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Review

Laboratory evaluation to field application of ultrasound: A state-of-the-art review on the effect of ultrasonication on enhanced oil recovery mechanisms

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A B S T R A C T

Ultrasonic applications have proven to be successful in the laboratory and in the field. However, a review on the influence of ultrasound on enhanced oil recovery (EOR) mechanisms, is still lacking in the literature. Herein, the state-of-the-art review on the impact of ultrasound on EOR mechanisms is presented. Ultrasound oil recovery mechanisms were identified. Main factors affecting oil recovery mechanisms were elucidated. The effects of ultrasound on EOR mechanisms were clarified. Laboratory and field applications of ultrasound were reviewed. Lastly, hitches encountered in ultrasound EOR have opened new avenues for research and solutions proposed. Experimental findings demonstrate that oil recovery by ultrasound ranges from 5-82% original oil in place, with extra oil recovery occurring between 10–20 minutes of ultrasonication. Oilfield results indicate that oil production increased in the range of 26.5–91%, water cut decreased by 4–28%, the success rate was between 75–90%, and the effect can last for 3–24 months.

Contents

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Introduction

Despite growing interest in renewable energy sources, oil and gas remain the primary source of energy. However, because of the drop in oil price and the covid-19 pandemic, the oil and gas company has recently witnessed a declining trend [1]. As a result, finding large new fields is difficult because it involves a lot of money. Many oil wells in the world that are in the middle or late stages of production may still contain significant oil reserves, but oil recovery efficiency from these wells is now less than 40% [2,3]. The use of advanced methods for enhanced oil recovery (EOR) is said to increase oil recovery by 50% [4]. In the oil and gas sector, chemical and physical EOR technologies are now employed to boost oil production from wells in the middle and late stages of production.

The traditional chemical method entails injecting polymers, surfactants, or alkali into the reservoir to lower the interfacial tension (IFT) between oil and water or increase the viscosity of displacing fluid to improve mobility [2,5–7]. Albeit this strategy has yielded some promising results in the field, the drawback is that long-term usage of these chemicals can pollute oilfields, the ecosystem, cause desertification, and diminish oil recovery. Hydrofracturing is the most utilized physical EOR process. This approach boosts oil production by 2–3 times (5–7 tons per day) by utilizing reservoir pressure [8]. However, the employment of 4–8 heavy unit equipment at the well, as well as packings and wellhead equipment, is required for this operation. All of this adds up to an expensive physical EOR method. Hence, there is a lot of interest in improving existing procedures and developing new ones.

Over the last four decades, researchers have looked at using ultrasound to stimulate and boost oil production. Ultrasound is a cost-effective and environmentally sustainable replacement for traditional secondary, chemical, and physical EOR procedures. Ultrasound has been found to activate chemical and physical processes in oil production in both laboratory and field tests [9–11]. Consequently, destroying the physical bonding in the boundary layer between the pores of the rock and the fluid, alter the rheology of fluid by breaking the bond between large molecules in viscous and heavy oil thereby allowing more solid components like resins, paraffin, and asphaltene to become mobile and breakdown of mineral deposits and deparaffinization [9]. According to Chensheng et al. [12], ultrasonic process parameters can affect the elimination of damage near wellbores. Laboratory results showed that frequency, power, time, and core initial permeability strongly influence the plugging removal. Also, field tests carried out in low permeability reservoirs in Northern Shaanxi and Daqing oilfield indicated that ultrasound treatment can increase oil production and the results were consistent with laboratory results. Likewise, Abdulfatah [13] used ultrasonic waves in a tertiary recovery phase to improve oil recovery of Niger Delta crude oil. They came to the conclusion that ultrasound could help recover up to 50% of the original oil in place (OOIP).

Previous reviews on the application of ultrasound in oil recovery have been on ultrasound transducers and new downhole tools used for EOR [8,14–18]. Likewise, Avvaru et al. [19] explained the mechanism through which cavitation intensifies individual unit processes such as EOR, demulsification of water in oil emulsion during the desalting stage, crude oil viscosity reduction, oxidative desulphurization/demetallization, crude oil upgrading, and oil shale. Hamidi et al. [20] provided an overview of recent laboratory, mathematical and field studies on ultrasound application to serve as a reference for future studies. Nevertheless, a review on the effect of ultrasound on EOR mechanisms is even now tenuous in literature. Thus, the review's aim.

Here, the impacts of ultrasound on EOR mechanisms are presented. Likewise, the distinction between these mechanisms is elaborated for physicist, sonochemist, mechanochemist, material, electrical, chemical, and petroleum engineers from academia and industry to have a comprehensive standpoint on how various parameters influence ultrasound and EOR mechanisms. Herein, the different ultrasound techniques were discussed. Thereafter, ultrasound oil recovery mechanisms were identified. Likewise, the main factors affecting oil recovery mechanisms were elucidated. Furthermore, the effects of ultrasound on EOR mechanisms were clarified. Also, laboratory and field applications of ultrasound were reviewed. Lastly, the hitches encountered in the application of ultrasound in oil recovery have opened new avenues for research and solutions have been proposed.

The remainder of this paper is organized as follows: the next section focused on the different ultrasound techniques. The third section depicts ultrasound oil recovery mechanisms such as cavitation, coalescence, Bjerknes force, microjets, peristalsis movement, sonocapillary effect, and acoustic streaming. The factors influencing ultrasound oil recovery mechanisms like frequency, sonication time, distance from the ultrasound source, ultrasound mode, power, and intensity were discussed in the fourth section. The fifth section was devoted to the effect of ultrasound on EOR mechanisms such as IFT, wettability, viscosity, emulsion, asphaltene precipitation, and deposition. Laboratory and field application of ultrasound oil recovery were presented in the sixth section, a review of key findings and outcomes from recent studies was con-

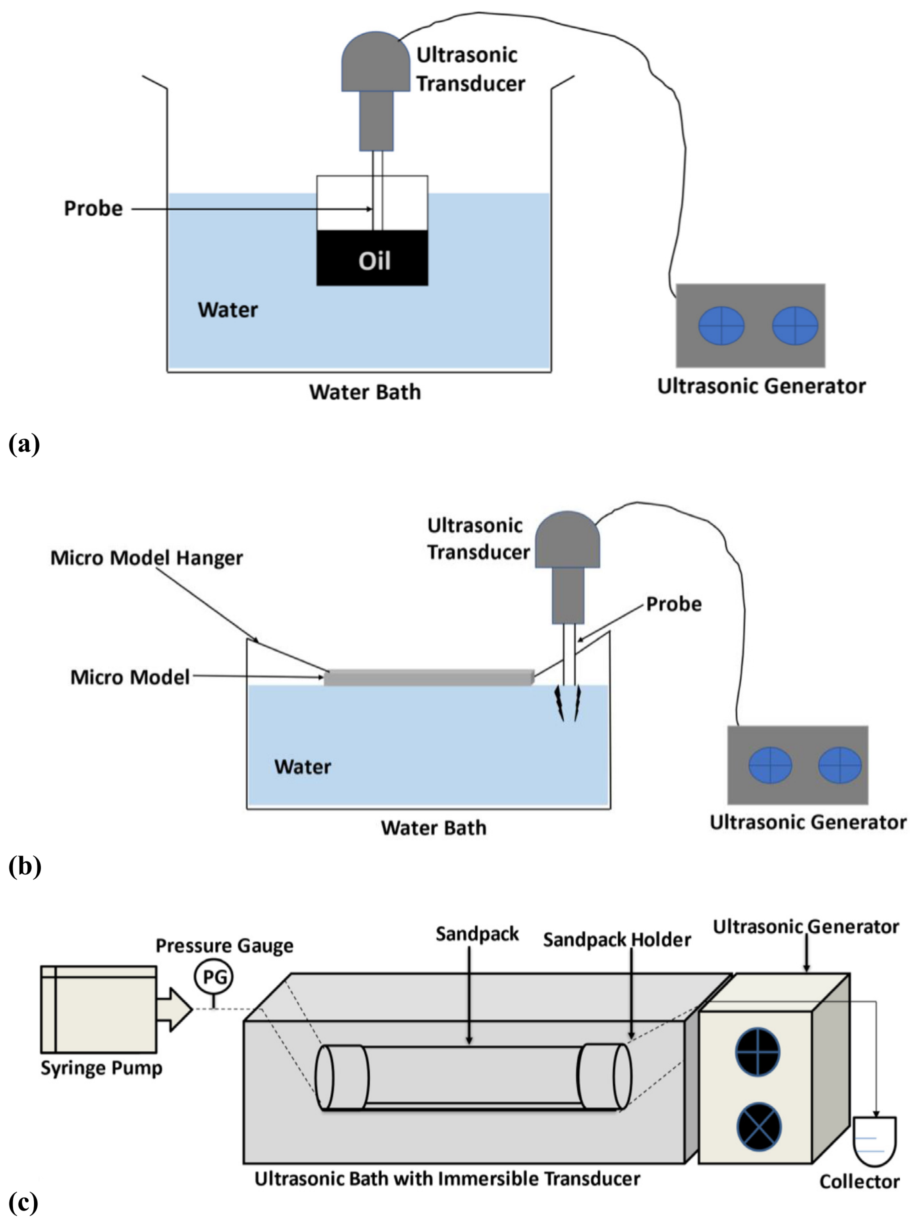

Fig. 1. Schematic illustration of ultrasound techniques (a) heavy oil upgrade, (b) oil displacement using micro model (direct techniques), and (c) indirect ultrasound technique.

ducted. The last section examined the difficulties, prospects, and future trends in ultrasonic oil recovery.

Ultrasound techniques

Ultrasonication is the production of high-power energy to medium which creates a region of high pressure (compression) and low pressure (rarefaction). The generation of these regions depends on the rate at which ultrasound is applied. The application of low pressure generates high intensity ultrasonic waves, which create small vacuum bubbles until saturation is achieved. Subsequently, at high pressure cycle bubbles collapse violently resulting in liquid jets of 280 m/s velocities. Ultrasound can be applied directly (probe type) or indirectly (ultrasonic bath) and both systems use transducers as the source of ultrasound power.

Direct ultrasound method

This method utilizes a probe to administer sound energy to the medium. Hence, energy is transmitted from the probe to the porous media directly. Consequently, the low energy input of around 20 kHz is sufficient to deliver a high energy concentration. The transducer converts the electrical energy to mechanical vibration and is transmitted through the tip of the probe. This method is very popular with heavy oil upgrading due to energy dissipation rate and intensity. This is because the direct method (Fig. 1a) increases the overall mass transfer coefficient and mixing due to acoustic streaming [21]. In similitude, energy intensity is higher with this method [21]. Nevertheless, this method can still be utilized for oil displacement experiments. In this case, a porous media (micro model) as shown in Fig. 1b, or Fig. 1b, or a macro model (Fig. 1c) can be introduced to the water bath. Hereafter, the probe should be placed directly inside the water for maximum exposure to ultrasonic waves.

Fig. 2. Image of cavitation captured with a high-speed camera [29].

Indirect ultrasound method

In this method, ultrasonic energy is transmitted to a water bath and then into the porous media. The water bath separates the porous media from the energy source. Hence, more energy input should be supplied (around 40 kHz). Ultrasonic baths consist of a stainless-steel tank with an immersible transducer (Fig. 1c). The energy is provided by an ultrasonic generator, which is then radiated into the water bath via an immersible transducer. The water bath was created to provide a suitable environment for ultrasound use. The ultrasonic bath method is more appropriate in applications that do not require a lot of power and require diffusion rather than focused energy. For instance, in oil displacement experiments where the force is applied across the entire surface of the porous media, which is in line with the result of Kamkar et al. [22] who stated that the influence of probe sonicator on wettability alteration was less than the bath. Hu et al. [23] compared recovery from oil refinery slurry using a mechanical shaker, ultrasound probe, and bath type. They stated that when the same solvent was employed, they found no substantial disparity in oil recovery between the probe and bath types. However, oil recovery was higher for both probe and bath than it was for mechanical shaking with the same solvent. Nevertheless, because energy is provided to a tiny section around the probe, the probe system is far more powerful than the bath type. In a bath type, ultrasonic energy can be greatly reduced by the water in the bath and the container's walls [23]. This implies that higher ultrasonic power and time might be required to obtain a satisfactory result when using the bath type. But by and large, the bath type can accommodate more liquid for treatment.

