

## Review

## Recent advances of ultrasound applications in the oil and gas industry

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## ABSTRACT

In the last two decades, ultrasound (US) technologies research has increasingly earned attention for applications in the oil and gas industry. Numerous laboratory and field research have proven ultrasonics as an efficient, sustainable and cost-effective technology for improving well productivity. This paper pursues the elaboration of a comprehensive review of the most recent research related to ultrasonic technologies for applications in the oil and gas industry. Statistical analysis of different functional categories and classification of the research publications were performed. Considering the research reviewed, there is a huge gap between numerical and field studies in comparison with the numerous laboratory studies, deeming it necessary to increase efforts on developing mathematical and numerical models and field-testing cases of the ultrasonic effect. A comprehensive review of the ultrasonic waves' mechanisms of action for enhanced oil recovery (EOR) and emulsification/demulsification was conducted. Despite the lack of consensus regarding the mechanisms, cavitation and thermal effects on wellbore fluid and formation rock have been widely accepted as two of the most influencing mechanisms. A compilation of the state-of-the-art research of numerical, laboratory and field studies in the last two decades was assembled. Most authors agreed that ultrasonics is a highly efficient method for EOR and emulsion treatment if the optimal conditions are identified and achieved. The development of screening criteria for the application of ultrasonic waves was recommended, as this technique and the same parameters should not be utilized for all reservoir types. Treatment with ultrasound waves has shown improvement of oil recovery efficiency rates of over 90% and viscosity reduction values over 80%. The most efficient results were observed when in combination with another conventional EOR method, where ultrasound boosts recovery efficiency. Potential new applications related to rock mechanics and additional research topics were also recommended.

## 1. Introduction

Current oil well stimulation methods such as acid stimulation are in many cases ineffective and might cause additional operational issues such as emulsion formation, secondary chemical reactions, among others. These methods also involve the use of dangerous contaminants jeopardizing the facilities, personnel, and the environment. Emerging new technologies such as ultrasound stimulation present numerous advantages compared to conventional methods required by the Oil & Gas (O&G) industry to perform maintenance operations and oil well stimulations. The present work intends to perform a comprehensive review of the available literature gathered regarding existing laboratory studies and field tests of the ultrasound technology.

Previous studies from different authors covered state of the art summaries for research related to ultrasound with quite specific scopes and timelines. The current work intends continuing previous

researchers' efforts with a wider focus integrating these reviews and publications, analyzing the most prominent applications for ultrasound technologies, and updating global summary with the latest publications and trends in ultrasonics and sonochemistry research.

After extensive research of different databases was carried out and organized into an indexed matrix related to ultrasonic/ultrasound technologies and sonochemistry. The resulting matrix was classified and examined considering industries or areas of study related to engineering, manufacturing and services. More than 470 research publications (over 7,000 pages of technical papers), 41 patents and 25 technical books related to ultrasound stimulation were accounted for in a period of two decades approximately.

Finally, the goal is to identify and unify criteria where there are sufficient arguments in terms of the research of acoustic cavitation mechanisms of action, key applications within the O&G industry, current updates in terms of equipment and technologies available for field

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applications, comprehensive analysis of advantages and disadvantages, and final recommendations for further research necessary to boost efficiency and optimize operational parameters.

For statistical analysis, research publications were classified per type of study, among other categories. These indicators covered the nature of the study such as purely theoretical studies, mathematical or computational modeling, and studies involving any laboratory testing and/or field testing, and in some cases, a combination of those. The analysis of these indicators helped assess the current state-of-the-art and the progress in mature technologies ready-to-use in the industry.

The distribution of publications per type of study can be seen in Fig. 1. In concordance with numerous authors, a lack of sufficient mathematical and numerical models simulating the mechanisms of US phenomena in the near wellbore area, and a dire necessity of field-testing applications in comparison with the laboratory studies can be observed. Most of the research only comprises laboratory experiments and measurements for specific applications or specific conditions. Further research simulating near wellbore conditions such as higher temperature and pressure or field tests to validate numerous experimental results are in order. The considerable absence of field tests publications might also be due to the fact that additional field experiences exist, but they have not been documented or published.

## 2. US in enhanced oil recovery

The main application found for US-assisted technologies aims for increasing oil production as an EOR method after the primary and secondary methods can no longer provide improved oil yield. Development and optimization of research resources and efficiency increase has been a priority. For this reason, the first task is to identify and understand the mechanisms that affect the ultrasonic waves to improve oil yield in the reservoir. It was noticed that the accepted mechanisms of action differ from one study to another, nonetheless, there are mechanisms widely accepted which can be considered useful for further research and applications.

