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REVIEW PAPER--PRODUCTION ENGINEERING

Conventional and electrical EOR review: the development trend of ultrasonic application in EOR

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Abstract
A small portion of oil can be extracted during primary and secondary stages of oil production, and significant quantities of oil remain in reservoirs. Enhanced oil recovery methods are used to extract the trapped oil with high viscosity in reservoirs and improve the efficiency of the production wells. Ultrasonic-based enhanced oil recovery method has become of considerable interest to researchers in recent years. This paper mainly presents the in-depth literature review of ultrasonic wave to investigate its application development trend in enhanced oil recovery. Besides, it also presents an overview of conventional enhanced oil recovery techniques such as chemical, gas, and thermal methods and nonconventional techniques such as electromagnetic and microwave heating. The results exhibit an increasing implementation of the ultrasonic waves for oil recovery since it is an inexpensive and ecologically sound method, can be applied in any type of reservoir, protects the well against damage, prevents heat loss, and enables stimulation freely.

Keywords Enhanced oil recovery · Conventional methods · Ultrasonic · Electromagnetic · Microwave heating

Introduction

Crude oil is a complex combination of different hydrocarbons such as carbon, hydrogen, sulfur, nitrogen, oxygen, metals, and salts. Hydrocarbons are the simplest organic compounds that include chemical and physical properties. The smaller hydrocarbon molecules (such as methane, propane, and butane) are found in natural gas. The larger hydrocarbons such as hexane and octane make up petroleum products. Marine organisms and macroscopic animals in plant died and settled in the bottom of the ocean approximately 2 billion years ago. Beneath the sediment in the ocean, and without oxygen, these fossils changed to a substance called kerogen. Then, kerogen slowly changes into oil or gas due to existing heat and pressure. Generally, the complete process takes at least a million years forming two main types of crude oil which are light and heavy oil. Light crude oil, which can be extracted easily, has low viscosity, low density, and high American Petroleum Institute (API) gravity. However, heavy crude oil has a viscosity ranging from 50 mPa s up to about 50,000 mPa s that has limited mobility under reservoir temperature and pressure and does not flow easily (Mai et al. 2009). The global in-place resources of heavy oil are about 991.18 billion tonnes in which 126.74 billion tonnes of that is recoverable (Liu et al. 2019). The average oil recovery rates in a worldwide scale and in the USA are 30% and 39%, respectively (Yernazarova et al. 2016).

Oil production is broken down into primary, secondary, and tertiary phases. The primary stage is the process of oil recovery based on the natural pressure or energy of the reservoir. At first, the pressure of the reservoir is noticeably higher than that of bottomhole inside the wellbore. Then, due to this pressure difference, the oil flows into the well and up to surface. Subsequently, the pressure of the reservoir decreases due to the sustained process of recovery. Thus, to avoid the effect of reservoir pressure reduction, artificial lift devices such as pump jacks are used to maintain the production and raise the oil to the surface (Andrei et al. 2010). The primary stage continues until either the available pressure in the reservoir is significantly low or the existence of the amount of water or gas in the recovery stream is very high. The average rate of oil extraction in the primary stage is between 5 and 20% of the original oil in place (OOIP)

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(Verma 2015). Influential parameters in oil extraction in the primary stage are the mechanism of drive and properties of oil and rock.

The secondary stage of oil recovery extends the field's productive life by increasing the pressure inside the reservoirs or by oil displacement directly into the production wells and driving oil to the surface through various methods. Adopted methods in this stage include hydrocarbon gas injection, which is a very costly method for oil companies, waterflooding, which is the most common method, carbon dioxide (CO_2) injection, chemical flooding, etc. (Green and Willhite 1998). The rate of oil extraction after employing the secondary recovery method can be increased up to 40%, depending on oil properties, geological and reservoir characteristics, and well configuration (Laherrere 2001; Hite and Bondor 2004; Chierici 2012; Ayirala and Yousef 2015). The recovery efficiency of primary and secondary stages is about 33% of OOIP (Godec et al. 2011), and about 67% of oil remains trapped in the reservoir (Bahadori 2018). The oil recovery rate in the primary and secondary phases is low mainly due to interfacial tension between oil and water (capillary forces), high mobility ratio, and the heterogeneities in the reservoir rock.

The tertiary recovery or enhanced oil recovery (EOR), which is usually enforceable after secondary recovery stage, is a technique used for displacement of the remaining oil trapped in the reservoir by applying injection of materials not normally present in the reservoir (Archer and Wall 2012). In other words, EOR is the technique or process where the physicochemical (physical and chemical) properties of the rock are changed to improve the efficiency of hydrocarbon production. The most significant aims of the EOR techniques are to reduce the interfacial tension between oil and water, reduce capillary pressure, and decrease of the mobility ratio between oil and water by increasing the viscosity of water (Littmann 1997; Williams 2003; Gharabi 2005; Zhu et al. 2005). Thomas (2008) pointed out that the type of reservoir has a remarkable influence on the EOR target, as shown in Fig. 1. In light oil reservoirs, application of the primary and secondary stages enables extraction of 55% of oil in place (OIP), and remaining oil (45%) can be recovered by using EOR methods. However, EOR methods are responsible for a very big portion of oil extraction in heavy oil reservoirs and tar sands since these types of reservoirs have a very poor response to the primary and secondary stages. The EOR techniques can be employed in circumstances such as when the well is damaged because of overusage of the drilling mud or it is damaged by salt and sediments, there is no increase in recovery rate while water and acid are injected into the well, there is low production rate while the well's production is potentially high, and heavy oil and paraffin are produced by the wells (Speight 2013).

Our contribution attempts to provide an overview of the conventional and nonconventional EOR methods, more specifically the development trend of the ultrasonic stimulation technique in oil recovery improvement. The section after Introduction is discussing conventional methods of EOR. In the next section, the EOR screening is discussed. The next section discusses electrical-based enhanced oil recovery (EEOR) which includes electromagnetic heating and ultrasonic stimulation. The next section presents conducted researches related to the implications of the ultrasonic waves in EOR. The last section contains our conclusions.