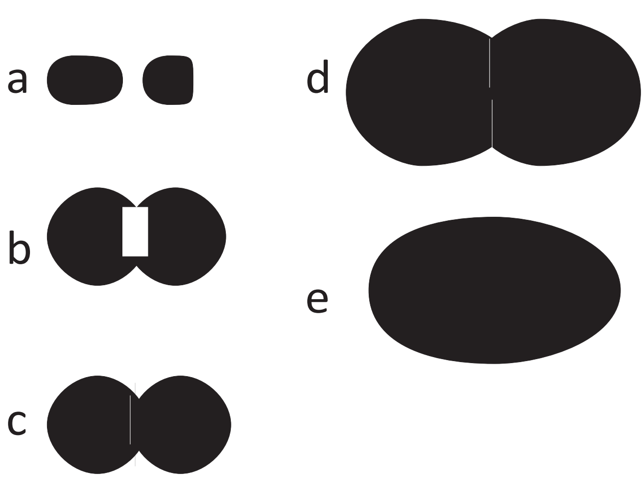

Fig. 3. Schematic illustration of the stages in coalescence mechanism (a) approaching bubbles for collision, (b) flattening of the bubble for contact and trapping of liquid, (c) drainage of liquid, (d) rupture and merging of the droplet, and (e) bubble coalescence [31].

Ultrasound oil recovery mechanisms

The movement of fluid in a reservoir is controlled by gravitational and capillary forces. Residual oil in the reservoir is in the form of droplets dispersed in water separated by the density difference of the oil and water. Gravitational forces act on the disparity amongst phases that completely saturate the medium. Forces of capillarity perform a vital role in liquid percolation through the pores. The liquid film reduces percolation by adsorbing onto the pore wall thereby reducing pore throat diameter. Small pore throat diameter may hinder percolation which can only be remedied if a pressure gradient is applied [24]. Nevertheless, ultrasound waves can reduce the influence of capillary forces by altering adhesion between rock and fluid causing oil coalescence. Also, other nonlinear effects by ultrasound such as cavitation, microjets, Bjerknes force, and peristalsis movement can increase the rate of fluid migration in porous media facilitating oil production [25]. Likewise, the generation of ultrasonic waves in porous media can accelerate the gravitational segregation of gas, oil, and water [26].

Cavitation

The creation and expansion of bubbles with a sinusoidal fluctuation in sound pressure are known as acoustic cavitation. The bubbles grow unstable and collapse after reaching a crucial size, releasing energy (Fig. 2). Hence, for cavitation to occur, the negative pressure in the rarefaction area must exceed the natural cohesive force within the liquid. Thereby, converting sound into thermal energy resulting in heating and boundary friction of the porous media [27]. This adiabatic process results in the accumulation of energy inside the bubble causing extremely high temperature and pressure conditions. Consequently, cavitation could result in an increased chemical reaction in solution due to the formation of primary and secondary radical reactions [28]. Thus, reducing the relative molecular mass of crude oil. For instance, Kim et al. [29] investigated the sonochemistry of heavy oil using ultrasonic cavitation. They reported that cavitation converted n-hexadecane into R1 fraction (<C16) and R2 fraction (>C16) by 4.46%. Also, cavitation is capable of breaking wax crystal structure in heavy oil and polarizing asphaltene molecules subsequently, reducing the branching chain's total length [30]. Besides, high pressure can impede cavitation however, impurities and dissolved gases in the fluid can promote cavitation [17].

Coalescence

Ultrasound induced coalescence is the fusion of two or more droplets of oil into a single bigger drop with a superior movement, becoming a stream when subjected to ultrasound [31,32]. This occurs when the increase in potential energy of the two-drops system is smaller than the relative kinetic energy [33]. Therefore, the theories of coalescence are founded on the collision of unencapsulated droplets approaching one another at constant velocity beginning with the flattening of the droplet surface and ending with a

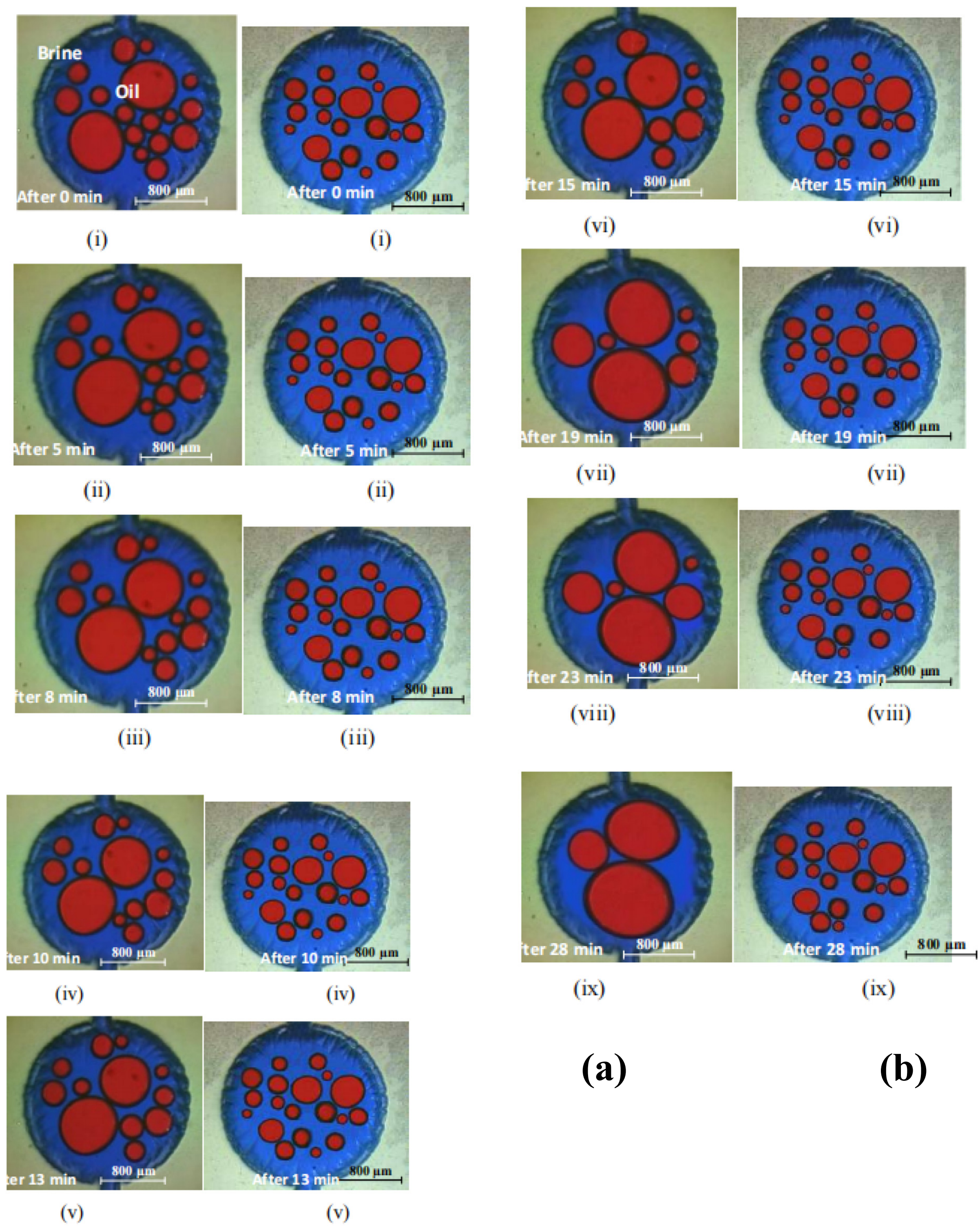

Fig. 4. (ai-ix) Formation of coalescence with the application of ultrasound (bi-ix) no changes to oil droplet without ultrasound indicating a bounce [34].

spherical shape of the droplet [31]. Hence, when ultrasound is applied to oil droplet in a porous media, expansion occur and the oil droplet approaches each other while expanding (Fig. 3a). Before the droplet make contact (within a distance of 10–100 microns), the adjacent drop surface flattens trapping liquid in between (Fig. 3b). The trapped liquid will continue to drain, electrostatic and van der Waals attraction becomes dominant (Fig. 3c) until the separation reaches a critical thickness (0.01–0.1 microns). Consequently, becoming unstable resulting in a rupture of the separation forming a merged droplet (Fig. 3d). The oil droplet with coalescence has an ellipsoidal shape however, due to the surface tension, it will relax to a spherical shape (Fig. 3e). Hence, coalescence can accelerate gravity phase separation in porous media thereby, improving the relative permeability of oil. Hamidi [25] investigated the stages in coalescence mechanism by ultrasound using two dimensional (2D) circular glass micromodel (Fig. 4).

Fig. 4a(i)-(ix) shows examples of coalescence after the ultrasound was applied. Fig. 4b(i)-(ix) without ultrasound shows an example of a bounce where the oil drop approaches each other and flattens but no coalescence. Fig. 4a(ii)-(iii) represents 5–8 minutes of ultrasound oil droplets approaching each other and flattening as the oil droplet expands. After 10–15 minutes of ultrasound (Fig. 4aiv-vi), the liquid film appeared to have drained, but the separation is still visible. However, some of the boundaries disappeared after 19–23 minutes of ultrasound leaving an ellipsoidal shape (Fig. 4avii-viii). Finally, after 28 minutes of ultrasound, only three oil droplets were left indicating that multiple coalescences are the mechanism in play here rather than a combined coalescence (Fig. 4aix).

Bjerknes force

The oscillation of bubbles in the acoustic field generates radiation pressure by other cavitation bubbles which can cause attraction or repulsion between the bubbles. Attraction or repulsion depends on the drop position in relation to the ultrasound field. Therefore, if the oscillations are in phase, the oscillating phase will be attractive, whereas if they are out of phase, it will be repulsive [35]. Hence, Bjerknes force can be defined as translational forces on droplets in a sound wave. Bjerknes forces are termed primary if they are caused by external sound field whereas secondary force is between pairs of bubbles in the same sound field. The proclivity of bubbles smaller or bigger than the resonant size to migrate up or down a pressure gradient and concentrate at the pressure node or antinodes is known as the primary Bjerknes force. On the other hand, the attraction or repulsion of bubbles oscillating in phase or out of phase with one another is defined by the secondary Bjerknes force [36]. Therefore, the Bjerknes force on a small oil drop in a sound wave can be expressed as:

$$F = -V\nabla P \quad (1)$$

whereas V is volume of the oil droplet and ∇P is acoustic pressure gradient on the bubble. Secondary Bjerknes force causes phenomena associated with mutual attraction, acoustic cavitation, and coalescence [37]. However, at low mechanical indices, primary Bjerknes force is thought to be a major contributor in dispersing residual cavitation bubbles away from the focus, and it is more dominating than secondary Bjerknes force [36]. Nevertheless, Yoshida et al. [38] demonstrated experimentally that the direction of secondary Bjerknes force reverses at a specific separation distance (threshold) between two bubbles (Fig. 5). Moreover, the threshold distance varies with the radius of the attached bubble.

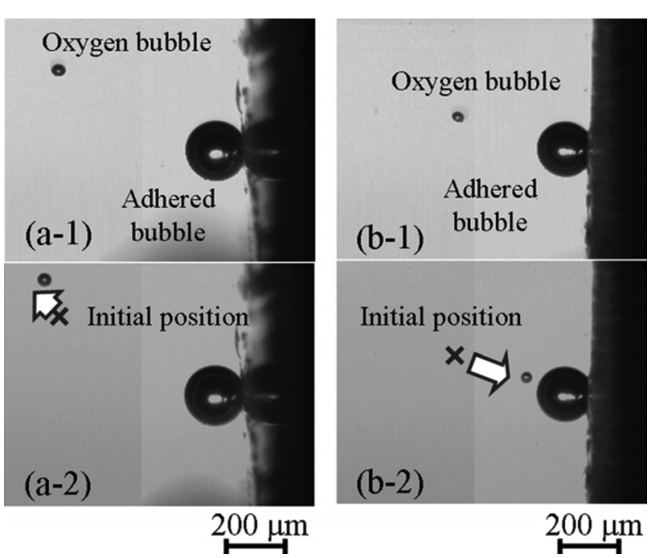

Fig. 5. Influence of initial separation distance between two bubbles on secondary Bjerknes force (a) repulsive force between bubbles, and (b) attractive force between two bubbles [38].