One of the most detailed studies about the mechanisms of action of ultrasound and the main variables influencing oil recovery found was done by Agi et al. [12]. It is considered that ultrasound can improve the movement of oil in the reservoir, by altering the capillary forces through changes in the adhesion between rock and fluid and accelerate the gravitational forces allowing the segregation of fluids with multiple phases. Ultrasound mechanisms capable of influencing these forces were identified as cavitation, coalescence, Bjerknes force, microjets, peristalsis movement, sonocapillary effect, and acoustic streaming.

Other classifications of these mechanisms for EOR methods contemplate crude oil viscosity reduction, wax crystallization inhibition

and oil reservoir permeability enhancement (formation damage) as the responsible for the oil mobility increase (Luo et al. [56]), or mechanical vibration, cavitation, and thermal action (Wang et al. [97]). A brief description of the latter is shown in Table 1.

Despite the discrepancies between the revised studies, the most widely recognized mechanism in ultrasonic wave treatment is cavitation, and for that reason, understanding the parameters affecting cavitation has been of utmost importance for the optimization of ultrasound and its applications. For the optimization of cavitation, a wider consensus of the influencing ultrasound parameters affecting this phenomenon was found in the literature.

The main parameters affecting cavitation are classified between two categories: acoustic parameters and medium properties (Luo et al. [56]). The acoustic parameters identified include frequency, acoustic intensity, exposure or treatment duration, distance from the US source, operation mode and field type. The medium properties consist of fluid viscosity, interfacial tension, saturated vapor pressure, dissolved gas, and solid porosity.

Despite the previous research publications, questions still surround the use and optimization of US-assisted oil technologies. The complex physical and chemical mechanisms involved, and the lesser understanding and incomplete mathematical models of these phenomena cripple the possibility of effectively simulating the behavior and efficiency of ultrasound waves. The lack of detailed numerical models has been widely recognized and solving this deficit is necessary to optimize parameters, preserve resources and save research time.

EOR mechanisms such as vibration, bubble cavitation, and friction produced by ultrasound can prevent coagulation of heavy oils and reduce oil viscosity by up to 86 %. Additionally, ultrasound waves can lead to pore deformation, increasing oil recovery and restoring damaged formations, and ultimately, heat generated during ultrasonic irradiation also reduces the viscosity and aids emulsion rupture (Otumudia et al. [74]). Combined with solvent treatment consisting of toluene and n-heptane, ultrasound can alter the asphaltene aggregation and chemical structure in heavy oils, and further decrease the viscosity in comparison to samples treated with only one of the techniques (Qajar et al. [78]).

US treatment efficiency is higher with lower frequencies between 20 and 30 kHz, acoustic intensities lower than critical values, increased irradiation time, intermittent US field application and lower fluid

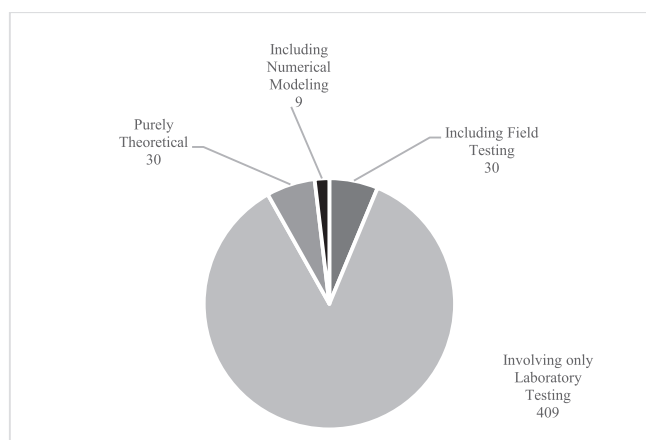


Fig. 1. Distribution of publications related to ultrasound technologies per type of study.

Table 1

Mechanisms for EOR proposed by Wang et al. [97].

Mechanism	Description
Mechanical vibrations	<ul style="list-style-type: none"> <li>• Destruction of cohesion between the plugged particles and the reservoir rock</li> <li>• Modification of the capillary pore size, reducing the surface tension of the pores, resulting in expansion and contraction of the capillary</li> <li>• Creation of micro-cracks in formation rocks</li> <li>• Increase of the local heating effect by means of the boundary friction</li> </ul>
Cavitation	<ul style="list-style-type: none"> <li>• Changes in sound pressure aiding the formation of continuously expanding bubbles quickly which break away from the capillary channels</li> <li>• Production of shock waves when the gas core collapses, which greatly enhances the mechanical action of the ultrasound waves</li> <li>• Reduction of the relative molecular mass of crude oil by breaking the molecular bonds of crude oil, thus reducing its viscosity, and improving its fluidity</li> <li>• Cascade of secondary effects such as such as chemical effects, sonoluminescence, dispersion and emulsification</li> </ul>
Thermal action	<ul style="list-style-type: none"> <li>• Acoustic energy is converted into thermal energy due to the absorption of the US waves in the aqueous media</li> <li>• Boundary friction at the interface of different media increases the temperature of the oil</li> <li>• Release of large amount of heat energy at the moment of bubble collapse during cavitation where the local temperature can reach thousands of degrees Celsius</li> </ul>