Conventional methods of EOR

Conventional EOR methods include chemical (CEOR), gas injections, thermal recovery, microbial (MEOR), low-salinity waterflood, and foam-EOR, among others. Each EOR method is constituted of different techniques which is shown in Table 1 (Kong and Ohadi 2010; Alvarado and Manrique 2010; Ayatollahi and Zerafat 2012; Viebahn et al. 2015; She et al. 2019).

CEOR methods include traditional methods such as polymer flooding, surfactant, and alkaline flooding, combined traditional methods such as surfactant–polymer (SP), alkaline–surfactant–polymer (ASP), etc., and foam processes.

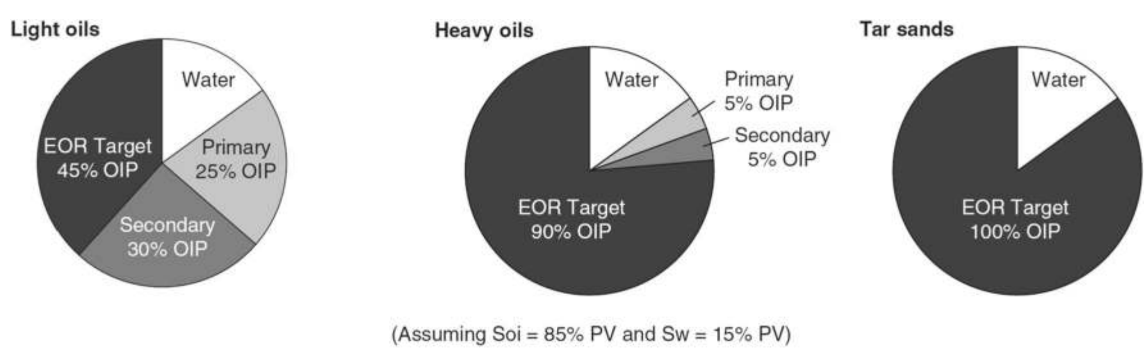

Fig. 1 EOR target for different oil reservoir types (Thomas 2008)

Table 1 Different methods of conventional EOR

Chemical methods	Microbial	Gas methods	Thermal methods
Alkaline flooding	Microbial flooding recovery (MFR)	Hydrocarbon gas injection	Steam flooding
Polymer flooding	Cycle microbial recovery (CMR)	N_2 injection	In situ combustion
Surfactant flooding	Microbial selective plugging recovery (MSPR)	CO_2 injection	Cyclic steam stimulation (CSS)
Micellar flooding	Others	Air injection	Steam-assisted gravity drainage (SAGD)
Alkaline–surfactant–polymer (ASP) flooding		Water-alternating-gas (WAG) injection	Electrical heating
Foaming agents, acids, and solvents			
Low-salinity water flooding (LSW)			

CEOR methods are applicable to light oil reservoirs (Alvarado and Manrique 2010), attempting to decrease interfacial tension (IFT), brine viscosity increment for mobility control, and sweep efficiency enhancement of the injected fluid (Shah 2012; Azam et al. 2013). Using these methods enhances either microscopic (pore scale) or macroscopic (volumetric sweep) displacement efficiency or both. For instance, polymer increases the macroscopic displacement efficiency, while surfactants improve the microscopic displacement efficiency. Polymer is used to viscosities the water by improving the mobility ratio and fluid flow patterns of a displacement process (Fanchi 2018). Surfactant, which contains one hydrocarbon chain (lipophilic) and a polar head (hydrophilic) (Hakiki et al. 2015b), reduces the IFT between oil and water and alters wettability. Alkali, which includes sodium carbonate and sodium tetraborate (Borax) as respective conventional and novel alkali, generates in situ soaps by reacting with organic-acid components present in the crude oil. Additionally, it reduces the surfactant adsorption by modifying rock surface-charge characteristic (Ayirala and Yousef 2015). However, these traditional chemical methods have disadvantages. For instance, the problem of using polymer is the loss of viscosity in the presence of reservoir brines and with temperature increase, and utilizing surfactant and alkali has efficiency loss limitation while flowing in porous media (Gbadamosi et al. 2019). Therefore, implementing combinational modes has attracted more attention, and their applications resulted in higher oil recovery rate. Lately, using foams combined with surfactants and polymers shows promising results in oil recovery improvement since it causes more stability and better control of mobility. LSW is one of the methods that causes oil recovery enhancement by injection of reduced water salinity. Although the first report of LSW application in EOR was published by Bernard (1967), it gained considerable attention from 2005 onward mainly because of its low facility investment and subsequently low cost (Katende and Sagala 2019; Marhaendrajana et al. 2018; Sheng 2014), and environmentally friendly manner (Marhaendrajana et al. 2018; Sheng 2014). Several LSW-based recovery mechanisms have been introduced by various researchers in the past couple of decades: for instance, a mechanism based on mixed wet clay release (Yu et al. 2019), PH effect (Austad et al. 2010), multicomponent ionic exchange (Lager et al. 2008), wettability alteration (Zhang et al. 2007), and osmotic pressure (Pollen and Berg 2018). However, there is a lack of consistent LSW mechanism which can be due to different test approaches, complexity of the minerals, crude oils, and aqueous-phase compositions and the interactions among all these phases (Chavan et al. 2019). More recent studies regarding different methods of CEOR can be found at Hakiki et al. (2015a) for polymer, Hakiki et al. (2015b) and Dang et al. (2018) for ASP, Haghighi and Firozjaii (2019) and Azam et al. (2013) for surfactant, Rai et al. (2015) for surfactant–polymer, Dang et al. (2014) and Goswami et al. (2018) for micellar flooding, Nasr et al. (2020), Syed et al. (2019), and Samin et al. (2017) for foam-EOR, Al-Sarihi et al. (2018), Almansour et al. (2017), Al-Saedi et al. (2019), Chen et al. (2006), Zekri et al. (2019), Fredriksen et al. (2017), and Alfazazi et al. (2019) for LSW.