Microjets

Microjets are formed during the final stage of cavitation bubble collapse near a surface whereby the acoustic bubble becomes asymmetric and the bubble wall accelerates more on the side opposite to the solid surface resulting in the formation of a strong microjet [39–42]. This will occur if the velocity of the bubble collapse is higher than that of acoustic wave propagation in a liquid [41,43]. Hence, the uneven fluctuation of the bubble wall near a solid wall causes microjet [43]. Microjets can accelerate to extremely high speed, this is because the kinetic energy of collapse from the interface is converted to the microjet. The velocity of the microjet is estimated at 100–200 m/s and the effect depends on the bubble diameter [40]. During the formation of the microjet, high localized pressure (Eq. (2)) is generated by the impacting microjet pushing the bubble towards the porous media wall [44]. Consequently, generating high temperature and mechanical stress which can improve the permeability of the porous media [45].

$$P = \alpha\rho CV \quad (2)$$

whereas P is pressure, ρ is liquid density, C is velocity of compressional wave in liquid, V is microjet velocity and α is multiplicative constant (varies between 0.41–3). Fig. 6 depicts the link between microjet and bubble collapse velocity. This implies that with an increase in acoustic pressure, the velocity of the microjets responds to changes in the velocity of bubble collapse [43]. Hence, bubble collapse velocity can be utilized to regulate and control the microjet indirectly.

Peristalsis movement

Peristalsis movement is a process whereby ultrasound wave distorts porous media pore wall in form of travelling transverse wave. The travelling wave along the pore wall results in peristaltic transportation of liquid movement by which fluid is squeezed to adjacent pores [46]. Peristaltic movement tends to produce a rising pressure in the direction of the wave consequently, the aqueous phase is more likely to flow than to stick to the pore's surface [27]. The usual condition in a peristaltic movement is that fluid in the contracted section moves opposite to the wave direction

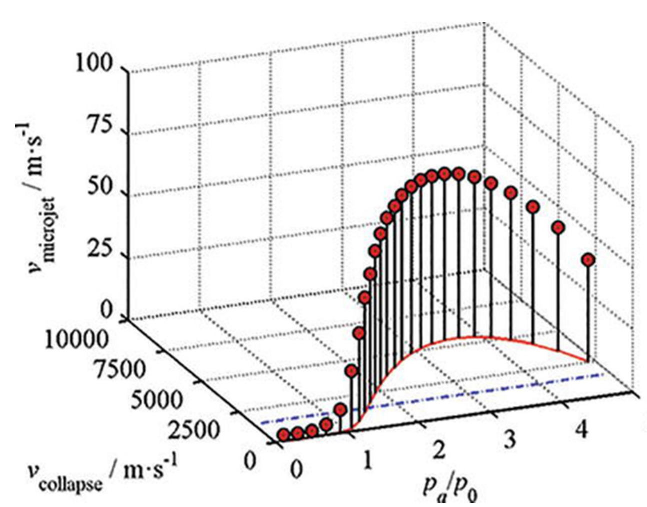

Fig. 6. Relationship between microjet and velocity of bubble collapse [43].

whereas the fluid in the enlarged sections moves in the direction of the wave inducing a net flow of liquid in the pores undistinguishable to peristaltic movement. Aarts et al. [47] carried out laboratory experiments to demonstrate the potential of the acoustic wave and to validate the peristaltic mechanism. They reported that the experimental results agreed with the theoretical which assumes that acoustic pressure waves in fluid deformed the wall of the solid elastically and that acoustic pressure waves in fluid propagate as in an unbounded medium (rubber). Despite this, the experimental results showed that the ultrasonic induced flow velocity is essentially unaffected by the rubber's hardness. This result contradicts the theory of peristaltic movement which might be attributed to the rubber with a single capillary. However, the impact of ultrasonic waves on natural porous media (Berea sandstone and Indiana limestone) with interacting capillaries of variable cross-sections were investigated by Hamida and Babadagli [46]. Their finding agrees with the theory of peristaltic movement when they reported that the compressibility of the fluid with Berea sandstone had a powerful impact on the net generated flow produced by the transverse wave deformation of the porous media. But for limestone, the result was less effective. This might be because of the less water-wet nature of the Indiana limestone enabling water in the cavities to compete with the vibrating bubbles.

Sonocapillary effect

Sonocapillary effect is the abnormal rise in liquid level and velocity due to additional pressure when it is subjected to a high ultrasound close to the entry of narrow spaces such as pores, capillaries, voids, and canals [48–50]. This occurs as cavitation bubbles collapse asymmetrically to form microjets which are directed to the capillary but-end. Consequently, microjets entering the capillary channels increase the height, speed, and penetration of the liquid in the capillary channel. Dezhkunove et al. [48] experimental study on water indicated that cavitation is a requirement for sonocapillary effect in assisting penetration of the surrounding liquid into a micro-channel. They demonstrated that in the absence of cavitation sonocapillary effect was absent. However, Rozina and Rosin [51] disagreed that cavitation was not the main mechanism for the formation of liquid flow penetration into the microcapillary channel. They concluded that gas capillary dissolution rather than cavitation affected the process of filling dead-end capillaries with a liquid by ultrasound [52]. Nevertheless, Tzanakis et al. [53] experimental results agreed with previous studies by Dezhkunove et al. [48] and Dezkhunove and Leighton [49] that collapsing activity of bubbles in the vicinity of the micro-capillary inlet was the possible mechanism responsible for the sonocapillary effect.

Acoustic streaming

Acoustic streaming is the rapid movement of fluid in a circular-like motion when the sound wave is propagated. When an ultrasonic wave is applied to a porous medium containing an aqueous suspension, fluid streams are generated in the direction of sound wave propagation [54]. The streaming fluid comprises of two components: (1) the main field made up of quickly moving eddies in which the fluid element oscillates around a mean position, and (2) a secondary field made up of relatively slow, time-dependent flow. Likewise, two forces of acoustic origin act on the fluid, the Stokes drag force from the induced acoustic streams and the acoustic radiation force from the ultrasound on the fluid. The net force (Eq. (3)) will cause the fluid to move away from the ultrasound source at a faster rate but the fluid velocity, on the other hand, will resist the fluid motion (Eq. (4)) until a steady-state and uniform fluid motion is attained (this can only be achieved when an appropriate path for the fluid to return is recognized) [55].

$$F = -\frac{\partial p_s}{\partial x} = 2\alpha E_o(r) \tag{3}$$

$$\upsilon(r) = \frac{\alpha E_o \alpha^2}{\mu}\varphi(r) \tag{4}$$

whereas F (N/m^3) is net force, p_s is radiation pressure (Pa), x (m) is path common to the ultrasound source exterior, r (m) is radiating coordinate on the ultrasound source exterior, α (Np/m) is adsorption factor, E_o(r) (J/m^3) is change in energy density throughout the ultrasound source exterior, $\upsilon(r)$ (m/s) is streaming velocity, $\varphi(r)$ is a variation of velocity across the diameter of the ultrasound source surface and μ (Pa.s) is fluid's coefficient of shear viscosity. Streaming velocity is proportional to the fluid's coefficient of absorption, shear viscosity, and volume factor. Therefore, acoustic streaming can be used to dynamically change capillary numbers [56]. Agi et al. [57] stated that ultrasound exposure increased capillary number because intense ultrasound could generate strong acoustic streaming which could reduce capillary force.

Factors influencing ultrasound oil recovery mechanisms

The parameters which influence ultrasound oil recovery mechanisms are discussed in detail in this section. Because ultrasound is a mechanical wave whose mechanics are primarily regulated by capillary and viscous forces, the process can be influenced by the frequency, power, and intensity of the ultrasound [46,58]. Previous studies have shown that ultrasound can increase the mobility of oil in porous media however, the level of penetration depends on the frequency of the ultrasound [35]. This is because the penetration depth is inversely proportional to their frequency and the amount of heat generated is proportional to the frequency of the ultrasound. This implies that the required frequency should be within the resonance of the ultrasonic transducers. Consequently, the amplitude of the induced vibration should be proportional to the level of power (intensity) applied on the transducer [59]. The study of these parameters to obtain optimum values have been carried out by Ning et al. [60] and Gao et al. [61]. For instance, the best possible temperature, power, and frequency for oil separation rate following ultrasound, according to Ning et al. [60], are 40 °C, 0.1 MPa, and 28 kHz, respectively. Nevertheless, Gao et al. [61] reported that the best way to treat oily sludge with ultrasound was to use a frequency of 25 kHz, intensity (0.35 W/cm^3), and power (300 W). However, according to Jin et al. [62], oil recovery rates can get to 95% when using a frequency of 28 kHz and a power of 400 W. When the ultrasonic power exceeds 400 W, however, oil recovery does not improve.

Power and intensity

Ultrasound power is the measure of the amplitude of vibration required to drive the transducer. Hence, ultrasound power is proportional to the amplitude. Most ultrasonic equipment has the capacity to vary the power generated. However, it is important to know the absolute power entering the porous media. Since most of the ultrasound energy is reflected, absorbed, or used in cavitation it is difficult to measure ultrasound power. Therefore, the calculation of the real power utilized in sonochemical processes is not always stated. But this can be done by chemical and physical methods. Chemical dosimetry, for example, is an indirect determination of hydroxyl (OH) radicals produced from sonoluminescence. While the physical method allows the direct or indirect assessment of the applied energy transferred by chemical or physical changes on the medium during ultrasonication [58]. The conventional physical method includes the aluminum foil method, acoustic pressure measurement (utilizing optical microscopes or hydrophones), and calorimetry. The calorimetry technique assumes that heat loss is negligible and the actual power is converted to heat which is dispersed to the porous media [63]. Hence an effective estimate of the ultrasound power introduced into the porous media is determined by.

$$P = m.C_P \frac{\partial T}{\partial t} \quad (5)$$

whereas P is ultrasound power (W), C_P is heat capacity of medium ($J.g^{-1}.\ ^{\circ}C^{-1}$), m is mass of sample (kg), $\frac{\partial T}{\partial t}$ is temperature rise ($^{\circ}C\ S^{-1}$). Consequently, the level of energy introduced into the porous media can be expressed as ultrasonic intensity. Ultrasonic intensity is the amount of energy emitted to the porous media through the radiating surface area of the transducer [63]. Hence, it is interrelated to the amplitude of the transducer and pressure of the sound wave [58]. It can be measured by determining the power introduced into the porous media.

$$Ultrasoundintensity(\frac{W}{cm^2}) = \frac{P}{S} \quad (6)$$

whereas S is emitting surface of transducer. Ultrasound power intensity involves a physical and chemical process. The physical process is mainly the mechanical effect of the ultrasound power intensity on the porous media. While the chemical process is the chemical effect generated by ultrasound cavitation in the porous media [18]. Increasing ultrasound power intensity increases the number of cavitation events and increases the area where cavitation bubbles form. Subsequently, both cavitation and non-cavitation mechanisms effects increases with increase in ultrasound power intensity [64]. However, to reach the cavitation threshold, a minimum value is necessary [58]. For instance, Luo et al. [65] stated that high ultrasound power intensity increases cavitation but when the ultrasound power intensity surpasses the critical value, cavitation bubbles frequently implode, limiting the energy stored in the bubbles. Therefore, excess ultrasound power intensity impedes the formation of cavitation bubbles and the ability to desorb oil.