viscosity (Adeyemi et al. [6]). He studied and reviewed US-assisted technologies for the O&G industry, focused on emulsification and demulsification and EOR, as well as studies of the optimization of fluid and US properties in EOR. He also introduced the idea of additional research studies of new treatment conditions such as the use of Raschig rings, temperature, and salinity of the environment, and how they affect the US effect.

There have been numerous research publications studying the comparison and combination of US and other stimulation technologies such as chemical injection. One of these studies was carried out by Hamidi et al. [32], Mo et al. [58], Khan et al. [46], among others. Ultrasound showed promise in improving core permeability considering the overall of efficiency, cost, and safety in comparison with other methods. Moreover, the development of ultrasound technology could be aimed at working in synergy with other EOR methods, complementing each other to further improve recovery rates and decrease operational costs. For example, during chemical treatment, a combination of the chemical injection and ultrasound enables the chemical to penetrate deep into the formation and even into the smallest low permeability pores to remove pore bridges, allowing an increase in the efficiency, a reduction in the volume of required chemicals and saving operation time.

Ultrasound was recognized as an inexpensive and ecological method that can be applied in any type of reservoir, protects the well against damage, prevents heat loss, and enables stimulation freely Shafai et al. [86], leading to an increasing implementation of ultrasonic technologies for oil recovery in the past years.

A global summary of experimental EOR applications, mechanisms and other US-related research studies was performed. Numerous applications as alternative EOR methods for US-assisted formation damage reduction, viscosity reduction, surfactant flooding, CO<sub>2</sub> flooding, waterflooding, enhanced diffusion of colloids, among others (see Table 2.). This summary might support the identification of research gaps, development of screening criteria, parameter optimization, and evaluation of technologies for field applications.

Regarding advantages in the equipment for ultrasonic stimulation, two main equipment are used in the sonication process: ultrasound generators and transducers. Most used transducers in the field of acoustic oil recovery are made piezoelectric ceramic transducers (PZT). However, such piezoelectric ceramic transducers are prone to a large capacitive resistance in a transmission system and high temperature sensibility, thus, reducing the system efficiency and resulting in a great waste of energy, observing transmission efficiencies around 10 % to 20 % (Wang et al. [97]). A new design of transducers consisting of lithium niobate crystals could increase the temperature resistance threshold up to 1200 °C and make them able to withstand the harshest downhole environments with higher pressure and temperature conditions (Agi et al. [12]).

Research surrounding field testing has been scarce amongst the entire research publications. Most of the published work which includes field testing has been carried out in Russia by Abramov, Abramova, Mullakaev et al. (Table 3) and proved that ultrasonic stimulation can successfully increase oil production by reducing formation damage and increasing oil mobility (by means of US-assisted viscosity reduction, heat generation and capillary effect). More recently, Chang et al. [23] studied the successful application of a Swiss ultrasonic stimulation technology in offshore wells in Asia. High power ultrasonic stimulation was applied in two offshore wells and results showed an increase of oil production of 30 % in one of the wells and restored communication between the production tubing and casing by removing the wax clogging the gas lift valves in the other well. There has not been published any research related to field testing of ultrasound technologies for EOR since 2019.

There has been some debate about the criteria for evaluation of wells for ultrasound treatment. A reservoir, fluid and optimal wave properties analysis has been discussed and recommended in order to increase the