MEOR is a biological technology that uses the injection of nutrients and microbial products such as gases (H2, N2, CH4, CO2), organic acids, solvents, biosurfactants, biopolymers, and biomass (microbial cells) to decrease water production in reservoirs, improve the oil recovery, or both (Putra and Hakiki 2019; Fanchi 2018). The implementation of these methods enhances the macroscopic displacement efficiency by decreasing oil viscosity and increasing reservoir pressure. Safdel et al. (2017) categorized the processes of MEOR into microbial flooding recovery (MFR) which is the most effective method (Ismail et al. (2017); Al-Sayegh et al. (2017)), cycle microbial recovery (CMR), microbial selective plugging recovery (MSPR), and others. Typically, in microbial flooding, microbes and nutrients are injected into reservoirs from the injection wells where microorganisms and their metabolites move along with water to assist the transport of oil toward and out of the production wells (Ke et al. 2018a). Compared with other EOR techniques, MFR includes a variety of advantages, such as lower energy consumption and the reduced loss caused by degradation by some of the endogenous microorganisms (Zahid and Khan 2007), more environmental friendliness (She et al. 2019; Ke et al. 2018b; Patel et al. 2015), and inexpensiveness (She et al. 2019; He et al. 2018a; Zahid and Khan 2007). He et al. (2018a) reported the cost per incremental oil for MEOR, gas flooding, steam flooding, combustion in situ, and chemical flooding in ranges such as from 1 to 4, from 2 to 8, from 3 to 6, from 5 to 10, and from 8 to 12 USD/bbl, respectively. In another study, Cui, (2017) estimated the cost of MEOR as 10 USD/bbl, while for chemical flooding, thermal production, and CO2 flooding, it was calculated as 21, 28, and 31 USD/bbl, respectively. For MEOR application, the reader referred to researches Câmara et al. (2019), Landa-Marbán et al. (2017), Gao (2018), and Haq et al. (2019), among others.

Gas injection methods involve the injection of gasses such as CO_2, nitrogen (N_2), hydrocarbon, and alternating hydrocarbon gas (WAG) into the reservoir in different schemes such as continuous, water alternating, and cyclic. The key mechanisms of these methods include maintenance of reservoir pressure, swelling of oil, and declining of oil viscosity (Sheng 2015). According to Jia et al. (2019), gas accessibility and economic consideration are main factors influencing the selection of gas type to be used in the field, and permeability level is the factor for scheme selection (continues schemes in cases with permeability larger than 0.01 mD, while cyclic scheme in ultralow permeability shale reservoirs). There are two types of gas injection which are miscible and immiscible. In the case of miscible gas injection, the injected gas is dissolved within the oil inside the reservoir and underlying oil starts flowing toward the production well. In this method, the gas is injected at or above minimum miscibility pressure (MMP). In immiscible gas injection, the injected gas is absorbed inside the oil and water and it will cause movement and mixture of oil blobs and start flowing toward the production well. In other words, the immiscible gas flooding causes the reservoir pressure enhancement, which in turn increases the macroscopic displacement efficiency, and subsequently, improves the oil recovery. In this method, the injection of gas needs to be below MMP. So, in this condition, the CO_2 and oil will not form a single phase. However, CO_2 will dissolve in the oil enabling oil swelling improvement and reducing oil viscosity (El-Hoshoudy and Desouky 2018). Additionally, gas injection in low pressure enables to keep the pressure of the reservoir in the stable condition causing prevention of production cutoff, and subsequently, facilitate more oil recovery (Al-Anazi 2007). According to Kulkarni (2003), the CO_2-based EOR is the second-most approach being implemented in heavy oil fields around the world after thermal approaches. However, its economic efficiency must be well considered before deployed in oil fields. In this regard, the initial capital cost of the project (wells drilling, CO_2 recycling plant, corrosion-resistant field production infrastructure, CO_2 pipeline network, and price of CO_2), the condition of the reservoirs, and the price of oil can be taken into account as the most influential parameters (Perera et al. 2016). The CO_2-assisted EOR is being used in 114 projects in the USA (Meribout 2018). The wide implementation of this method in the USA is because of available natural sources of CO_2 and the existing CO_2 pipeline network (Manrique et al. 2007). The CO_2 injection method is beneficial due to its large storage capacity (Perera et al. 2016) and decreasing atmospheric gas emissions through CO2 storage (Bachu and Adams 2003), while its drawback is it alters the volumetric sweep efficiency (Meribout 2018). The CO_2 gas is injected either continuously or in alternate slugs with water, known as WAG flooding. Adoption of WAG process results in better recovery from improved mobility control in contrast to continuous gas injection (Ayirala and Yousef 2015). In fact, the high ratio of mobility is not beneficial to oil recovery since it causes early gas breakthrough and availability of a small amount of recycled gas in the high-permeability zone (Jia et al. 2019). Saneifar et al. (2017) pointed out that one of the problems of WAG is some degree of loss of injectivity in most floods, more specifically in reservoirs with permeability less than of 10 mD. Adjusting WAG ratios and drilling new wells assist in decreasing this loss as they provide different configurations of EOR site-specific CO_2 injection (Núñez-López et al. 2019). The hydrocarbon and nitrogen injections are broadly implemented for cases such as gas cycling, maintenance of reservoir pressure, and gas lift in oil fields. They are noncorrosive and cheaper than CO_2-based EOR (Stevens et al. 1999). The most recent literature regarding gas injection utilization can be found in researches done by Buenaventura et al. (2014), Gbadamosi et al. (2018), Lashgari et al. (2019), Belazreg et al. (2019), Wan et al. (2015), and Tovar et al. (2018).

