dipped inside a tank of 1 m height containing water of height 0.6 m. A 2 l glass cylinder containing 0.25 m height of oil sample (e.g., crude oil) is also placed in the water. The dimensions of the ultrasonic device are shown in Fig. 5.

Hence, the setup emulates to some extends a typical oil reservoir for which crude oil is surrounded by water. A thermocouple coupled with a temperature display unit is placed inside the oil sample in order to record the actual temperature rise induced by the ultrasonic probe. This latest features adjustable parameters that include the frequency (from 15 to 120 kHz) and the power (up to 3 kW). The generator used in this paper does not provide the flexibility to change the frequency; instead it only incorporates the change in output power. For a specific output power (350 W) and operating frequency (20 kHz) of the ultrasonic transducer, the temperature distribution for different materials has been recorded. At first, three types of target mediums have been used including water, olive oil, and vegetable oil. The ultrasonic probe is immersed inside water at a depth of 10 cm. An initial temperature of water was kept constant for all the experiments. A mathematical relationship is used to find out the pressure distribution based on the temperature distribution. This relationships of temperature with pressure $P$ is derived by using the correlation function with an accuracy of $+5\%$ and a fourth order polynomial respectively and is given as [35–37]:

$$P = P_0 - 2E^{-0.6T^4} + 5E^{-0.6T^3} - 0.01297T^2 + 7.2355T + 1299.4$$

(10)

$P_0$ is the initial pressure and is calculated for vegetable oil, water and olive oil as:

![Fig. 5. Lab experiment setup.](image-url)
\[ P_0(\text{Vegetable Oil}) = \left( \frac{894 \text{ kg}}{\text{m}^3} \right) \times \left( \frac{9.81 \text{ m}}{\text{s}^2} \right) \times (0.25 \text{ m}) = 0.0216 \text{ atm} \]

\[ P_0(\text{Water}) = \left( \frac{1000 \text{ kg}}{\text{m}^3} \right) \times \left( \frac{9.81 \text{ m}}{\text{s}^2} \right) \times (0.25 \text{ m}) = 0.0242 \text{ atm} \]

\[ P_0(\text{Olive Oil}) = \left( \frac{800 \text{ kg}}{\text{m}^3} \right) \times \left( \frac{9.81 \text{ m}}{\text{s}^2} \right) \times (0.25 \text{ m}) = 0.0194 \text{ atm} \]

Figs. 6 and 7 show some experimental results (Temperature and Pressure) obtained with olive oil, vegetable oil, and water. Hence, a nonlinear rise in temperature and pressure has been observed. The reason is the attenuation of ultrasonic waves when they hit the glass. This phenomenon causes heat dissipation in the glass bottle causing sudden rise in temperature. Heat dissipation also raises the temperature of oil sample contained in glass bottle because of heat conduction. After some time (i.e., after 3 min), the ratio of rise in temperature drops. This is because the surrounding water starts to absorb the dissipated energy from the oil sample and glass container.

Similarly, in case of vegetable oil, the temperature and pressure profiles exhibited similar development than olive oil. The temperature rise followed almost a similar trend as it did in case of olive oil but with fewer rises in temperature. This is because of less heat dissipation in vegetable oil based on its lower viscosity (57 m.Pa.s) at room temperature as compared to olive oil (84 m.Pa.s).

In the second phase of the experimental work, further experiments were conducted using a core sample saturated with crude oil (50 API) in order to estimate its corresponding recovery factor when it is exposed to 20 kHz and 100 W ultrasonic waves. A density bottle with a volume of 25 ml is filled with crude oil, which is then weighted by using precise weight balance (Citizen CX265, Serial No. 157604/06 Poland, with is accurate to the level of 5 digits after decimal point. It can record the weight from 1 µg up to 210 g accurately in temperature range of 19 to 35°C). The obtained weight is then divided by the volume of the bottle in order to record the density of crude oil. The weight balance needs some time to provide a stable output. However, some care is required to prevent any flow of air near the weight balance as it may disturb the weight measurement process. A photograph view of the setup is shown in Fig. 8. For temperature measurement, a thermocouple (Pt 100, WS 130 Series, Deange, Taiwan) fixed with temperature display is used. Its sensitivity ranges from −50°C to 300°C, which is enough for the requirement of experiment.

The core sample is exposed to ultrasonic waves for an overall duration of 1 h with 10 min step. Hence, six (6) measurements were recorded in this way. In addition, in order to avoid the excessive temperature rise in the ultrasonic probe a cooling time of 8 min and 40 s is provided between each measurement. This cooling time is attributed towards the weight measurement and settlement time for the temperature display.

After every ten (10) minutes, the weight of the core is recorded and divided by the density of the crude oil to estimate the volume of oil being extracted with the application of ultrasonic waves. The core sample is weighted before and after oil saturation providing the amount of original oil in place inside the core as 885 mm cubed. Weight of core as a function of ultrasonic wave application time is shown in Fig. 9.
6. Numerical simulations

To validate the model illustrated in Section 4 and to compare the experimental results, numerical simulations have also been performed using a finite element-based method. Hence, a coupled model of Darcy flow and acoustic pressure in COMSOL multiphysics has been used to estimate the pressure distribution in the target medium when it is subjected to ultrasonic waves. Furthermore, a model developed by [38] is used to estimate the oil recovery from this pressure distribution.