**Table 2**  
Research publications with experimental testing.

Application	Reference	Study Overview
CO <sub>2</sub> flooding	Wang et al. [95]	US application for oil–gas miscibility during CO <sub>2</sub> flooding and extraction of tight oils
	Hamidi et al. [36]	US-assisted CO <sub>2</sub> flooding in a porous media, parameters optimization incl. temperature
Enhanced diffusion of colloids EOR	Yeh and Juarez [102]	US application for colloidal particles mobility increase of in porous media
	Qajar et al. [78]	Effect of US and solvent treatment on heavy oil rheology and asphaltene structure
	Abdulfatah [11]	US as EOR using Niger Delta crude oil
	Agi et al. [10]	Acoustic parameters study for recovery of kerosene and paraffin
	Arabzadeh and Amani [20]	US as EOR by means of free fall gravity drainage
	Mohsin and Meribout [62]	Model for US as EOR
	Naderi and Babadagli [70]	Immiscible displacement processes under US waves
EOR from sludges	Najafi [71]	US as EOR by means of free gravity drainage
	Lins et al. [53]	Study of US treatment combined with mechanical stirring for oil recovery from waste lubricant oil
	Luo et al. [55]	Effect of US treatment on oil recovery from oily sludges
	He et al. [37]	US parameters study on EOR from sludges
Formation damage	Gao et al. [27]	US waves on the oil components removal from oily sludge
	Otumudia et al. [75]	Effect of ultrasound in removing plugging using glass models to simulate oil reservoirs
	Ghamartale et al. [29]	Permeability and pore structure enhancement using US
	Wang and Huang [96]	Water-induced damage treatment using US and chemicals
	Khan et al. [44]	Permeability recovery on water-induced damaged cores using US
	Naderi and Babadagli [69]	Capillary interaction and EOR study using US waves on rocks
	Taherynia et al. [92]	Imbibition studies on limestone samples from Iranian fields
	Khan et al. [47]	Permeability recovery on damaged cores using chemicals and US
	Guo et al. [31]	Effect of US waves on fluid density, porosity and permeability
	Li et al. [49]	Effect of US on shale gas flow characteristics and gas production
	Mo et al. [58]	Colloidal precipitates removal using US and chemicals
	Karami et al. [42]	Condensate blockage removal using US treatment
	Ainuddin et al. [15]	Influence of US amplitudes on the removal of condensate in heterogeneous glass packs
Khan et al. [45]	Removal of calcium carbonate in the near wellbore region	
Khan et al. [46]	Comparison of US and chemical to remove calcium carbonate plugs	
Pu et al. [77]	Removal of inorganic scale damage using US	
Zhang et al. [106]	Removal of calcium carbonate using US and chemical treatment	
Kunanz and Wolfel [48]	Scale removal using US treatment	
Xu and Bao [100]	Removal of asphaltene using US and chemicals	
Zhou and Wang [108]	Removal of paraffins using US and chemicals	
Otumudia et al. [73]	US parameters and rock pore geometry on asphaltene removal	

(continued on next page)

Table 2 (continued)

Application	Reference	Study Overview
	Rezaei Dehshibi et al. [82]	Study of effect of US treatment on asphaltene deposition
	Salehzadeh et al. [85]	Study of US effect of asphaltene aggregation and deposition
	Mousavi et al. [63]	US effect on rheological prop. and viscosity of heavy oils
Surfactant flooding	Wang et al. [99]	Effect of frequency on removing drilling fluid, paraffin deposition, polymer and inorganic scale plugs
	Agi et al. [14]	Paraffin recovery using US along with water and surfactant flooding enhancement and critical micelle concentration study
Viscosity reduction	Hamidi et al. [34]	Effect of US on phase behavior of surfactant-brine-oil system
	Tahmasebi Boldaji et al. [93]	US effect on heavy oil viscosity using mathematical and ANFIS models
	Cui et al. [24]	Effect of metallic nickel particles addition in the US treatment process for increased cavitation
	Lv et al. [88]	Effect of US on the viscosity and pour point of crude
	Hua et al. [38]	Effect of US on the viscosity of heavy crude oil
	Rezaei Dehshibi et al. [81]	Study of the US assisted recovery of two crude oils with differences in viscosity (light and heavy oil)
	Shie et al. [87]	Application and mechanism of ultrasonic static mixer in heavy oil viscosity reduction
	Mullakaev et al. [68]	US effect on the viscosity and congelation temperature of crude oils with various compositions
	Hamidi et al. [35]	Effect of US on pressure drop and viscosity in porous media
	Razavifar and Qajar [80]	US effect on viscosity of oil with a high asphaltene concentration
Waterflooding	Aliev et al. [17]	US influence on rheological properties of heavy oil
	Rahimi et al. [79]	US effect on rheological behavior of extra heavy oil
	Wang et al. [98]	US effect on ultra-heavy oil viscosity reduction
	Alhomadhi et al. [16]	Effect of US on mobility of oil during waterflooding
	Li et al. [50]	US-assisted waterflooding in low-permeability reservoirs
	Mohammadian et al. [60]	US-assisted waterflooding as oil recovery method
	Mohammadian et al. [61]	US-assisted waterflooding as oil recovery method
	Mohammadian et al. [59]	US effect on oil recovery in waterflooding
	Taheri Shakib et al. [90]	KCl scales removal using US-assisted waterflooding
	Taheri Shakib et al. [91]	NaCl scales removal using US-assisted waterflooding
Nanotechnology	Agi et al. [13]	US assisted flooding and cavitation to enhance heavy oil recovery using empty fruit bunch SiO <sub>2</sub> nanoparticles (EFBSNP)
	Agi et al. [11]	US-assisted crystalline starch nanoparticles production w/ ascorbic acid

success of the treatment, as well as pulse or continuous mode of operation before employing ultrasound stimulation. Agi et al. [12] proposed criteria for selection of suitable wells from light and heavy oil reservoirs depending on fluid and reservoir properties. Field tests showed good improvement in oil recovery and decrease in water cut shown under the influence of ultrasound at the specific conditions Hamidi et al. [32] consistent with the mentioned criteria.