Thermal methods are the main EOR process for heavy oil extraction (Li et al. 2017). Thermal EOR is typically implemented on shallow reservoirs with large fields. These methods enhance both macroscopic and microscopic displacement efficiencies by the reduction in viscous forces and interfacial tension, respectively. Conventional thermal-based EOR techniques include in situ combustion and steam-assisted methods such as CSS, SF, and SAGD. In situ combustion method is the injection of air or oxygen in order to generate heat between 450 and 600 °C within the reservoir by burning about 10% of the OIP. The generated heat causes a reduction in the surface tension, reduces the oil viscosity in an area near the combustion zone, and increases the oil permeability. This method can be applied on wide range of reservoir and crude-oil types (Zhao et al. 2015). The main problems of this method can be considered as severe corrosion, toxic gas production, and gravity override (Thomas

2008). In CSS (also known as Huff n' Puff) method, steam is injected into the reservoir for about a month, and then the well is shut in for few days for heat distribution. The rate of oil production at the beginning is high due to a variety of factors such as high initial oil saturation, high increased reservoir pressure, and lowered oil viscosity. The production of the well will continue for several months until the oil recovery rate decreases into uneconomic rate when the cycle is necessary to be repeated. The recovery factor of this method is low, and it is between 10 and 40% OIP. SF is a pattern-driven method, and its performance depends on geology and pattern size enormously. Typical recovery factors are between 50 and 60% OIP (Thomas 2008). In SAGD technique, the injection well (upper horizontal well) is used for continuous low-pressure steam injection to the formation which in turn causes the creation of steam chamber (steam-saturated zone). The gravity force causes gradual expansion of the steam chamber vertically. The steam chamber transfers the heat of the injected steam into the formation and causes oil movement and drainage (due to gravity force) toward the production well (lower horizontal well). According to Speight (2011), using the SAGD method improves the steam–oil ratio and enables improvement in oil recovery by 60% to 70%. Adoption of conventional thermal-based EOR results in easy extraction of the oil by adding heat to the reservoir which causes oil viscosity reduction and lighter components vaporization. However, these methods are not suitable for heavy oil reservoirs or deep wells because of their excessive heat loss (Eskandari et al. 2015). In addition, application of these methods in long-term recovery of crude oil usually leads to formation damages due to deposition of paraffin near the wellbore, reduction in the formation permeability, incursion of outside liquids and solids for various types of production operations, and consequently, reduction in the rate of oil production (Mohsin and Meribout 2015; Meribout 2018). Furthermore, thermal methods are not environmentally friendly and cause an increase in greenhouse gas production (Mukhametshina and Martynova 2013). Also, adopting thermal methods in heterogeneous reservoirs is not favorable (Sadeghi et al. 2017) since there is a possibility of occurrence of early fluid breakthrough and sweep reduction due to fractures and high permeability streaks (Saeedfar et al. 2016). Additionally, the steam-assisted methods include high implementation and operation cost (Xiaoxiong et al. 2018), less economic efficiency in thin pay zones and low-permeability formations (clark 2007), not applicable on for deep or very shallow reservoirs (Bientinesi et al. 2013), and their efficiency is highly influenced by geological properties of the reservoir (Bientinesi et al. 2013). Finally, these techniques are considered as time-consuming methods and need huge resources of water (Saeedfar et al. 2016) for heating since they usually heat a large area of the reservoir (Chakma and Jha 1992). The comprehensive information regarding thermal methods can be found at Sheng (2013), Wu and Liu (2019), Shen (2013), Banerjee and Hascakir (2018), and Ghalenavi et al. (2020).

EOR screening

The different characterization of EOR methods declares the fact that one particular technique should not be utilized for all reservoir types. Thus, the most suitable method needs to be identified for specific reservoir conditions which can be obtained through EOR screening. The goal of EOR screening is to select an optimized method among alternatives or prioritizing alternatives based on reservoir characteristics and oil properties criteria. These criteria can be grouped into rock and fluid parameters in which rock parameters include porosity, permeability, initial oil saturation, and depth, while gravity, viscosity, and temperature comprised fluid parameters (Kamari et al. (2015). Different methods are adopted for EOR screening purposes: for example, using tables and graphs (Kamari et al. 2015), artificial intelligence (AI) methods [Suleimanov et al. (2016), Eghbali et al. (2016), and Hartono et al. (2017)], and multicriteria decision analysis (MCDA) (Khojastehmehr et al. 2019). The details of the above-mentioned studies with their findings are summarized in Table 2. Beside these studies, Kang et al. (2016) comprehensively studied EOR screening criteria for onshore and offshore fields and introduced screening criteria for successful application of EOR techniques such as hydrocarbon gas miscible, CO_2 miscible, and polymer processes in offshore oil fields. Another point regarding utilization of EOR method in a certain oil field is that besides technical issues (reservoir characteristics and oil properties, and operation complexity), economic factors such as investment cost (Hartono et al. 2017) and worldwide oil price are also essential to be taken into account before final decision-making process (Kamari and Mohammadi 2014).

Electrical-based EOR (EEOR)

Besides conventional EOR methods, some nonconventional methods such as electrical heating techniques are also being utilized to improve the recovery of heavy oil, which constitute 70% of total world oil reserves (Mozafari and Nasri 2017), in terms of efficiency, cost, and time (Jeong et al. 2015). EEOR methods include electromagnetic heating, ultrasonic stimulations, etc. Basically, these methods supply the electrical energy to the reservoir, which will cause an increase in oil temperature or make vibrations in the hydrocarbon molecules. This will result in a reduction in oil viscosity and increase in the oil mobilization and consequently increase in oil production. Commonly, the mechanisms of

Table 2 EOR screening studies

Researcher	Number of EOR methods	Field	Number of tested reservoirs	Reservoir		
				Location	Condition	Formation
Kamari et al. (2015)*	12	Onshore	1	Iran	Naturally fractured	Carbonate
Eghbali et al. (2016)**	4	Onshore	7	USA Venezuela France	Depleted non-fractured	Sandstone
Suleimanov et al. (2016)***	7	Onshore and offshore	11	Canada Azerbaijan	–	–
Hartono et al. (2017)****	15	Onshore	9	Indonesia	–	Sandstone
Khojastehmehr et al. (2019)*****	10	Onshore and offshore	65	Iran	–	Carbonate and sandstone