Numerical simulation was performed for the case of ultrasonic application to olive oil, sunflower oil and water. Hence, similarly to the experiments, an operating frequency of 20 kHz has been used with an output power of 350 W. Fig. 12 provides a detailed block diagram view of the simulation model, while Table 1 exhibits the other parameters of simulation. The parameters considered in Table 1 are realistic in nature and have been collected from literature to prove the validity of the model.

All of the three liquids were considered in separate simulations and placed at distance of 15 cm from the source, and olive oil placed at the same distance. The reason of using these fluids, prior to use crude oil was to have an idea of the effect of ultrasonic waves on different type of oils in terms of temperature and pressure rise. Figs. 10 and 11 summarize the simulation results. In Fig. 11, the vertical and horizontal axes represent the width and length of the oil reservoir (3 and 10 m, respectively as mentioned in Table 1). The temperature distributions have been plotted as a function of distance from ultrasonic source while surface plots are presented for pressure distributions. The temperature distributions as shown in Fig. 10 provide an insight into the behavior of different type of liquids for application of ultrasonic waves. The reason behind high temperature after 15 cm in case of vegetable oil and olive oil is the change of material. Since the viscosities of vegetable and olive oils are different from water and also they

<table>
<thead>
<tr>
<th>Properties</th>
<th>Values</th>
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<tr>
<td>Frequency</td>
<td>20 kHz</td>
</tr>
<tr>
<td>Input power</td>
<td>10 kW</td>
</tr>
<tr>
<td>Heating time</td>
<td>01 year</td>
</tr>
<tr>
<td>API gravity of crude oil (at 20 deg C)</td>
<td>15</td>
</tr>
<tr>
<td>Initial temperature</td>
<td>55 deg C</td>
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<tr>
<td>Mean heat capacity of oil at constant pressure</td>
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</tr>
<tr>
<td>Heat transfer coefficient of rocks</td>
<td>1 mW/(m K)</td>
</tr>
<tr>
<td>Reservoir dimensions</td>
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</tr>
<tr>
<td>Ultrasonic source dimensions</td>
<td>Point ultrasonic source</td>
</tr>
<tr>
<td>Distance between ultrasonic sources</td>
<td>10 cm</td>
</tr>
<tr>
<td>Type of medium</td>
<td>Crude oil (50 API)</td>
</tr>
<tr>
<td>Porosity of reservoir</td>
<td>23%</td>
</tr>
<tr>
<td>Permeability of reservoir</td>
<td>200 mD</td>
</tr>
</tbody>
</table>

Fig. 9. Weight of core sample as a function of ultrasonic exposure in minutes.

Fig. 10. Radial temperature distribution obtained from simulations after 10 min of application of ultrasonic wave.

Fig. 11. Comparison of pressure distributions obtained from Computer simulations for different liquids exposed to Ultrasonic waves, (a) olive oil, (b) vegetable oil, (c) simple water.
are contained in glass, this led to high temperature concentrations inside the oil as opposed to outside water. Another reason could be reflections and refractions of ultrasonic waves at water–oil interface which result in high temperature at the interface.

The obtained results were around 70% in agreement with those obtained from experimental results. The mismatch comes from the variation of operating frequency and power of the ultrasonic generator which were constantly varying up to 20–25 watts and 0.1 kHz offering no control over them. In simulation, a non variant average power level was defined which resulted in the difference in power level of practical transducer and the one used in simulation. This was a major reason behind the mismatch between experimental and numerical solutions.

6.1. Validation of experiments with simulation using crude oil

A coupled model of Darcy flow and Acoustic Pressure in COMSOL multiphysics has also been used to estimate the oil recovery from a core sample. Ultrasonic waves were applied for different amount of times ranging from 10 to several minutes with a step of 10 min. Fig. 13 shows the 3D pressure distribution after 60 min of simulation.

A comparison of oil recovery between the experimental results and simulation results is provided in Fig. 14. The OOIP obtained from simulation was calculated using equation 9 of the fluid flow and knowing the volume of the initial oil in place. Hence, both the viscosity and differential pressure was updated during each iteration in the flowchart algorithm shown in Fig. 4. In addition, the permeability and porosity of the reservoir were set to be same as the ones of the core sample used in the experiments.

It can be observed that a before around 30 min, a substantial mismatch between the experimental results and simulation exist. This may be due to the instability in the output power of the ultrasonic generator as it was not immersed inside water. Instead ultrasonic transducer was placed in direct contact with the core sample to decrease reflections from air as shown in Fig. 9. Beyond 30 min, a good matching could be obtained. Hence, a good recovery rate of around 88.2% of OOIP was obtained after 30 min of continuous generation of ultrasonic waves. This can be even higher with the use of multiple injection wells.