Frequency

Ultrasound frequencies vary from 18 kHz to 10 MHz when applied to a medium [41]. The use of ultrasound within these frequency ranges can be divided into high and low frequencies. High frequency sound ranges from 2-10 MHz are related to the chemical effect of the medium while Low frequency (power ultrasound) lies between 18–100 kHz and provides a physical effect to the porous media [58,66]. Consequently, altering the frequency of ultrasound to the porous media changes the wave interaction with the fluid and the characteristics of the bubbles formed. Low frequency, for example, causes more intense cavitation, which results in increased focused temperature and pressure at the cavitation spot [67]. High frequency bubbles tend to collapse less violently producing low temperature and pressure hence more collapse per time [64]. This implies that the formation and intensity of cavitation in porous channels diminish as the ultrasonic frequency rises. This is because the ultrasound rarefaction phase creates negative pressure that isn't strong enough to cause cavitation due to time and intensity constraints. Also, the phase of compression and decompression is too short that the liquid molecules cannot be separated to form void for microbubble to collapse [59,67]. For instance, Fig. 7 shows that at higher frequency, larger power intensity is required to generate cavitation. Hence, the frequency chosen should depend on the application needed. Low frequency is required for intense temperature and pressure. High frequency

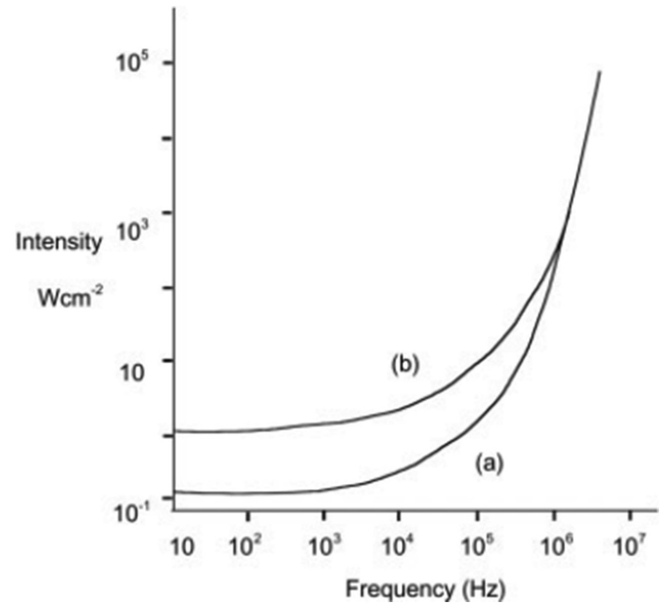

Fig. 7. Increase in frequency increases power intensity threshold needed for cavitation (a) water (b) air [68].

for electron transfer. High frequency, for example, may improve the quantity of available radicals in the system. Even while cavitation is less violent, it occurs more frequently, providing more opportunities for free radical production. This might be due to the shortened bubble lifetime which might have increased the number of free radicals escaping from the cavitation spot to the bulk solution thereby facilitating the bulk reaction to proceed [67].

Sonication time

Ultrasound oil recovery mechanisms can be influenced by the duration of exposure. Three stages can be observed during the application of ultrasound with time. The first stage is the dissolution stage which occurs within the first 15 minutes of ultrasound exposure. The ultrasound reaches an equilibrium point early at this stage. Subsequently, acoustic cavitation accelerates the desorption of oil and impedes re-adsorption [65]. This concurs with previous findings of Hamidi et al. [69] and Agi et al. [54] they stated that microemulsions formed by ultrasound in the first 15 minutes are the more stable and short duration of ultrasound generates more emulsion. The second stage is slow, the mass transfer is carried out by diffusion and acoustic streaming, which lasts up to 60 minutes. This is because as the ultrasound duration increases cavitation bubbles slowly take effect on the oil molecules on the porous media's inner layer. The adsorption site on the solid surface will be free once the innermost oil molecules have been desorbed, allowing oil to re-adsorb. The coverage angle steadily lowers as the oil molecules are removed off the solid surface, until the adsorption rate equals the desorption rate [65]. Finally, in the third stage, with increasing time, the efficiency curve flattens after the adsorption–desorption equilibrium is established. This concurs with previous work by Wang et al. [17] when they reported the pace of core permeability recovery is constant when cumulative ultrasound treatment time exceeds 60 minutes. In similitude, according to Mo et al. [70], ultrasound has a stronger effect in eliminating colloidal precipitation in cores when used for 0–60 minutes, however, as the ultrasound intensity increases, it achieves a maximum and stabilizes.

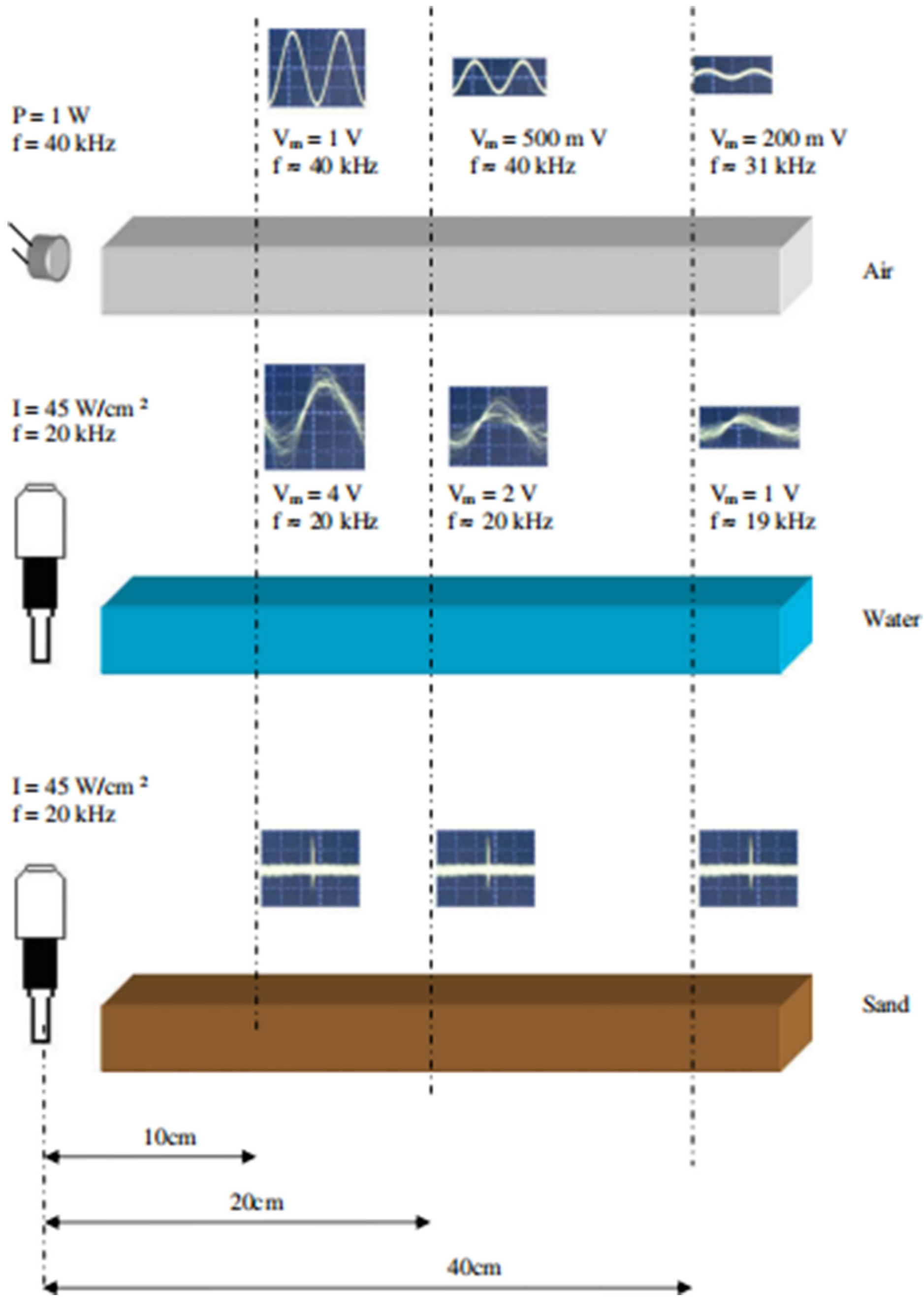

Fig. 8. Schematic illustration of ultrasound penetration through different mediums at a distance of 10, 20, and 40 cm [35].

Distance from the ultrasound source

The extent of dissemination through porous media is one of the important factors controlling ultrasound wave application. During penetration of non-linear wave via porous media the shape of the wave could be altered when they travel through a long distance thereby losing its energy [71,72]. Consequently, shorter distance to the ultrasound transducer will result to less attenuation. This implies that attenuation is proportional to the square of frequency and ultrasound energy is proportional to the frequency [35,70]. For example, ultrasound wave propagation through three different mediums (air, water, and sand) at distances of 10, 20, and 40 cm were investigated by Naderi and Babdagli [35] (Fig. 8). These measurements give us an idea of ultrasound wave attenuation in air, water, and sand. Fig. 8 shows that for air, from 10-20 cm, the ultrasound signal reduced by one-half. Ultrasound wave power at 20 cm was a quarter of that at 10 cm distance. At 40 cm, the ultrasound wave amplitude showed a decrease in the power of about one-fifth of the 20 cm point. On the other hand, for the experiment in a water bath, the amplitudes and frequencies decreased from 4 V–2 V and 20.26 kHz–20.08 kHz at 10–20 cm from the source. The amplitude and frequency decreased further to 1 V and 18.79 kHz at a 40 cm distance from the source. Whereas no-wave information was received for sand. Hence, low frequency wave is more applicable in penetrating porous media for longer distances compared to high frequency as high frequency results in high attenuation.

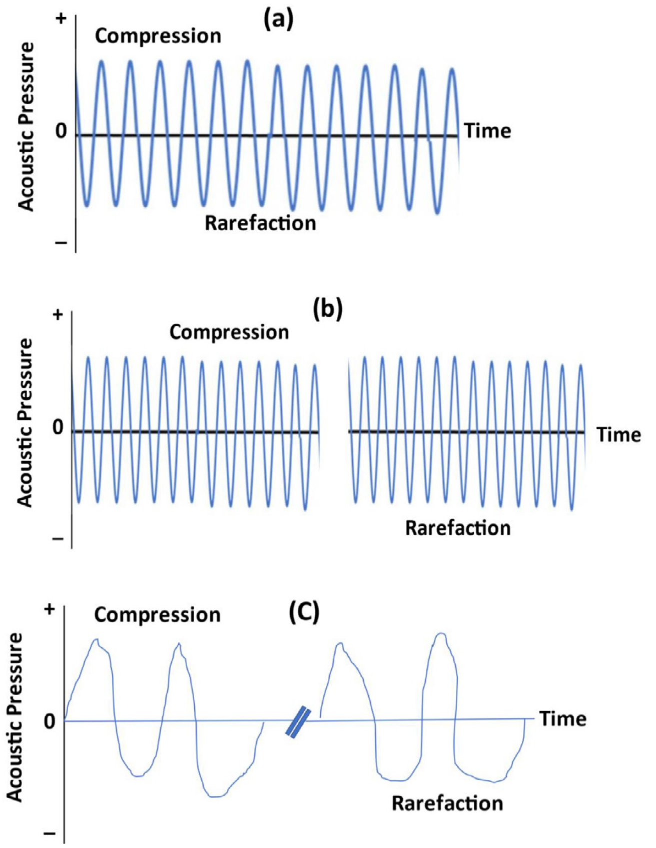

Fig. 9. Schematic illustration of ultrasound wave (a) continuous, (b) gated continuous, and (c) intermittent.

Continuous and intermittent mode

Ultrasound can be delivered uninterruptedly (continuous mode) or supplied with periodic interruptions (intermittent/pulse mode). Continuous ultrasound is a simple sinusoidal wave that utilizes a single wave frequency having constant amplitude (Fig. 9a). Continuous ultrasound is most commonly used when thermal effects are desired nevertheless, the non-thermal effect can also occur. Some equipment uses amplitude modulated wavefront (gated continuous) where the pressure is varied as a function of distance at a fixed time or as a function of time at a fixed point in space (Fig. 9b). The intermittent mode pressure amplitude is not constant and is zero for most of the time (Fig. 9c). Consequently, no acoustic energy is emitted between pulses and the ultrasound propagates through the medium as small packs of acoustic energy. This can be achieved by any combination of on/off duration. Intermittent ultrasound is more effective in enhancing bulk mass transfer. Hence, acoustic pressure, velocity, acceleration and droplet displacement may reach a peak value an order of magnitude greater than those in the continuous mode [54]. This is because intermittent ultrasound generates strong resonance that increases cavitation bubbles in the form of microjets which influences the acoustic environment of the medium. Likewise, ultrasound power intensifies immediately the generator is turned on resulting in stronger and more violent cavitation bubble collapse [72,73]. On the other hand, ultrasound power will lose intensity with time if allowed to continue (continuous mode). Table 1 presents some studies outlining ultrasound oil recovery mechanisms and the factors influencing their efficiency.

Effect of ultrasound on EOR mechanisms

The existence of IFT between oil and water (capillary forces), a high mobility ratio, and reservoir rock heterogeneities are the main causes of low oil recovery [26]. Ultrasound introduces mechanical vibration which influences capillary forces in the porous media causing remarkable changes in the shape of the interface between two immiscible fluids. Consequently, large water droplet is converted to small droplet in an oil layer along the pore wall. Subsequently, the decline in IFT between these layers can result in emulsification [77,78]. Also, ultrasound can adsorb on the pore's boundaries thereby increasing the effective cross-section of the pores and a series of physical mechanisms such as a change in wettability can increase the rate of oil migration in porous media [25,79]. Nevertheless, ultrasound can influence the physical and chemical properties of hydrocarbon, however, an increase in temperature is the most important cause of oil viscosity reduction. Therefore, heat generation, vibration, and cavitation by ultrasound can reduce the viscosity of crude oil, alter wettability, reduce asphaltene precipitation and deposition, emulsification, and decrease in IFT of oil and water are the most important mechanisms that improve oil recovery factor [80]. Hence, one or more of these mechanisms may have a simultaneous influence on oil recovery.