Remarks

*	In terms of technical issues, polymer, CO_2 miscible and immiscible are most suitable techniques Thermal methods and the added alkaline solvent method are not suitable for the naturally fractured carbonate reservoirs Totally, suitability of EOR methods is as follows: CEOR: in mid-viscosities, mid-depths, and mid-densities; gas flooding methods: in light oils, low viscosities and deep reservoirs; thermal methods: in shallow reservoirs, viscous and heavy oils
**	CO_2 miscible injection for a low-temperature and shallow reservoir with light reservoir fluid Hydrocarbon miscible injection for a very deep reservoir with a very high temperature Polymer flooding for reservoir with medium depth and temperature, high viscosity oil (low API gravity) Steam injection for a very shallow depth reservoir and high permeability of rock with very low API gravity fluid CO_2 miscible and HC miscible for reservoir with a medium temperature, high depth, very low viscosity, and light API gravity
***	The CO_2 flooding is the most prominent technique for Alberta's oil reservoir condition, followed by hydrocarbon flooding and polymer flooding Miscible CO_2 and immiscible nitrogen are most suited techniques in Guneshli (offshore Azerbaijani reservoir)
****	CEOR is suitable for minimum depth and temperature reservoir, and low viscosity and light oil Heating-based EOR is suitable for high oil viscosity cases Gas-based EOR is suited for light oil reservoir with high temperature
*****	The most important criterion among screening criteria is lithology CO_2 (Immiscible and miscible) is the first choice In onshore reservoirs, immiscible CO_2 and hydrocarbon gas injection for onshore reservoirs and CO_2 injection and steam flooding in offshore reservoirs are best methods Miscible N_2 method ranked as the least important technique

these methods are based on heating the well (both vertical and horizontal) or formation. The former one utilizes a thermal process to heat the steam chamber or the near-wellbore well directly (Yao et al. 2019), while the latter mechanism implements the SAGD method to heat the formation by gravity drainage (Yongbin et al. 2017). Compared to the steam flooding method, the electrical heating methods are more efficient in a heterogeneous reservoir environment (Carrizales and Lake 2009), and they are better in the reservoir depth and heat loss control aspects (Acar 2007). The limitations and benefits of different EEOR techniques are mentioned in Table 3.

Electromagnetic (EM) heating is an alternative method for heavy oil recovery by heating the reservoir fluids without much loss of heat to the surroundings. In fact, EM heating refers to heating produced by the absorption of EM energy by the molecules information. The EM methods can be divided into three categories depending on the frequency of electrical current being used: inductive heating (IH), low-frequency (resistive), and high-frequency where current is alternating (Eskandari et al. 2015). The mechanisms for low-frequency and high-frequency heating are electric conduction, which results in Joule heating, and dielectric polarization, respectively (Saeedfar et al. 2016). IH is used to generate heat near wellbore in vertical wells by installing the inductive tool close to the heavy formation of the reservoir. In IH, a range of low- and medium-frequency electric currents can be applied which depends on the presence of energy (Hascakir et al. 2008). Low-frequency electric current may occur when low-frequency alternating current,

Table 3 Comparisons between EEOR techniques

EEOR method	Limitations	Benefits
Electromagnetic (EM) heating		
Inductive	Providing only limited heat around the wellbore (Hasanvan and Golparvar 2014)	*More safer, advanced, and high quality of heating procedure, high efficiency and faster heating (Lucía et al. 2018) *Applicable on various types of reservoirs with different characteristics (Oliveira et al. 2009) *Favorable for reservoirs which thermal methods are not suitable (Rehman and Meribout 2012)
Low frequency	Non-uniform temperature pattern (Saeedfar et al. 2016)	Can be considered as an alternative for steam injection method and suitable for reservoirs with high permeability or fractures (Rehman and Meribout 2012)
MW & RF heating	*Effective energy only able to penetrate into the very near wellbore region (Hasanvand and golaparvar 2014) *Limited penetration depth of microwaves in conductive mediums (watersaturated fluid) (Troch et al. 1996)	*Propagation ability independent from transporting material (Carrizales et al. 2008) *Covering heat distribution over a large volume of reservoir (Bientinesi et al. 2013; Saeedfar et al. 2016) *The formation of geology is not much effective on this method. Highly efficient method in the energy generation-radiation process. Favorable for off-shore oil fields in terms of equipment compactness (Bientinesi et al. 2013)
Ultrasonic	Low capacity and efficiency of ultrasonic cavitation (Wan et al. 2019)	*Cost-saving and environmental-friendly method (Wang et al. 2020) *Application while oil production operation is running (Sun et al. 2011) *Precise positioning of wellbore stimulation (Mohsin and Meribout 2015) and stimulation for any interval of interest (Meribout 2018) *Suitable for high water-saturated and depleted reservoirs (Rehman and Meribout 2012)

which is less than 60 hertz (Hasanvand and Golparvar 2014), flows through the reservoir (Martin et al. 2017), and electrical energy is converted into heat. It can be applied in various kinds of reservoirs with various formation depths and porosities, permeabilities, temperatures, pressures, and thicknesses. (Oliveira et al. 2009; Rehman and Meribout 2012). In IH, the heat is generated as a result of hysteresis and ohmic losses in the steel casing, while in low-frequency, heat is created due to ohmic losses associated with ionic conduction through the continuous water phase (Vermeulen and McGee 2000). High-frequency electric current can be utilized for microwave (MW) heating and radio-frequency (RF) methods. At high frequencies, dielectric heating prevails where the dipoles formed by molecules tend to align themselves, resulting in rotational movement with a velocity proportional to the frequency of alteration that generates heat. The schematic of IH, low- and high-frequency heating is depicted in Fig. 2. Water saturation, salinity, and frequency are key factors in the successful implementation of EM heating (Eskandari et al. 2015). Adoption of any type of this method is dependent on reservoir fluid properties (e.g., resistivity, dielectric permittivity) and other formation