Shafiai et al [86] considered the idea that one specific technique should not be utilized for all reservoir types, making it necessary to

Table 3

Summary of research publications related to US field tests.

Reference	Overview	Main Characteristics	Findings
Chang et al. [23]	First application of ultrasonic technology in offshore wells in Southeast Asia	Irradiation time 20 min/ft Frequency 20 kHz US power 1 kW	<ul style="list-style-type: none"> <li>Oil production increased by 30 % in well X after US treatment</li> <li>Pressure communication between tubing and casing in well Y successful removal of wax clogging gas lift valves by US</li> <li>Potential for stimulation of the tubing walls and gas lift valves if any plugging suspected</li> </ul>
Abramov et al. [3]	Study of influence of ultrasound on fluid viscosity under reservoir conditions	US generator 9 kW Frequency 19 kHz Max. temperature 65 °C Exposure time 24 h	<ul style="list-style-type: none"> <li>Oil production increase by 0.4 tons/day</li> <li>After 4 h treatment, viscosity reduction of 16 % was observed</li> </ul>
Mullakaev et al. [65][66]	Testing of US equipment in 27 wells in Samotlorsk field	Frequency 19 kHz Max. temperature 85 °C US power 2 kW	<ul style="list-style-type: none"> <li>Average increase in production rate by 75 %</li> <li>Well productivity index increased by 40 %</li> <li>Decrease in water cut by 8.2 %</li> </ul>
Abramov et al. [2]	Study of a selective ultrasound technique for perforated regions in horizontal wells with high water cut	Oil density 940 kg/m <sup>3</sup> Paraffin content 47 wt% Viscosity 6,800 mPa.s US generator 2–10 kW Frequency 13–26 kHz	<ul style="list-style-type: none"> <li>Oil production increased by 91 %</li> <li>Water production decreased by 20 %</li> </ul>
Mullakaev et al. [64][67]	Testing of thermoacoustic equipment in Samotlorsk field, Samara region and Utah, USA	Frequency 19 kHz Max. temperature 85 °C US power 2 kW	<ul style="list-style-type: none"> <li>Production increased by 75 % in Samotlorsk, 107 % in Samara region, and 4.45 ton/day for over 6 months in Green River Formation</li> </ul>
Abramova et al. [5]	US treatment for enhanced oil recovery	Over 100 wells with different characteristics Frequency 13–26 kHz	<ul style="list-style-type: none"> <li>Success rates of 90 %</li> <li>Oil production rate increased 40–100 %</li> <li>Effects sustained for 3–5 months</li> <li>Additional testing for efficiency without pump optimization effect confirmed US oil productivity enhancement and water cut reduction</li> </ul>
Abramov et al. [4]	Application of ultrasonic enhancement on failing wells by stimulating the wells with an ultrasound source	Permeability 20 mD Porosity 15 % Frequency 18–27 kHz US power 10 kW	<ul style="list-style-type: none"> <li>Production rate increased by 50 %</li> <li>For wells with high permeability and porosity, potential increase for up to 85 %</li> <li>For wells with low permeability and porosity, recommended combined treatment with chemicals</li> </ul>

perform an EOR screening by analyzing the work of Kamari et al. [40] and Kang et al. [41]. The most suitable EOR methods need to be identified for specific reservoir conditions which can be obtained by selecting an optimized method among alternatives or prioritizing alternatives based on reservoir characteristics and oil properties criteria. Summaries compiled in this work might contribute to the development of screening criteria for US-assisted technologies successful application or combination with other EOR techniques such as emulsification, water/surfactant/CO<sub>2</sub> flooding, hydrocarbon gas miscible, polymer processes, among others.

### 3. US in emulsion treatment

Important applications for the ultrasonic waves in the O&G were found to treat emulsions, for both emulsification and demulsification. Ultrasonic assisted methods and technologies showed the ability to improve oil recovery and emulsions separation. Same as for EOR applications, it was observed that combined treatments with ultrasound waves assisting other conventional methods have been studied, showing that US-assisted emulsion separation methods can be considerably more efficient than standalone treatments.