IFT reduction

Expansion and compression during ultrasonic application applies stress to the oil–water interface, overcoming the forces that holds larger droplets together and breaking them down into smaller ones [81]. Consequently, increasing the outward motion, surface activity and hydrophobicity at the oil–water contact [81,82]. Thereby, enabling faster adsorption at the interface, forming an interfacial film, induce steric and electrostatic interaction resulting in increased cavitation threshold reducing interfacial instability [81]. Firoozabadi and Ramey [83] related IFT using the difference between water and hydrocarbon densities, temperature and critical temperature (Eq. (7)). Since ultrasound vibration generate heat and subsequently rise in temperature, according to Eqs. (7)–(9), the IFT between water and hydrocarbon can be calculated.

$$\sigma^{1/4} = \frac{a_1 \Delta\rho^{b_1}}{T_r^{0.3125}} \tag{7}$$

$$\Delta\rho = \rho_w - \rho_{ho} \tag{8}$$

$$\sigma = \left[\frac{1-(\rho_w-\rho_{ho})+1.76}{T_r^{0.3125}}\right]^4 \tag{9}$$

whereas σ is IFT (mN/m), T_r is critical temperature (°C), a_1 and b_1 are constants (mN/m), ρ_w and ρ_{ho} are the density of water and heavy oil (g/cm^3), respectively. For example, Mohammmadian et al. [84] calculated the IFT of different fluids using Eq. (7). They reported that although IFT decreased in all the cases, the reduction did not have any substantial influence on the capillary number. In similitude, Hamida and Babadagli [79] comparing the drop shot at different ultrasound intensities obsereved that the drop shape did not change with increasing instensity. They concluded that the hypothesis that ultrasound alters the IFT between oil and water is questionable. These insignificant results/changes might be because: (1) The increase in temperature did not reduce IFT to ultra-low values since it increased the number of nuclei, which increased cavitation. As a result of the increased vapour pressure, cavitation may develop, and the breakup of large droplets into smaller ones may increase [81] and (2) Long duration of ultrasound might increase

Table 1
Ultrasound oil recovery mechanisms and the factors influencing their efficiency.

Author/Year	Ultrasound Technique	Mechanisms	Influencing Parameters	Findings
Gaikwad and Pandit [74]	Probe	Coalescence	Time & Power	Low power causes coalescence because small droplets collide more frequently, resulting in a rise in the number of droplets and acoustic streaming velocity.
Sawarkar et al. [21]	Bath & Probe	Cavitation	Time	The study revealed that an ultrasonic horn is more effective in bringing about the upgradation than an ultrasonic bath.
Naderi and Babadagli [35]	Probe	Bjerknes Forces & Peristalsis Movement	Intensity, Frequency & Distance from source	The imbibition recovery was then linked to ultrasonic strength, frequency, and distance from the source.
Hamidi et al. [25]	Bath	Cavitation	Power & Frequency	In all situations, increasing ultrasonic power resulted in a greater drop in liquid viscosity. In temperature-controlled studies, the drop in viscosity was inversely proportional to increasing the frequency.
Hamidi et al. [69]	Bath	Coalescence, Acoustic Streaming & Bjerknes Forces	Time, Continuous and Intermittent Mode	When ultrasound is applied for a brief length of time, emulsification takes precedence over demulsification.
Hu et al. [23]	Bath & Probe	Cavitation & Microjets	Power & Time	When the same solvent was used for the probe and bath treatments, there was no substantial change in oil recovery.
Noruddin and Wan Sulaiman [75]	Bath	Cavitation	Continuous & Intermittent Modes	The use of intermittent mode can save costs.
Noruddin et al. [71]	Bath	Coalescence	Distance from the source, Continuous & Intermittent modes	A shorter distance will lead to less attenuation. Vibration and long-distance energy will lose energy as it passes across the medium.
Agi et al. [57]	Bath	Bjerknes Force & Cavitation	Time, Distance from the source, Intensity, Intermittent & Continuous Mode	Ultrasound increased capillary number
Yeh and Juarez [56]	Probe	Acoustic Streaming	Frequency	Using the most intense acoustic field possible could result in powerful acoustic streaming.
Agi et al. [27]	Bath	Cavitation, Peristaltic Movement	Time, Intermittent, Intensity & Continuous Mode	The results demonstrate that when compared to continuous ultrasound and longer duration, ultrasound with a short duration and sporadic pulses can recover more oil.
Agi et al. [54]	Bath	Cavitation, Acoustic Streaming & Bjerknes Force	Intensity	Surfactant flooding is more effective with ultrasonic waves when the concentration is higher than critical micelle concentration (CMC) and the intensity is high.
Kadyirov and Karaeva [76]	Probe	Cavitation	Power Intensity & Time	Cavitation localized near the surface of the ultrasound source can decrease the intensity of ultrasonic treatment.
Mo et al. [70]	Probe	Cavitation	Frequency, Time & Power	They concluded that the optimum ultrasonic frequency & power is 25 kHz & 1000 W, respectively. Also, ultrasonic processing time should be controlled within 120 minutes.
Luo et al. [65]	Probe	Cavitation	Time, Acoustic Intensity & Frequency	Low-frequency ultrasound causes larger and more energetic cavitation bubbles, according to their findings.
Kamkar et al. [22]	Probe & Bath	Cavitation	Time	Variance analysis showed that ultrasonic time and all the parameters had a meaningful influence on the mechanisms.

IFT. For instance, Hamidi et al. [69] stated that IFT increases for long duration of ultrasound compared to short duration. This is because the formation of microemulsion is stable during short duration of ultrasound. As the ultrasound duration increases the heat generated by the ultrasound demulsify the microemulsion causing rupture, distabilization and volume of microemulsion produced at the interface will be less which might have resulted to the increase in IFT. Similarly, Han et al. [85] reported that ultrasound can increase the interfacial area between two immiscible phases and decrease IFT by 5 mN/m, which they attributed to the strong emulsification and cavitation function of ultrasound. Likewise, Li et al. [86] reported that ultrasonic waves can change the oil components by aquathermolysis, heating effect thereby weakening the intermolecular interactions as molecular distance increases, lowering the IFT.

Wettability alteration

On a three-phase system (air/gas, water, and solid), contact angle describes how the liquid phase wets the solid phase. Fig. 10a shows the geometric parameters on a shape of drop on a solid surface. The principle of volume conservation states that when a force is applied to a liquid, it can expand its surface area rather than its volume. Introducing Youngs Eq. (10) and energy balance Eq. (11) to the geometric parameters of a spherical cap (Fig. 10a), present an ideal situation (Eq. (12)) where all the energy introduced is converted to surface energy. Fig. 10b shows that before ultrasound application the known initial parameters are initial volume (V_0), contact angle (θ_0) and height (h_0) which signifies original shape of the drop. Application of 80% of ultrasound changed the shape of the drop (Fig. 10b), the resulting height (h) and ultrasound energy introduced can be obtained from Eq. (12).

$$Cos\theta = \frac{\gamma_{SG} - \gamma_{SL}}{\gamma} \tag{10}$$

$$\partial U = T\partial S + \gamma_{SL^{\partial B}} + \gamma_{SG^{\partial B}} + \gamma\partial A \tag{11}$$

$$\frac{\Delta U}{\gamma} = (1 - Cos\theta_0)\left(\frac{2V_0}{h} - \pi\frac{h^2}{3} - B_0\right) - \pi\left(h_{0^2} - h^2\right) \tag{12}$$

whereas θ is contact angle, γ is surface tension, γ_{SG} is solid–gas surface tension, γ_{SL} is solid–liquid surface tension, ∂U is internal energy differential, T is temperature, ∂S is entropy differential, B is droplet area base, A is liquid boundary area of gas, γ_{SG} and γ_{SL} are energy density of each surface interface. Subsequently, low contact angle

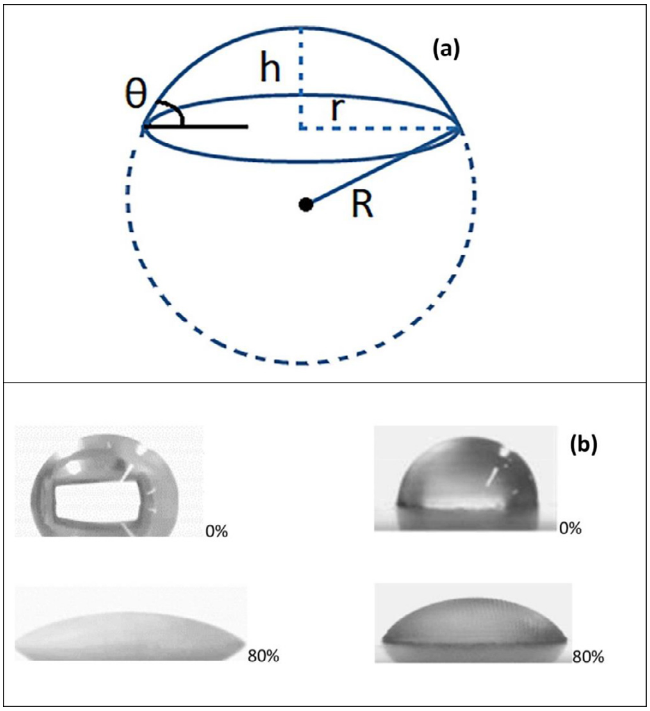

Fig. 10. (a) Schematic representation of geometric parameters of a spherical cap of a drop of liquid on a solid surface (b) change in contact angle before and after application of ultrasound [87].

will result in spreading of the liquid on a solid surface as shown in Fig. 10b. Therefore, a drop of liquid on a solid surface exposed to ultrasound will experience excitation and the drop will vibrate deforming the shape [87]. Hydrogen (*H*) bond between the oil and solid surface may be disrupted by mechanical vibration caused by ultrasound cavitation. Water molecules can thus sustain adsorption sites by forming new *H* bonds with the material. Furthermore, throughout the sonication process, co-current flow improved, resulting in water bubbles. During the initial stages of bubble collapse, both the acceleration and velocity of the bubble wall will quickly increase, generating shock waves when these bubbles collide with the porous medium wall. When the bubble explodes, the oil clinging to the wall dislodges, causing the rock's wettability to change from oil-wet to water-wet [77]. Consequently, ultrasound will enlarge the surface of the drop thereby reducing the contact angle. Nonetheless, when the drop is extended in a wetting system, it cannot rescind. As a result of the vibration driving force and contact angle hysteresis, contact angle is altered when liquid is exposed to low and high frequency ultrasound [87]. Furthermore, ultrasound can change the surface of mineral rocks to hydrophilic [88]. This is because during ultrasonication, dissolves gases and water vapor in the cavitation bubbles experiences a thermal decomposition resulting in the formation of OH and H radicals. Likewise, ultrasound changes the surface morphology of mineral rock surface by increasing the surface roughness thereby decreasing the contact angle [88].

Viscosity reduction

The dipole–dipole and dipole-induced dipole interactions created by dipolar molecules (heteroatoms) in crude oil and polarizable molecules (aromatic components) determine the viscosity of the crude oil. Therefore, dispersion force, dipole/polarization, and the crude oil's capacity to interact with polarizable solutes are the key elements impacting crude oil viscosity [30]. Hence, in order to lower crude oil viscosity, the dispersion force should be raised and interactions should be reduced. This can be accomplished through ultrasound high-energy output adsorption by a crude oil sample, which raises the oil sample's boundary friction and temperature. Consequently, the wax in the oil sample dissolves, lowering residual oil's intermolecular cohesion and viscosity. Furthermore, mechanical vibration by ultrasound increases amplitude, velocity and accelerates elastic particles enhancing the mobility amongst macromolecules and micro molecules [89]. Also, ultrasound cavitation collapse can produce instantaneous high temperature and high pressure resulting in strong wave and micro-jets flows altering inner composition of oil sample. Likewise, cavitation bubble collapse can affect organic matter in crude oil causing cleavage of chains in the macromolecules and subsequently degradation [90]. As a result, various macromolecules in oil samples are broken down into tiny parts, and the heavy oil's carbon–carbon bond breaks into two free radical compounds (R* and R'*) with reduced molecular weight (Eq. (13)), lowering viscosity. During the homolytic detachment of water molecules, both H and OH radicals are generated (Eq. (14)). Accordingly, OH radical combines with the alkane to generate a new alkyl radical (abstraction reaction) (Eq. (15)) [91].

$$RR' \rightarrow R^{*}R^{*'} \tag{13}$$

$$H_2O \rightarrow H^{*} + OH^{*} \tag{14}$$

$$RH + OH^{*} \rightarrow H_2O + R^{*} \tag{15}$$

$$H_2 \rightarrow 2H^{*} \tag{16}$$

Therefore, H radical is from water or dissolved H by ultrasound (Eq. (16)). Cui et al. [30] stated that cavitation impact can degrade crude oil wax crystal structure, polymerize large macromolecules, shorten the length of branched chains and break the length of long alkanes to shorter alkanes, resulting in viscosity reduction. Therefore, it may be inferred that viscosity decrease mechanisms of crude oil by ultrasound is by cavitation effect, mechanical vibration and heat generation.