6.2. Simulation results with multiple injection wells

In order to assess the performance of the ultrasonic-based EOR for a typical case when more than one injection wells are deployed,
another set of simulations were performed. It consists of four injection wells, within which an array of ultrasonic sensors were placed as illustrated in Fig. 3. Hence, the same ultrasonic actuators have been defined at four different locations of the reservoir and the resulting pressure and temperature distributions have been recorded as shown in Figs. 17 and 18, respectively. It has been found that the use of multiple injection wells enhances the pressure and temperature rise within the reservoir which in turn leads to improved oil recovery as opposed to single injection well.

Figs. 15 and 16 show the pressure and temperature distributions resulting from a single actuator which was placed in mid of the left side of the reservoir. The maximum temperature obtained was 69°C while the pressure reached up to 257 psi. High temperature has been found in the area surrounding the ultrasonic source. Pressure distribution has been found almost uniform while temperature is highest near the source and decreases as the distance from source is increased. Similarly, the recovery rate may increase up-to 96.7% of OOIP.

A comparison between Figs. 15 and 17 shows that the overall pressure of the reservoir was raised for the case of multiple injection wells. Moreover a high pressure also started developing at the sides which will ultimately push the fluid towards the center where the production well is located. Fig. 17 also provides an insight for prospective temperature distribution obtained in case of four ultrasonic sources placed in different injection wells. It shows that the temperature would be high on the sides of the production well (which is located in the center of injection wells as shown in Fig. 1), resulting in accumulation of hydrocarbons in the center. This would ease the process of recovering oil from the production well as the majority of oil will be accumulated at its place. In addition, there would also be a continuous pressure force from the sides pushing the fluid towards the production well and hence increasing the chances of recovery.

Fig. 15. Pressure distribution in oil reservoir model.

Fig. 16. Temperature distribution in oil reservoir model.

Fig. 17. Pressure distribution in oil reservoir model with four ultrasonic sources placed in four injection wells.

Fig. 18. Temperature distribution in oil reservoir model with four ultrasonic sources placed in four injection wells.
6.3. Employment of a stack of piezoelectric transducers

In another set of simulations, it has been demonstrated that the use of a stack of piezoelectric materials separated by steel has significant impact on pressure distribution within the reservoir. This is evident from Fig. 19 showing surface pressure plot with 2 piezoelectric materials operating at 1 kV & 20 kHz and joined together in cascaded form through a thin strip of stainless steel. Two injection wells have been considered with each one of them containing two ultrasonic sources. Initial pressure was defined as 0 atm and maximum pressure of almost 51 atm could be achieved with this setup.

Efficiency of these ultrasonic sources has also been checked by using boosters and horns of length $\lambda/2$ and made of aluminum as suggested by Kim et al. [25]. Simulation results as shown in Fig. 20 indicate that employment of horns and boosters enhance the efficiency of the stimulation setup even more raising the pressure up to 400 atm. Both the booster and horn were carefully modeled for operation at 20 kHz frequency. The output diameter of the horns exposed to the liquid medium is kept at 20 cm (typically the diameter limit of oil reservoirs) while the length of complete package of stack of sensors, booster and horn was almost 25 cm so than an array of actuators can easily deployed. Horn and booster are mainly considered as hollow cylindrical objects made of aluminum and filled with air.

It has also been found that the pressure distribution is not uniformly distributed inside the liquid because the ultrasonic sources installed in the injection wells are at the same height facing each other. This line of sight placement of ultrasonic sources ultimately results in attenuation of ultrasonic frequencies. One possible solution would be the placement of ultrasonic sources at different heights in each injection well. It has been verified by changing the position of ultrasonic sources placed inside the right sided injection well. New positions of the sources are defined as 0.7 m and 0.3 m as opposed to 0.5 m and 0.2 m, respectively. Simulation result provided for the new placement of sources (Fig. 21) strengthens the above statement by providing an in depth pressure distribution as opposed to Fig. 20.

7. Conclusion

Ultrasonic generator and transducer have been used operating at 20 kHz and 350 W of output power and the effect of ultrasonic waves have been investigated on different types of fluids. Significant increase in pressure has been observed with the use of ultrasonic waves proposing it as a good candidate for in situ oil recovery. An ultrasonic stimulated EOR setup, together with a mathematical model for ultrasonic stimulations have also been suggested. The numerical simulations have been performed by using a finite element method (FEM) and considers the main EOR parameters. This include both the geophysical (i.e., porosity, permeability, temperature rise, and fluid viscosity) and acoustical (e.g., acoustic penetration and pressure distribution in various fluids and mediums) properties of the wells. Significant improvement over traditional methods has been noticed using oil saturated core sample. Simulation results were compared with the experimental findings and a satisfactory matching could be obtained. Finally, a reservoir model has been proposed with multiple ultrasonic transducers employed in different injecting wells and the findings from computer software simulations have been presented, analyzed and discussed. Hence, multiple ultrasonic actuators have been found as a good alternative for improvement in the efficiency of ultrasonic-based EOR.

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References