Table 4 shows a list of the most recent research for US alone and US-assisted technologies for emulsion treatment, showing a range of studies to understand the main influencing parameters and mechanisms, emulsification and demulsification applications, and oil recovery rates obtained.

Numerical assessments of the coalescence of water droplets in water-in-oil emulsions and oil droplets in oil-in-water emulsions addressing the

**Table 4**  
Research publications for emulsions applications.

Reference	Overview
Adeyemi et al. [8]	Experimental and numerical analysis of the emulsification of oil droplets in water with ultrasound
Adeyemi et al. [9]	Study of US assisted coalescence of water droplets in oil including techno-economic assessment
Adeyemi et al. [7]	Effect of various parameters on the acoustic pressure and coalescence time of water droplets in oil phase
Sadatshojaie et al. [84]	Study of US treatment for separation of medium gravity crude oil emulsions
Ronchi et al. [83]	Application of a US-assisted technique for removing oil from oily water without demulsifiers using Raschig rings
Luo et al. [57]	Effect of US parameters on emulsion separation with different physical properties
Lim et al. [51]	Study of the effect of US waves amplitude on the demulsification of crude emulsions at different temperatures
Vahdanikia et al. [94]	Study of the simultaneous influence of US waves and microorganisms on the stability of w/o emulsions
Atehortua et al. [21]	Use of a high frequency ultrasonic standing wave coalescence chamber to separate water in crude oil emulsions
Xu et al. [101]	Study of demulsification/dehydration for crude oil using US waves
Luo et al. [54]	Study of the application range and optimal parameters for separating water-in-oil (W/O) emulsions using ultrasonic standing waves
Khajehesamedini et al. [43]	Study of the feasibility of using low-frequency ultrasonic waves to reduce chemical demulsifiers consumption in the pretreatment of crude oil
Pedrotti et al. [76]	Development of an automated system for mapping and evaluating the acoustic intensity distribution for demulsification efficiency measurements
Yi et al. [103]	Study of demulsification using a combined treatment of US and chemical demulsifier
Antes et al. [18]	Comprehensive study for the evaluation of US frequency effect on demulsification of crude oil emulsions
Hamidi et al. [33]	Study of US effect on brine-oil interfaces (emulsion) in a reservoir using Hele-Shaw model
Antes et al. [19]	Study on the feasibility of indirect application of low frequency US for demulsification of crude oil without using chemical demulsifiers

effect of various parameters on the acoustic pressure and coalescence time were considered. For the coalescence of water in W/O emulsions, the numerical simulation provided acceptable results, and the experimental validation showed that the coalescence time decreased within the range of interfacial tensions. The cause for this decrease was considered to be because lower interfacial tension produces more stable emulsions. Consequently, at lower interface tension between water and crude oil, higher resistance to the coalescence of the droplets due to improved emulsion stability was observed (Adeyemi et al. [7]). In the case of oil droplets in O/W emulsions, numerical simulations accurately modeling both trend and magnitude of the derived acoustic pressure data were obtained. The experimental results also showed the influence of ultrasonication on different variables. As the power and frequency increased, smaller size bubbles were obtained, and the catastrophic break up became more intense obtaining higher Weber numbers, thus, showing signs of improved emulsification (Adeyemi et al. [8]). An emulsion separation technique comparison was also carried out between US, electrostatic and microwave assisted technologies. US-assisted separation confirmed lower coalescence time with growing interfacial tension. Additionally, ultrasound proved the most potential in energy and economic savings, and the best option to be used as a standalone technique or in synergy with other techniques for emulsion separation, same as for applications in EOR (Adeyemi et al. [9]).

Sadatshojaie et al. [84] evaluated the performance of ultrasonic waves in demulsifying crude oil emulsions using a novel horn-type piezoelectric ultrasonic transducer. Tests proved that applying ultrasound caused water separation effectively and rapidly, even in the absence of any chemical (demulsifier). Nonetheless, in samples with initial water cuts of > 20 %, long irradiation times (approx. 5 min) resulted in a decline in water separation compared to two-minute tests.