Reducing asphaltene precipitation and Deposition

Asphaltene is a high-molecular-weight polar aromatic molecule with fused benzene, naphthalene, and phenanthrene rings that is soluble in toluene but insoluble in straight chain hydrocarbons like n-heptane or n-pentane [19,92]. Several elements such as pressure, temperature, crude oil composition, and one or more mechanisms such as polydispersity, steric colloidal, aggregation, and electrokinetic action cause asphaltene to precipitate and deposit around the wellbore during oil production [79,92]. Consequently, asphaltene precipitation may result in significant pressure drop, loss of efficiency in production, reduction in porosity, permeability and wettability alteration [93,94]. Ultrasound application causes increase in temperature and cavitation bubble effect which changes the thermodynamics of the crude oil asphaltene fraction thereby, mitigating against precipitation and deposition. Taheri-Shakib et al. [95] reported that ultrasound induced cavitation phenomenon in the porous media which led to a shear force causing cracking of the asphaltene thus reducing the adherence force between the asphaltene and rock surface. Besides, cracks on the interconnected asphaltene by ultrasound increased the solubility and improved permeability by 80%. Fig. 11 shows flooding in different spot of micromodel with and without ultrasound. When the flooding with n-pentane was executed without ultrasound, asphaltene molecules turn out to be thermodynamically unsteady resulting in precipitation and deposition (Fig. 11a). As the flooding continuous, the deposited molecules start to gather and accumu-

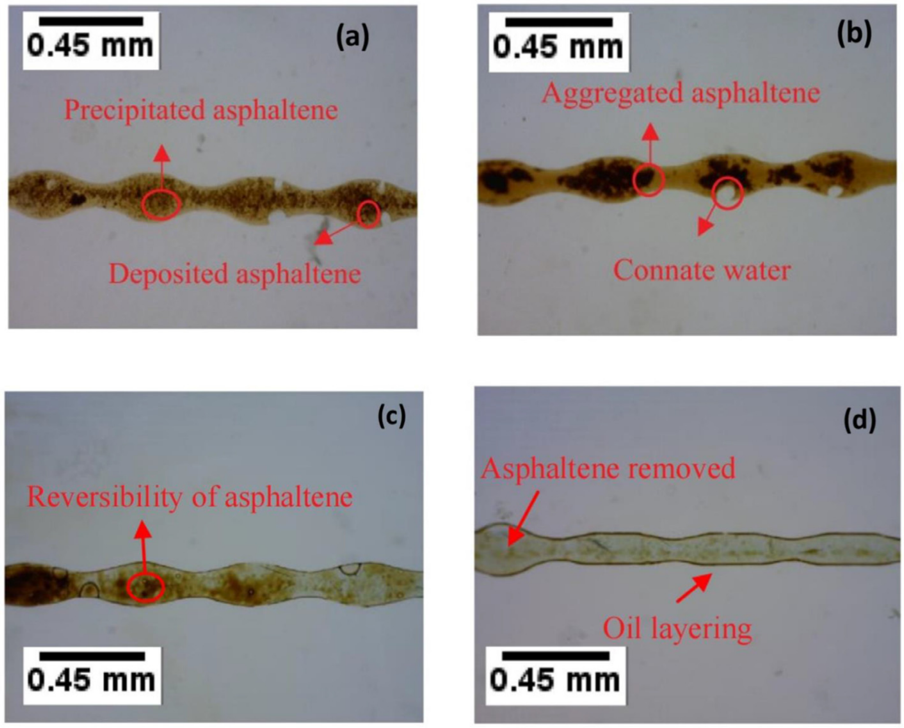

Fig. 11. Flooding in a different spot of micromodel without ultrasound (a) asphaltene precipitation and deposition (b) aggregated asphaltene. Flooding with ultrasound showing (c) reversibility of asphaltene and (d) asphaltene removal [78].

late, forming large particles causing asphaltene aggregation (Fig. 11b). Ultrasound vibrations revert the precipitation of asphaltene and removed deposited asphaltene from the porous media (Fig. 11c, d). Application of ultrasound changed the wettability of the porous media to hydrophilic by overcoming the surface tension between the particles and the surface. Consequently, separating the layer of the oil and wall from the surface causing the layer of oil to diminish by peristaltic movement (Fig. 11d).

Emulsification

Emulsions are dispersion of two or more insoluble liquids such as oil and water. However, these types of emulsion are thermodynamically unstable with narrow phase separation or degradation due to temperature changes resulting in flocculation and coalescence [69,96]. Hence, energy is needed to disperse the tiny droplets of one of the liquids (disperse phase) into the other liquid (continuous phase). Ultrasound can provide high intensity acoustic energy to form new interface. In an oil/water (O/W) emulsion, emulsification begins once one of the liquids achieves cavitation limit. Usually, the less viscous liquid will cavitate and becomes the continuous phase of the emulsion. During cavitation bubble collapse near the surface of two liquids, shock waves cause efficient mixing of the two layers [97]. Consequently, stable emulsion can be attained therefore, it is possible to obtain emulsion in the absence of emulsifier. Nevertheless, the droplet of a rough premix can be disrupted in the dispersion zone by mechanical agitation [96]. In such situation, the newly formed emulsion can be stabilized against coalescence by introducing emulsifier into the system. Emulsifiers can increase the viscosity of the continuous phase to reduce the mobility of droplet thereby preventing coalescence. When surface active agent such as surfactant are used as emulsifiers, they can adsorb at the interface between the two phases and stabilize the droplet of the disperse phase of the emulsion. For instance, surfactant solution began to diffuse and disseminate into the oil phase after ultrasound was applied (Fig. 12a). Diffusion resulted in mixing of the phases to form water/oil (W/O) emulsion (Fig. 12b). Ultrasound breaks large droplets into smaller ones thereby overwhelming interconnected force holding big drops and emulsify the liquids [54]. Initially, only surfactant diffusion into the oil was seen; however, when ultrasonic was applied, the oil phase began to diffuse into the surfactant, resulting in an O/W emulsion. (Fig. 12c, d). This could be attributed to the breakdown of the oil and surfactant solution interface's instability, as well as acoustic streaming [82]. Though for longer duration of ultrasound the emulsion generated at the interface becomes less [69]. The heat generated by continuous application of ultrasound can weaken and rupture the stabilizing film surrounding the dispersed phase of the emulsion forming large droplet (coalescence). Comparing the phase behavior of surfactant brine oil system under short and long duration ultrasound, Hamidi et al. [69] concluded that applying short duration (15 minutes) of ultrasound produces more volume of emulsion compared to cases with no ultrasound and long duration of ultrasound. Table 2 summarizes some experimental results on the impact of ultrasound on EOR mechanisms.

Application of ultrasound in EOR

Scientists and researchers have tested and confirmed the success of ultrasonic applications in the laboratory and in the field. High-intensity ultrasound has been shown to improve oil recovery in the field and in the laboratory. Ultrasound creates mechanical vibrations that have a significant impact on interfacial and viscous fluids by increasing heat and mass transport across interfaces thereby mobilizing residual oil [57]. The amount of residual oil mobilized in porous media is controlled by the capillary number (Nc) and mobility ratio (M).

$$M = \frac{K_r D}{K_r d} \times \frac{\mu_d}{\mu_D} \quad (17)$$

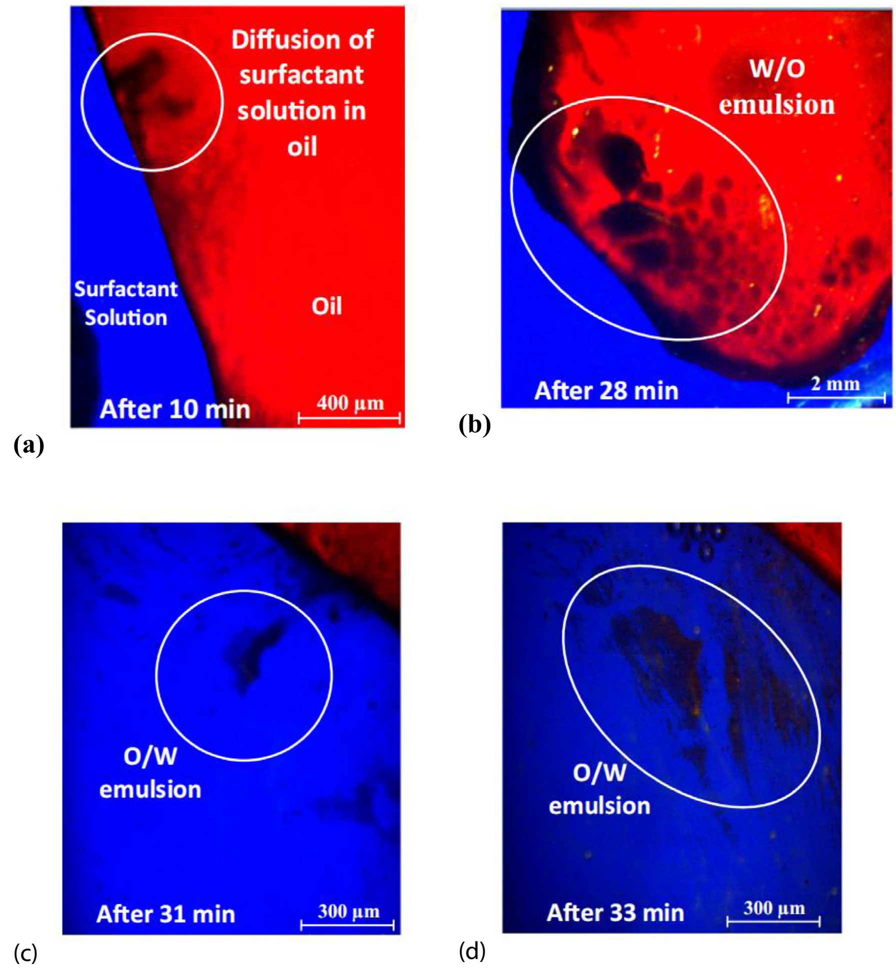

Fig. 12. Emulsification under ultrasound showing the sequence of water diffusion into oil at (a) 10 minutes (b) 28 minutes (c) 31 minutes and (d) 33 minutes [82].

whereas $\frac{K_rD}{K_rd}$ is ratio of the displacing fluid's relative permeability to the displaced fluid and $\frac{\mu_d}{\mu_D}$ is ratio of displaced fluid viscosity to that of the displacing fluid. Hamida and Babadagli [79] presented a density modified *Nc* to assess the variation in capillary number with ultrasonic application.

$$N_C = \frac{\mu_O A f}{\sigma} \times \frac{\rho_O}{\rho_w} \tag{18}$$

whereas μ_O is viscosity of oil phase, A is amplitude of ultrasound vibration, f is ultrasound frequency, σ is IFT, ρ_O is density of oil and ρ_w is density of water.