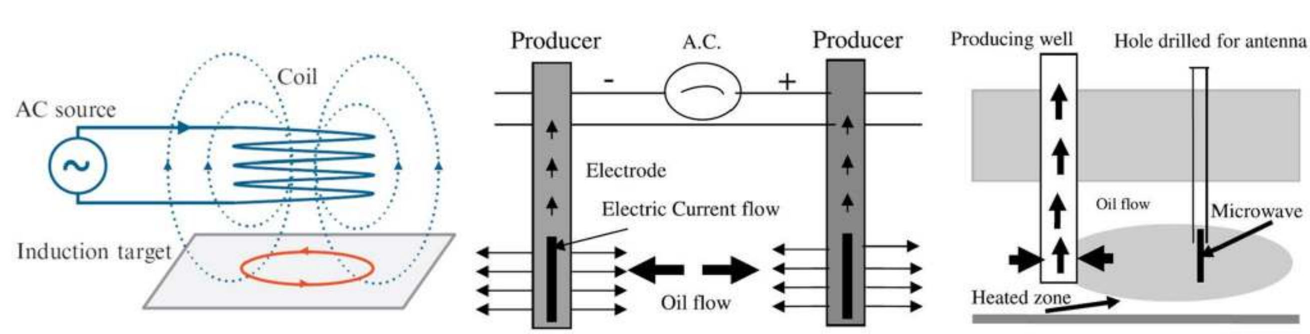

Fig. 2 Schematic of IH (Lucía et al. 2018) (left), low-frequency (middle) and high-frequency (right) (Chhetri and Islam 2008)

characteristics (Saeedfar and Law 2018). The applied methods of EM use the physical fields of various natures rather than a substance. Adopting the EM method enables to perform heating far from its source since EM field is able to penetrate the viscous oil and the rock matrix (Zhang et al. 2018). These methods are less resource- and energy-intensive and economically more expedient compared to those used at present (Mullakaev et al. 2015), and contribute to processing time saving (Mutyala et al. 2010). EM heating can be the best alternative option wherever EOR methods cannot be implemented due to permafrost and other environmental constraints (Sahni et al. 2000). For more in-depth information regarding electrical heating methods and applications, the reader referred to Hakiki et al. (2017), Ali et al. (2020), Oloumi and Rambabu (2016), and Ramcharan and Hosein (2019).

Microwave heating is another alternative to enhance oil extraction. The range of MW (high-frequency waves with short wavelength) is between 300 and 300,000 megahertz. This method requires less power and energy and does not require any fluid to be injected. Usually, microwaves are either transmitted by a material, absorbed or reflected. In microwave heating, microwaves interact with the water molecules, which are set into circulatory motion and collide quickly with other molecules with the frequency collisions equal to the frequency of applied MWs resulting in volumetric heating (Okassa et al. 2010). The temperature rise causes the oil viscosity reduction and concurrently improvement in the oil recovery. The MW heating procedure can be influenced by different factors such as power level, standing time, cycling, applied frequency, dimensions of the cavity and position of the material (Mohsin and Meribout 2012). This technique is mostly used in the locations where conventional EOR techniques are difficult to be implemented such as shallow reservoirs (Carrizales 2010; Rehman and Meribout 2012). The advantages of MW heating for heavy oil recovery consist of high dielectric heating effect (Ovalles et al. 2002), controlled and direct way of heating of the specific area (Chakma and Jha 1992), energy and cost efficiency (Mozafari and Nasri 2017), no requirement for transportation and storage, application to heterogeneous environments, and no risk of chemical reactions with other materials found inside the reservoir, etc. Its main disadvantage is that the depth of penetration of microwaves in conductive mediums is limited (Troch et al. 1996). Therefore, when thick and heavy oil is covered by certain quantity of water, MWs will not be able to reach the oil content since they can only penetrate mostly few millimeters in the water layer (Westermark et al. 2001).

RF method is based on wave propagation and uses radiation of EM originated from an antenna beside an oil reservoir layer (Bera and Babadagli 2017). The range of RF is between 300 kilohertz and 300 megahertz for subsurface heating (Saeedfar et al. 2016). This method is mostly implemented to gain cumulative heavy oil around the borehole (Bientinesi et al. 2013). RF method is beneficial because of high-speed heating (Wang et al. 2019), small heat loss (Ceruttia et al. 2013; Wang et al. 2019), not much affected by geology formation, a large volume of reservoir coverage, and high efficiency in the energy generation and radiation process. (Bientinesi et al. 2013). However, it is relatively more expensive than low-frequency and IH methods (Wang et al. 2018).

Ultrasonic-based EOR is another technique for the oil extraction enhancement and/or to remove formation damage around the wellbore by supplying the mechanical vibration in elastic media. The ultrasonic is in the form of energy which is generated by a longitudinal mechanical wave with a frequency above 20 kHz. It is categorized into low frequency (20 kHz–1 MHz) and high frequency (above 1 MHz). However, high frequency of ultrasonic has a better performance compared to low frequency when the velocity of waves and their thermosonic influences are taken into account (Han 2003). Moreover, the effects of ultrasonic intensity should not be neglected since they have a proportional relationship with the enhancement of oil recovery (Westermark et al. 2001). The aim of ultrasonic waves application is to generate hydrodynamic waves downhole by providing continuous energy for dislodging trapped oil at a distance from the source.

Ultrasound waves produce vibrations in the reservoir, which would facilitate the oil production by changing the capillary forces, adhesion between rocks and fluids and cause oil coalescence (Kouznetsov et al. 1998, Hamida and Babadagli 2005a, b, c). Due to the very close acoustic impedance of water and oil, the induced energy of ultrasound waves is not heavily altered during its propagation, which depends on elasticity, size of grain, and density of the rock (Gharabi 2005), into the oil–water mixture. Hence, ultrasound waves can reduce the viscosity of heavy oil and increase oil production (Wegener et al. 2001). Oil recovery using ultrasound waves needs different equipment such as ultrasonic generator and detector, piezoelectric ceramic transducer, etc. The schematic diagram of ultrasonic-assisted oil recovery is depicted in Fig. 3. However, it is an inexpensive method due to its simple implementation. According to Wang et al. (2020), car-mounted type of equipment, currently, is mostly used in ultrasonic-assisted oil recovery projects; its only requirements are one cable car and five workers. Besides, Meribout (2018) mentioned that the cost of polymer injection device can be up to 230,000 US$, while the ultrasonic device is much cheaper (90,000 US$). Thus, application of this technique causes huge saving in the cost of oil recovery operations.