### 4. US in oil Pre-Treatment processes

Recent work regarding the use of ultrasound waves for crude oil pre-treatment processes was revised. Nasri et al. [72] reported the use of ultrasonic waves to improve the desulfurization process of crude oil in Iran. The study included the effect analysis of different parameters, including ultrasound power, phase transfer agent (PTA) amount, catalyst amount, preheating temperature, and reaction time. The results indicated that increasing ultrasonic power, reaction time, and catalyst amount had positive influences on sulfur reduction, observing an optimal point in increasing PTA and preheating temperature. The first 10 min of the treatment were equivalent to three times in sulfur reduction of ultrasound assisted oxidative desulfurization (UAOD) process than that of the process during the latter 90 min. A similar study was performed by Fan et al. [25] in Saudi Arabia. The UAOD of Arabia extra light oil was performed at 60 °C and was able to remove 56.5 % of sulfur from the oil feedstock. The use of ultrasound instead of mechanical stirring significantly shortens the reaction time by over 80 % (from 80 to 15 min). Lin et al. [52] explored the effects of different parameters on desulfurization rate in UAOD. Parameters such as reaction temperature, reaction time, oxidant and demulsifier quantity were studied. It was proven that the ultrasonic treatment was able to improve the desulfurization efficiency by about 10 % with a power of 100 W and a frequency of 70 kHz. Lin also found that adding ultrasound can promote heterogeneous reactions, improve the activity of oxidants, and promote the degradation of macromolecular compounds.

Sinhmar et al. [89] combined an extractive and oxidative desulfurization approach based on ultrasound (US) and ultraviolet (UV) irradiations with additives using toluene and thiophene as representative fuel and model sulfur component, respectively. The desulfurization process was considerably improved when the combination of US and UV irradiation was applied rather than the standalone methods. This demonstrated that the combined US/UV approach coupled with use of oxidants and catalyst can promote the optimum conditions for a successful removal of thiophene.

Guida et al. (2022[30]) described a numerical approach to model ultrasonically induced cavitation (UIC) reactors including advanced computational fluid dynamics (CFD) models and bubble dynamics. This algorithm simulated the operation of an UIC reactor designed for the desulfurization of fuels using the oxidative (ODS) process.

Yi et al. [104] studied US assisted bio-desulfurization (BDS) using ultrasonic radiation to pre-oxidize the compounds before the BDS process. Findings revealed that the application of US before BDS procedure significantly improved its efficiency and allowed sulfur removal in shorter time.

## 5. US in oil recovery from Sludges, Wastewater, tar or oily sands

Some oil recovery or environmental applications to separate oil from waste for final deposition or treatment have been studied. There have also been an interesting application for recovery applications. Nevertheless, there is still a considerable lack of information especially on the pilot scale and field applications such as US-assisted treatment for oil recovery/removal from wastewater, oily sludge, tar or oily sands. Nevertheless, all the research found was mostly experimental.

On recent research in this field, the work of Luo et al. [55] was found. He studied the acoustic parameters and operating conditions that determine efficiency of oil recovery from oily sludge. The results exposed an improved efficiency of oil recovery from oily sludges using ultrasound and optimal parameters for increased desorption of oil from solid particles were found. Luo et al. attributed this improvement to the breakage that mechanical effects such as shock waves and micro jets due to acoustic cavitation can provoke on the hydrogen bonds between asphaltenes and solid particles, thus facilitating oil recovery from oily sludge.

Gao et al. [28] worked on the optimization of ultrasonic parameters based on pilot tests on oil removal from oily sludge. Removal rates of up to 60 % and oily sludge contents of 42 % were achieved, with the possibility of further improvement by the addition of surfactants. In 2015, Gao et al. [27] also investigated the removal of different components from oily sludge using ultrasonic treatment. Applying frequencies between 25 and 100 kHz, results showed that optimal ultrasonic washing performance in terms of oil extraction rate and efficiency was observed at 25 kHz. Another interesting finding from this experience was that ultrasonication could overcome high energy thresholds, resulting in an increase in the removal of asphaltenes and resins, with the removal of asphaltenes particularly affected by frequency.

Jin et al. [39] used a combined treatment of ultrasound waves, chemicals and heating to treat oil sludge from an oil storage tank and evaluated the effects of temperature, time, frequency, power, and other factors on oil recovery. Results showed that the combined US-assisted treatment reduced the oil content of oil sludge from 43.13 % to 1.01 %. Compared with traditional thermochemical cleaning, the oil recovery was higher with the combined treatment system.

As mentioned in previous sections, Zhang et al. [105] studied ultrasound treatment in conjunction with freeze/thaw process for treatment of oily sludge. The US-assisted process accomplished an acceptable performance by considering 80 % of oil recovered from wastewater with only 10 min of treatment.

Membrane ultrafiltration improved by using ultrasound to reduce membrane fouling process was studied by Borea et al. [22]. Results showed a significant reduction of membrane fouling rates at the higher membrane flux and lower US frequency applied, and improved removal of organic matter and turbidity if applied ultrasound at a higher frequency (130 kHz). These results prove the applicability of this combined process for the upgrading of membrane ultrafiltration and as an alternative option to conventional wastewater treatments.