Laboratory experiments

Albeit ultrasound field application has been commercialized for oil recovery, determining its economic feasibility and the physics of the process must be clarified at laboratory scale. Additional oil recovery by ultrasound has been attributed to steady displacement front produced by pore vibration and focused pressure [46]. Alhomadhi et al. [26] reported that oil recovery by ultrasound vary between 5%-10% OOIP. However, the additional oil recovery occurs between 10–20 minutes of ultrasound, which could be attributed to the formation of a more stable emulsion during this period. Likewise, the cycled intermittent stimulation was associated with the greatest oil recovery. Contrarily, Louhenapessy and Ariadji, [100] stated that circular wave is better at increasing oil recovery (3%) compared to intermittent longitudinal wave (Table 3). The increase was attributed to the propagation of circular waves which produces P and S waves which has a significant effect on oil recovery. Nonetheless, Agi et al. [57] and [27] reported that intermittent ultrasound when compared with continuous, recovered more oil which, agree with previous study by Alhomadhi et al. [26]. For example, Fig. 13 depicts a sequence of images from an experiment in which paraffin was used in conjunction with both intermittent and continuous ultrasound. The intake is at point A, while the outflow is at point B. The white part in the image symbolizes water, while the red indicates leftover oil in the micromodel after a certain period. Observing the snapshot, compared to paraffin with continuous ultrasound and no ultrasound (Fig. 13b, c), intermittent ultrasound with paraffin had a smaller amount of leftover oil in the micromodel (Fig. 13a). This is because W/O split did not occur within the porous material during the brief ultrasound session. Continuous wave stimulation for 40–45 minutes, on the other hand, can recover more oil, but W/O separation occurs, as a result limited oil retrieval and fast water breakout occurred. Oil recovery by ultrasound also depends on the type of oil. Lighter molecular liquids recover more oil than heavier liquids and the temperature impact is important in breaking the heavy chain. Dollah et al. [101] reported that for kerosene oil waterflooding recovered 40.4% OOIP, ultrasound improved recovery by 6.6% at 35 °C. At 45 °C and 55 °C, recovery improved by 10.4% and 14.6%, respectively. Waterflooding recovered 38.9% of crude oil, while ultrasound at 35 °C improved recovery by 2.8%. Waterflooding

Table 2
Summary of experimental results on the impact of ultrasound on EOR mechanisms.

Author Year	EOR Mechanisms	Ultrasound Mechanisms	Findings
Shedid [92]	Viscosity, Asphaltene Deposition & Precipitation	Not Stated (NS)	Ultrasonic irradiation decreased the size of the asphaltene cluster and reduced the tendency to precipitate
Hamida and Babadagli [79]	IFT, Wettability & Viscosity	Cavitation & Sonocapillary Effect	Water film adhesion to the inner wall of the capillary, resulting in increased capillary pressure.
Hamida and Babadagli [98]	IFT & Viscosity	Cavitation, Sonocapillary Effect, Peristaltic Movement & Bjerknes Forces	Ultrasound increased the rate of diffusion
Gaikwad and Pandit [74]	Emulsification, IFT & Viscosity	Coalescence, acoustic streaming & cavitation	During ultrasonic emulsification, a drop fracture, as well as, a drop coalescence phenomenon has been seen.
Mohammadian et al. [84]	Viscosity, IFT & Emulsification	Cavitation	Temperature rises by ultrasound led to a reduction in viscosity and IFT. Formation of the emulsion was observed.
Alhomadhi et al. [26]	Emulsification	Coalescence	Ultrasound stimulation was recommended for depleted reservoirs.
Hamidi et al. [25]	Viscosity	Cavitation	In a temperature-controlled experiment, viscosity reduction was inversely related to frequency.
Hamidi et al. [69]	Emulsification & IFT	Coalescence	Short duration (15 minutes) of ultrasound yielded more volume of microemulsion and IFT remained low compared to cases without ultrasound & long duration
Hamidi et al. [82]	Emulsification	Coalescence & Acoustic Streaming	The combined impacts of interfacial instability, oleic and aqueous phase diffusion, acoustic streaming, and the creation of emulsion due to ultrasonic radiation facilitated liquid percolation in porous media.
Huang et al. [89]	Viscosity	Cavitation, Micro jets	Ultrasonic viscosity reduction of ultra-heavy residue is superior to that of heavy residual oil, suggesting that the higher the viscosity of residual oil, the better the ultrasonic viscosity reduction impact.
Dehshibi et al. [78]	Asphaltene Deposition, Wettability, IFT & Emulsification	Cavitation	The formed asphaltene became reversible due to ultrasonic waves, and the deposited particles on the wall were reversibly solubilized. Emulsion formation is also caused by a decrease in the IFT between the oil layer and the water droplets.
Taheri-Shakib et al. [95]	Asphaltene Deposition & Restoring Permeability	Cavitation	Ultrasound creates turbulence and cavitation, causing a change in the structure of the asphaltene conglomerations deposited in the cores and restoring formation damage.
Kadyirov and Karaeva [76]	Viscosity	Cavitation	The strength of ultrasonic treatment is determined by the crude oil's original rheological properties.
Luo et al. [65]	Viscosity, Asphaltene Precipitation & Deposition	Microjets & Cavitation	Mechanical processes such as shock waves and microjets can break the H bonds between asphaltenes and solid particles due to acoustic cavitation.
Cui et al. [30]	Viscosity, Asphaltene Precipitation & Deposition	Cavitation	Because of the cavitation effect, the structure of asphaltene changed, resulting in a drop in viscosity.
Ahooei et al. [93]	Asphaltene Deposition	NS	The use of ultrasound was successful in removing asphaltene deposits.
Sarasua et al. [87]	Wettability	Sonocapillary Effect	Ultrasonic vibration reduces the contact angle in wetting systems with no return. The contact angle decay depends on the ultrasonic amplitude for a particular frequency.
Wang et al. [80]	Viscosity	Cavitation	The viscosity of the crude oil is lowered by 39% after 8 hours of ultrasonic processing.
Hassanzadeh et al. [88]	Wettability	Cavitation	The surface of the minerals grew more hydrophilic in the presence of low-powered sonication pre-treatment.
Liu et al. [99]	Viscosity & Emulsification	Cavitation	The amounts of heteroatoms, resins, and asphaltenes in heavy oil samples with high viscosity fell significantly after ultrasonic treatment and the extent of high carbon chain to low carbon chain conversion was greater.

recovered 34.12% of engine oil (heavy oil), while ultrasound boosted recovery by 1.5%. Temperature rises were recorded for the system during ultrasonication thus decreasing viscosity of oil. Mohammadian et al. [84] inferred that during ultrasonication 10 °C increase in temperature can reduce the viscosity of water and kerosene by 17% and 20%, respectively. Similarly, to reduce residual oil saturation with ultrasound, capillary numbers in the range of 10^{-5} to 10^{-4} are required.

Field results

The early use of seismic wave to rejuvenate oil well involved the use of sound wave of a much higher wavelength than ultrasound. When such a wave passes through porous medium, it is dispersed into higher harmonic (ultrasonic) waves, resulting in a sequence of phenomena such as (1) rupture of the surface film, (2) coalescence of oil drop with oscillation, and (3) stimulation of oil drops trapped in capillaries [4]. There are some aspects of sonication that are crucial to resuscitate a dead oil well using ultrasound: (a) increase of the flow through the rocks into the pumping pool by removing wellbore blockage, (b) activating the oil by lowering of the viscosity of the oil, making it easier to pump, and (c) detachment of paraffin and other deposits such as salt [9,102]. Consequently, ultrasonic treatment of oil wells can result in a higher production coefficient and a lower proportion of water in the fluid. Field tests were performed in Western Siberia and Samara Region by CUT-service (oil service company) between 2010–2012. During that time, Western Siberia produced 4.4 tons per day, while the Samara Region produced 10.2 tons per day. Ultrasonic well stimulation resulted in a 33% rise in well productivity index and a 4% decrease in well fluid water cut. But then, productivity index declined by 5.6% and the water cut increased by 1.5% when the pumping equipment was optimized without ultrasound [4]. Mullakaev et al. [103] studied oil output from 27 producing wells following ultrasonication, finding a 70–80% increase in oil production rate, a 40% rise in well productivity index, 8.2% reduction in water cut, success rate of 75–85% and duration of effect was between 5–12 months. Similarly, Abramov et al. [9] found that ultrasound treatment resulted in a 39% improvement in productivity factor and 5% reduction in water cut. They came to the conclusion that ultrasonic treatment of vertical wells had a 90% success rate and a 40–100% boost in production. For horizontal wells, treatment with ultrasound was

Table 3
List of some experimental studies and field application of ultrasound in EOR.

Author/Year	Application Type	Oil Recovery	Findings
Mohammadian et al. [84]	Laboratory Experiments	16% OOIP	For less viscous fluids, the recovery of ultrasonic assisted water-flooding was higher.
Abramov et al. [102]	Oilfield	0.14 tons/day	In wells with permeability greater than 20 mD and porosity greater than 15%, ultrasonic treatment can boost oil output by up to 50%, success rate of 85% and duration of effect between 3–12 months.
Alhomadhi et al. [26]	Laboratory Experiments	41–59% OOIP	When residual oil saturation was present, wave stimulation was more effective than when the original oil was present. As a result, this approach is recommended for usage in depleted reservoirs.
Mullakaev et al. [4]	Oilfield	4.4 & 10.2 tons/day	The well productivity index increased by 33% on average, while the water cut of the well fluid decreased by 4% on average. Up to 90% of treatments are successful and the effect can last for 4–24 months.
Abramov et al. [104]	Oilfield	63 bbl/day	Only zones with low water and high oil output were treated based on geophysical studies, resulting in a 20% reduction in water cut and a 91% increase in oil production after treatment of the test well.
Abramov et al. [105]	Oilfield	>26.5%	Viscosity reduction of 16% demonstrated in the well utilizing ultrasonic downhole tool without the use of chemicals was sufficient to produce heavy oil hydrocarbons.
Mullakaev et al. [108]	Oilfield	8.1 tons/day	The average well productivity index increased from 0.14 to 0.29 (107%) and water cut decreased by 28%
Mullakaev et al. [103]	Oilfield	5.4 tons/day	The average rise in well production rate was 70–80%, the average increase in well productivity index was 40%, the average drop in well fluid water cut is 8.2%, success rate of 75–85% and duration of effect 5–12 months.
Mullakaev et al. [110]	Oilfield	Increased by 4 tons/day	Water cut decreased by 8.6% and duration of ultrasound effect was between 6–10 months.
Hamidi et al. [111]	Laboratory Experiments	40.9% OOIP	In uncontrolled temperature experiments, more oil was retrieved than in controlled temperature experiments.
Agi et al. [57]	Laboratory Experiments	32–70% OOIP	The best oil recovery was achieved by combining intermittent vibration, high intensity, and a short distance from the energy source.
Agi et al. [27]	Laboratory Experiments	32–82% OOIP	Heavy oil recovered a higher percentage of oil in a shorter ultrasound time than light oil, whereas lighter oil recovered a higher percentage of oil in a longer ultrasound period.
Louhenapessy and Ariadji [100]	Laboratory Experiments	16–64.76% OOIP & Sor	Circular waves, as opposed to intermittent longitudinal waves, are better in increasing oil recovery by 3% and decreasing residual oil saturation (Sor) by 3%, according to the study's findings.
Luo et al. [65]	Laboratory Experiments	62.8% OOIP	Asphaltene dominates oil and solid particle adsorption in ultrasonic fields, affecting oil recovery significantly.
Wang et al. [80]	Laboratory Experiments	65.9% OOIP	This result indicates that the ultrasonic assisted CO_2 flooding can effectively reduce the minimum miscibility pressure and improve the recovery

performed in Western Siberia, production increased by 91% and water cut decreased by 20% [104]. The historical production of heavy oil field of Green River Formation, Utah, USA by El Paso company was 290 bbl/d, ultrasound stimulation led to additional production of 3,476 barrels in 6 months [4]. The rise in oil recovery can be credited to decrease in viscosity by ultrasound. For instance, Abramov et al. [105] reported a 26.5% increase in oil production after ultrasound reduced viscosity of oil by 16% in Tartarstan Field. Likewise, after ultrasonication of oil wells, vibration quickly reduced viscosity and accelerated the flowing velocity, resulting in an increase in production rate from 6.96 to 9.98 tons per day in 10 producing wells in the Shengli oilfield [106]. Presently, field application of ultrasound is centered around USA, China and Russia (Fig. 14). Table 4 summarizes the criteria for selecting a candidate well for ultrasound treatment [4,107].