The ultrasonic-based EOR includes several mechanisms due to complexity of its physical process and its effects on

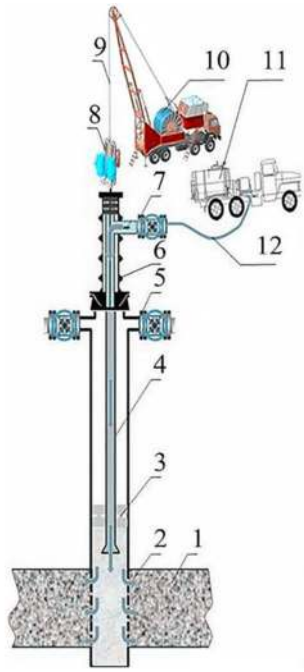

Fig. 3 Schematic diagram of ultrasonic-assisted oil recovery (Mullakaev et al. 2017): (1) oil formation; (2) ultrasonic downhole tool; (3) packer; (4) tubing; (5) casing valve; (6) lubricator; (7) discharge line; (8) umbilical cable feed; (9) umbilical cable; (10) wire line truck ПКС-5; and (11) pump unit СИН-32, 12-house

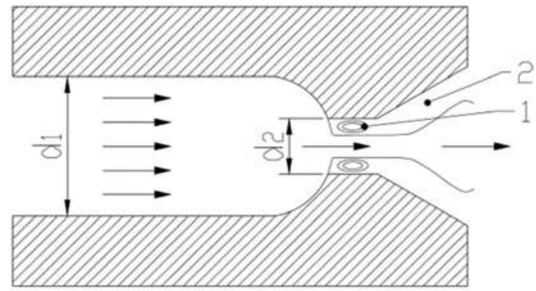

Fig. 4 Mechanism diagram of cavitation jet technology: (1) low-pressure tangential region and (2) low-pressure eddy region

the reservoirs. One of the main mechanisms is the increase in oil viscosity reduction as a result of either mechanical vibration, cavitation (the process of the growth and collapse of liquid hollow bubbles) interaction or heating (Wang et al. 2020). The heavy oil includes small molecules that are restricted by large molecules such as colloid, long-chain free radicals, asphaltene, etc. In vibrational effect, the application of high frequency and high intensity of ultrasonic waves in elastic medium can increase the amplitude, velocity, and acceleration of elastic particles considerably. This will result in formation of strong movement between the small molecules and chains of larger molecules with great inertia, which in turn causes an increase in frictional force among molecules, breaking of the molecular chain and loosening the large molecules, and finally, reduction in heavy oil's viscosity. In cavitation effect, the application of high frequency and high intensity of ultrasonic waves causes the availability of instantaneous high temperature and high pressure due to collapse of cavitation bubbles, oxidation–reduction reaction, polymerization or depolymerization of large molecule substances, damage in the molecular chains, and subsequently, lessening of the viscosity (Shi et al. 2017; Gu et al. 2003). However, the limitations of ultrasonic cavitation are the low processing capacity and treatment efficiency (Wan et al. 2019). To mitigate this problem, they have suggested to use cavitation jet technology in which bubble collapse occurs when bubbles flow out of the low-pressure eddy region with the fluid, and consequently, the energy will be released because of sudden pressure growth. The mechanism diagram of cavitation jet technology is depicted in Fig. 4. In heating effect, thermal energy is produced due to absorption of ultrasonic waves inside the propagation medium. Then, oil temperature increases because of frictions at the boundary surface of different media. Finally, the heat energy will be released when cavitation bubbles collapse.

Application of ultrasonic wave includes variety of advantages such as fast and easy implementation, protection of wellbore formation against damages (Wang et al. 2020), cost-effectiveness and efficiency (Wang et al. 2020), no pollution to the reservoir (Wang et al. 2020), high compatibility with other EOR methods, variety of applications (Mohammadian et al. 2011; Zhang et al. 2013; Abramova et al. 2014; Wang et al. 2020), precise positioning of wellbore stimulation, stimulation for any interval of interest (Meribout 2018), and finally no need for chemical solvents injection such as acids (Amro et al. 2007, Sun et al. 2011). The ultrasonic-based EOR can be a very good alternative in a condition that the heavy oil is covered by the certain water quantity, in which microwaves are not able to reach the oil layer due to their limited penetration ability, because of its low alteration of energy while propagating into the mixture of oil and water (Wegener et al. 2001). The development of high-efficiency equipment, the correct selection of candidate wells, and the mathematical modeling of physical processes that accompany acoustic well stimulation are the solutions to increase the efficiency of this method substantially (Mullakaev et al. 2008, Mullakaev et al. 2009a, b, Abramov et al. 2013). The ultrasonic technique can be used in all reservoir types and may also be suitable in heterogeneous environment (Fairbanks and Chen 1970, Amro et al. 2007). A long time ago, this method has been successfully applied in a Russian oil field (Siberia) in 1990 and in oil fields of Texas and California in the USA in 1974 and 1992, respectively (Naderi and Babadagli 2010). Its most recent implementations in oil fields are summarized in Table 4.