Zhao et al. [107] studied the US-assisted synthesis of a new flocculant for remotion of the turbidity and oil from water, significantly improving flocculation performance.

In case of oil separation from oily sands, Fu et al. [26] proposed an

extraction process assisted with a dual-frequency ultrasound technology for oil sand separation. A comparison of single frequency and dual frequency ultrasound treatment with surfactants was performed. Dual rate ultrasound stimulation yielded a considerably higher oil recovery rate of up to 95 % in comparison to single frequency treatment with short time of exposure. Therefore, dual-frequency ultrasound assisted surfactant extraction showed high efficiency and low resource consumption, proving to be an excellent option for the treatment of oily sands.

Another study performed by Ronchi et al. [83] proposed a methodology to remove oil from oily production water using low-frequency ultrasound. In his research, he investigated the application of low-frequency ultrasound waves to separate synthetic heavy crude oil-in-water using Raschig rings as most previous studies focused only on low viscosity dispersed phases (vegetable oils). The effects of frequency, temperature, US irradiation time, oil content of synthetic oil-in-water emulsions, and different materials were evaluated. High removal efficiencies of up to 76 % were obtained, especially using high frequencies and lower oil contents. These results show great promise of low-frequency US association of glass Raschig rings for treating the produced water to remove oil.

Zou et al. [109] proposed a new process for ultrasonic-assisted surfactant extraction of bitumen from Buton oil sands with recovery rates of over 90 % and promising applications.

Luo et al. [56] provided a summary review for oil extraction from oily sands including US-assisted methods. Even though most of their research and references dated back to a decade ago, they can be considered for background of applications and references for future studies, especially experimental experiences highlighted in their work.

## 6. Conclusions

From these summaries and reviews, we can conclude the following:

- Ultrasonic stimulation is a promising technology that has proven to be highly efficient, environmentally friendly, and low cost for EOR by reducing the formation damage, unclogging perforation channels and increasing oil mobility. Nonetheless, there are numerous requirements for optimization.
- The effect of ultrasound frequency, power output, irradiation time are considered some of the most influential variables on the efficiency of the treatment. However, the optimal values depend on several conditions, some of which have been partly identified and some of which have yet to be identified or studied further.
- Numerical and mathematical studies are required to understand the ultrasound mechanisms of action and the effect on the reservoir and the fluids. Higher understanding and development of more comprehensive and enhanced US models and the ability to simulate the effect will allow the possibility to save valuable research time and resources, and to increase the success rate of ultrasound based and assisted applications.
- The application of ultrasound waves in combination with other conventional technologies significantly boosts oil recovery rates and overall treatment efficiency in comparison to standalone treatments. For example, US-assisted chemical treatments can promote the use of greener alternatives of chemicals and surfactants, decrease chemical consumption, improve contact areas between the reagents and the reservoir, and reduce operation time and resources. More research studies are required in the evaluation of ultrasound integration with reagents alternatives in the industry.
- The utilization of ultrasound waves for the treatment and separation of emulsions has also been proven. US parameters play an important role that can completely change the effect. Research showed that irradiation time can cause oil separation from the emulsion up to a peak or critical value, and further exposure over this critical value caused the opposite to the desired effect. Ultrasound frequency,

power output and emulsion composition were also considered key parameters affecting the treatment performance.

- The application of ultrasound waves has not been limited to EOR and emulsion treatment applications. US based technologies for the treatment of wastewater, sludge, oily and tar sands have been studied with successful cases and promising results.
- Several experimental studies support the application of ultrasound technologies as a suitable EOR method, however, there is not enough research on field trials in order to optimize ultrasonic parameters. Conducting additional field studies is highly recommended to validate current experimental data, provide comprehensive understanding of the US effect in complex environments, evaluate existing technologies and equipment, and ultimately, develop accurate numerical and computational models of the mechanisms.
- Additional research studies of new treatment conditions such as the use of Raschig rings, temperature and salinity of the environment and how they affect the US effect are recommended for the future.
- New research models need to be proposed as a combination of highly focused R&D projects, and comprehensive evaluation and trials of existing technologies.

#### CRedit authorship contribution statement

**Jesus Mierez**: . **Murtadha J. AlTammar**: Funding acquisition, Supervision, Writing – original draft. **Khalid M. Alruwaili**: Funding acquisition, Supervision. **Rima T. Alfaraj**: Funding acquisition, Project administration, Supervision.

#### Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Jesus Ricardo Mierez reports financial support was provided by Rexonic Ultrasonics AG. Jesus Ricardo Mierez reports a relationship with Rexonic Ultrasonics AG that includes: employment..

#### Data availability

Data will be made available on request.

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