Challenges and outlook

Ultrasound technology is an environmentally friendly and energy efficient approach in recovering oil, but the drawback is that it must be applied in situ and positioning of transducers is a major problem. The inefficiency of downhole ultrasonic radiation where the wave range do not exceed 1 m, vibration and energy travelling long distance attenuates. For instance, according to Agi et al. [57], positioning the micromodel 15 cm from the transducer retrieved more oil than placing it 30 cm from the transducer for both heavy and light oil. Naderi and Babadagli [35] stated that the intensity of ultrasound will decrease proportional to $1/r^2$ distance to the transducer. The closer the transducer to the porous media, the lesser the attenuation of the emitted energy. Likewise, in oilfield application it is recommended to place the ultrasonic downhole equipment near the side wall of the well. This can result in more uniform distribution of the ultrasound radiation and wilder penetration [104]. Other challenges include:

(i) Transducers efficiency

Transducers are mainly made of piezoelectric ceramics which are not resistant to high temperature and pressure reservoir condition. Piezoelectric ceramics are not tolerant to deep and ultra-deep reservoir conditions hence it cannot function underground for long [15]. They also contain heavy metals which are not environmentally friendly. Transducer's efficiency can be poor at high frequency over 1 MHz due to internal wave reflections and power losses induced in the cable might occur. To overcome these limitations ultrasonic transducers should be made of lightweight materials that are environmentally friendly, free of heavy metals (lead) and can withstand the harsh reservoir conditions. For example, Wang et al. [112] designed a high power ultrasonic downhole transducer made of lithium niobate crystals installed with a spring-piston auto-balancing device that can withstand 9.5 mPa oil pressure. Lithium niobate piezoelectric is free of lead and has a high Curie temperature of 1210 °C. Hence, it can withstand deep and ultra-deep reservoir conditions and can last for a long time.

(ii) Continuous mode

Presently, field application of ultrasound has been carried out in the continuous mode. Nevertheless, the earthquake event that sparked sequence of research did not occur continuously. Agi et al. [27,57] stated that compared to continuous ultrasound, intermittent ultrasound can recover more oil. This is because the intensity of ultrasound is intense in the first 15 minutes and more emulsions are produced during this period [69]. Therefore, intermittent application of ultrasound in oilfield can be cost effective. The intermittent mode is recommended for heavy oil production where blockage of the pore spaces occurs frequently. Therefore, ultrasound treatment can be performed intermittently to prevent blockage [4].

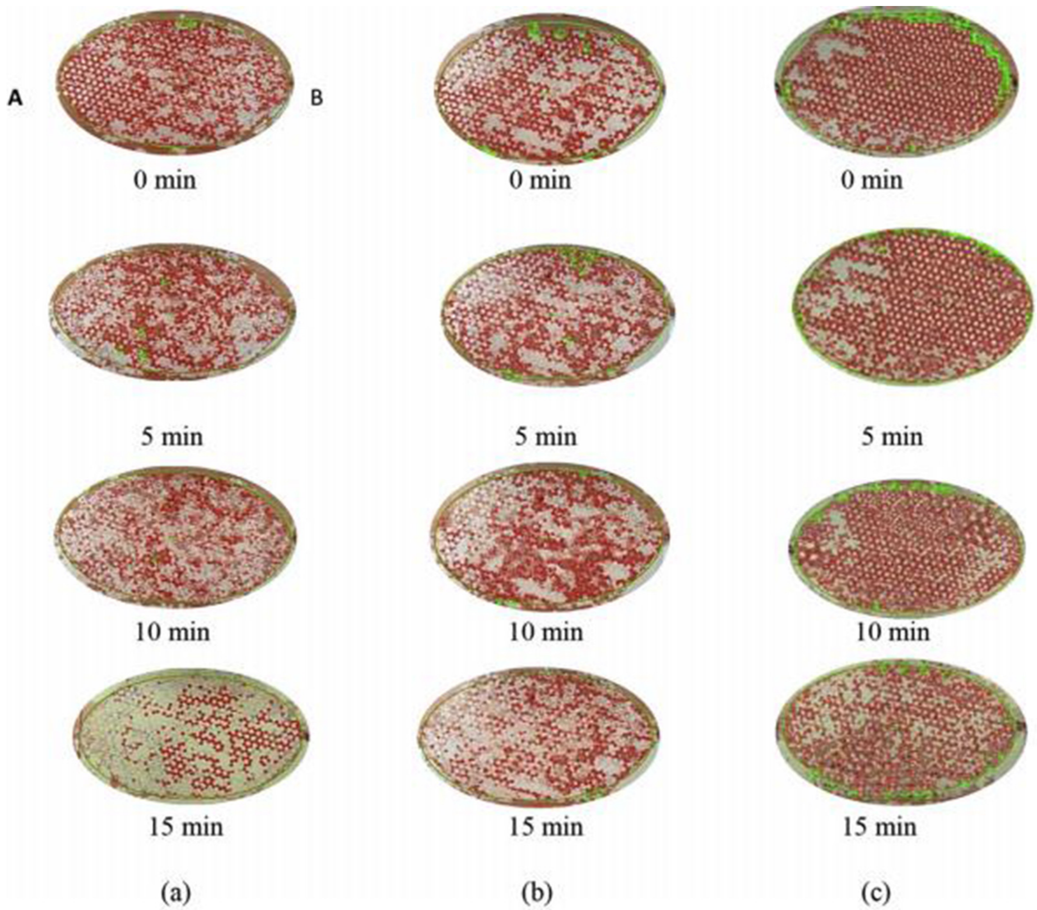

Fig. 13. Series of snapshot from 2D micromodel experiment (a) intermittent ultrasound, (b) continuous ultrasound, and (c) no ultrasound [57].

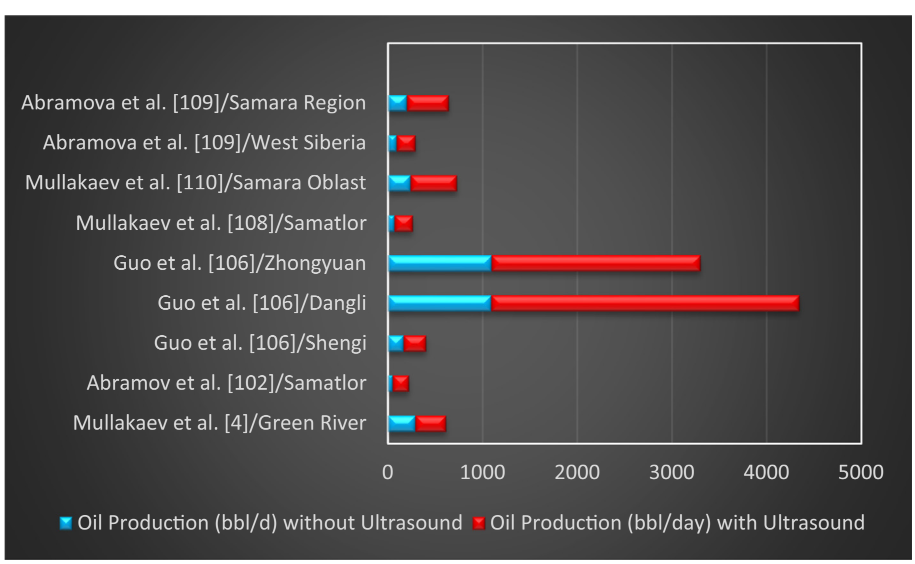

Fig. 14. Oil production at different oilfields before and after application of ultrasound [4,102,106,108–110].

(iii) Optimization of influencing parameters

Previous studies have shown that the efficiency of ultrasound application is dependent on various parameters such as time, frequency, distance from the source, mode of application, power and intensity. However, the optimum condition for laboratory application is still debatable. For example, Ning et al. [60], Jin et al. [62] and Gao et al. [61] all reported different optimum condi-

Table 4
Criteria for selecting oil wells for ultrasound treatment.

Light Oil Well Attributes	Data	Heavy Oil Well Attributes	Data
Decrease in Formation Pressure (%)	≤25	Proportion of Paraffin, Tarry & Asphaltene (%)	≤50
Water Cut (%)	≤80	Oil Saturation (%)	>50
Number of Layers in the perforated interval	≤10	Reservoir Type	Terrigenous or Carbonate
Thickness of Pay Zone (m)	≥3	Paraffin Crystallization	<BHT & FT
Spontaneous Potential	>0.5	Intake Capacity of Injection Wells	≥20
Permeability (μm^2)	>0.25	Sump (m)	>2
Clay Content (%)	≤15		
Dynamic Viscosity (mPa s)	≤25		
Oil Production Decline not Associated with Formation Pressure or Technical Issues	X2		

*BHT: Bottom Hole Temperature and FT: Formation Temperature.

tion for ultrasound application. This discrepancy might be due to the different method employed (probe or bath type), which varies from one research institution to another. There is need for optimization studies for even agreement of data to fully utilize the potential of ultrasound EOR in the field. Nevertheless, based on laboratory experiments and oilfield applications, it is recommended that the ultrasound treatment time should not exceed 60 minutes [9,17,65,70]. Power ultrasound is recommended for heavy oil recovery as intense temperature and pressure can be generated. Also, low frequency can propagate for longer distance.

(iv) Offshore application

Ultrasound oil production has been widely used onshore oilfields; however, offshore oil production is scarce due to the harsh reservoir condition. Alhomadhi et al. [26] recommended ultrasound for reservoir with high water saturation or a depleted reservoir which is consistent with criteria for selecting light oil well for ultrasound in Table 4. Likewise, Shafiai and Gohari, [113] stated that ultrasound treatment is very effective on wells with permeability above 20 mD and porosity higher than 15%. Also, downhole ultrasound stimulation can be used to rejuvenate failing oil wells and increase their production. Most offshore reservoirs have high porosity and permeability hence development of new transducers that can withstand the high temperature and pressure of offshore reservoir is desirable. Therefore, it is proposed that the current piezoelectric ceramic transducers used in onshore application should be replaced with lithium niobate transducers that can withstand the harsh reservoir condition of offshore reservoirs.

(v) Short transmission distance

The major challenge of ultrasound is its limited range of effectives. To overcome this challenge the design of ultrasound equipment should take into consideration the following properties. (1) Geophysical properties such as porosity and permeability of the reservoir, (2) Acoustic properties like penetration in various fluid and mediums, and (3) Geometric parameter of the reservoir like diameter and length of the well. Geophysical studies before ultrasound treatment enables you to select the optimal zones for treatment thereby enabling treatment of zones with low water and high oil production. For example, Abramov et al. [104] reported that when geophysical studies were conducted before ultrasound treatment water cut decreased by 20% and oil production increased by 91%. Furthermore, the limited range of ultrasound because of the low amplitude mechanical vibrations generated by the transducer can be amplified. This can be achieved by placing several half wavelength boosters to cover longer distance [114]. Furthermore, the use of one injection well and the line-of-sight placement of ultrasound transducers will eventually result in attenuation of the ultrasonic frequencies. It is recommended that multiple injection wells which is typical with conventional EOR techniques should be used. Whereby, the production well is surrounded by four injection wells and the transducers are placed at different heights in each injection wells. This will enable continuous pressure force developing from the side of the injection well to push oil towards the production well. Consequently, temperature will be high on the side of the production well which is located at the center of the injection wells. Thus, increasing oil recovery as opposed to single injection well.

Conclusions

In this paper, the impact of ultrasound on EOR mechanisms are presented. Likewise, the distinction between these mechanisms is elaborated. The outcomes of laboratory experiments match those of oilfield tests and new research opportunities have arisen as a result of the obstacles encountered. The following significant conclusions were derived from the findings of this study.

1. Direct method is preferable for heavy oil upgrading due to the energy dissipation rate while the indirect approach is better suited for oil displacement tests that require diffusion rather than focused energy.
2. High pressure can impede cavitation however, impurities and dissolved gases in fluid can promote cavitation which is a requirement for sonocapillary effect. On the other hand, coalescence can accelerate gravitational phase separation in porous media thereby improving relative permeability of oil.
3. A review of the literature reveals that excessive ultrasound power inhibits the formation of cavitation bubbles and the oil desorption from solid particles. Low frequency waves penetrate porous media more effectively and for longer distances than high frequency waves due to high attenuation. Intermittent ultrasound improves bulk mass transfer more than continuous ultrasound. As a result, peak values for acoustic pressure, velocity, acceleration, and droplet displacement may be an order of magnitude higher than in the continuous mode.
4. The results indicate that ultrasound vibrations can reverse asphaltene precipitation and remove deposited asphaltene from porous medium. By overcoming the surface tension between the particles and the surface and was able to transform the wettability of the porous media from hydrophobic to hydrophilic.
5. Finally, the review experimental data show that oil recovery by ultrasound ranges from 5-82% OOIP, with extra oil recovery occurring between 10–20 minutes of ultrasound, which could be due to the production of a more stable emulsion during this time. Oilfield results indicate that oil production increased in the range of 26.5–91%, water cut decreased by 4–28%, success rate was between 75–90% and the effect can last for 3–24 months.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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