Table 4 Recent application of ultrasonic technique in oil fields

References	Country	Field name/location	Recovery rate increase
Abramov et al. (2013)	Russia	Western Siberia	Up to 50%
Abramova et al. (2014)	Russia	Western Siberia and the Samara region	Between 40 and 100%
Abramov et al. (2015)	Russia	Western Siberia	23–33 tons/day
Mullakaev et al. (2015)	USA	Green River Formation	Averagely, 4.45 tons/day
	Russia	Western Siberia	Averagely, 4.4 tons/day
	Russia	Samara Region	Averagely, 10.2 tons/day
Abramov et al. (2016)	Russia	Western Siberia	91%

Except ultrasonic wave application in viscosity reduction, it has been recently applied for a variety of purposes such as size preventing paraffin precipitation (Xu et al. 2011), distribution of nanosized mist (Kudo et al. 2017), enhancing water vapor permeability (Bounos et al. 2017), cleaning turbine engines' oil filters (Nguyen et al. 2016), elimination of plugs (inorganic scales, drilling fluid, and polymer) in oil production (Taheri-Shakib et al. 2018; Wang et al. 2017), and separation of water from heavy crude oil emulsion (Antes et al. 2017).

Ultrasonic-based EOR previous studies

The history of vibration-based oil recovery studies goes back to 1950s when oil recovery increase is observed after the earthquakes occurrence and cultural noises. From that time till present, numerous studies have been conducted to investigate different aspects of ultrasonic waves implications in EOR such as ultrasonic sources, diverse fluid types, and change in influential parameters of EOR, e.g., viscosity, permeability, pressure, temperature, and interfacial tension. The first study on the application of ultrasonic waves and how they affect oil extraction is related to the study on the correlation between the water level and the stimulation caused by earthquakes (Griffing 1950). Duhon and Campbell (1965) investigated the utilization of ultrasonic waves with frequencies between 1 and 5.5 megahertz in waterflooding and concluded that ultrasonic energy enhanced the oil extraction; it causes remarkable effect on fluid displacement efficiency and negative correlation among the frequency, cavitation, and recovery. Nosov (1965) observed a decrease in the viscosity of polystyrene solution under sound waves. Fairbanks and Chen (1970) observed that the heat produced by ultrasound waves can significantly boost the percolation rate. Johnston (1971) reported that the application of ultrasonic waves reduces the surface tension and viscosity, which in turn causes oil percolation increase and subsequently enhancement in oil recovery. In a study by Gadiev (1977), ultrasound wave radiated to oil-saturated unconsolidated sand packs and it was observed that both production rate and cumulative oil production increased significantly. Neretin and Yudin (1981) observed that ultrasound waves implementation caused an increase in the oil displacement rate by water in the well's loose sands. Ganiev et al. (1989) proposed that ultrasound would deform the pore walls and alter the radius of the pore since traveling waves along pore walls may cause a "peristaltic transport" of fluid displacement. Pogosyan et al. (1989) concluded that ultrasound waves increase the gravitational separation of water and kerosene. Shaw Resource Services (1992) implemented ultrasonic radiation in two field tests in California and reported that oil extraction was boosted up to 45%. Nikolaevskii (1992) observed that the ultrasonic vibrations created enable the oil drops to recover their mobility. Aarts et al. (1998) numerically and experimentally proved deformation of pore walls and fluid velocity enhancement in porous media as a result of ultrasonic radiation.

Gunal and Islam (2000) showed that ultrasonic treatments do not change crude oil rheology as a function of temperature. Guo et al. (2004) applied ultrasonic waves to oil fields in China and observed an increase in oil production. Hamida and Babadagli (2005a, b, c) examined the influence of ultrasonic wave on capillary imbibition and concluded that matrix–fracture interaction type and capillary imbibition depending on the fluid may cause oil recovery enhancement when ultrasonic waves are applied. Hamida and Babadagli (2005a), Hamida and Babadagli (2007a, b, c), and Hamida and Babadagli (2007a) investigated the capillary interaction between the matrix and fracture under different ultrasonic intensities for different fluid types. The results of their experiments indicated that the application of ultrasonic energy may increase the surfactant solubility and the rheological properties of polymers may be altered. Amro et al. (2007) conducted experiments to investigate the effect of ultrasound waves on the movement of additional oil in reservoir. The wave stimulation experiments showed that oil recovery enhanced in both horizontal and vertical corefloods. In a study by Hamida and Babadagli (2007b), the influence of high-frequency, high-intensity ultrasonic radiation at the interface between immiscible and miscible fluids was analyzed. They found that ultrasound acts to stabilize the interfacial front and that such effect is most pronounced at low viscosity ratios. Hamida and Babadagli (2008a, b) adopted the pendant drop method to investigate the effect of ultrasound on flow through a capillary. They found a remarkable change in the interfacial forces between oil and water. Hamida and Babadagli (2008a) analyzed the influence of high-frequency and high-intensity ultrasonic radiation on the immiscible and miscible displacement. Miscible experiments showed that the ultrasonic radiation enhances molecular diffusion and causes little change in both fractal dimension and lacunarity at low and higher injection rates, respectively. The experiments by Naderi and Babadagli (2008a, 2010) stated that ultrasonic radiation increases the recovery and has a significant influence on oil-wet samples.

Najafi (2010) analytically and experimentally investigated the effect of ultrasound on gravity drainage and percolation of oil by using fluids of different viscosities. They concluded that the radiation acts in opposition to capillary pressure effect. Mohammadian et al. (2011) experimentally found that the recovery of waterflooding increased as a result of ultrasonic stimulation. Mohammadian et al. (2013) investigated the effects of sonication radiation on oil recovery by ultrasonic waves-stimulated waterflooding. Their experiments indicated that the recovery of waterflooding increased for all cases. Abramov et al. (2013) and Mohsin and Meribout (2015) suggested a new method for the ultrasonic-based EOR. Alhomadhi et al. (2014) investigated the ability of ultrasound waves to mobilize additional oil. They observed an increase in the rate of oil displacement. Abramova et al. (2014) developed ultrasonic equipment and tested it in two different regions in different geological conditions. They observed significant improvement in oil production. The study by Keshavarzi et al. (2014) stated that the recovery factor of the free gravity drainage process of the oil highly increased under radiation of ultrasound waves. Gao et al. (2015) examined the effect of different frequencies of ultrasonic on different oil components elimination from oily sludge. They found that the highest efficiency and oil recovery rate were achieved when the ultrasonic washing with a frequency of 25 kHz is applied. Hamidi et al. (2015) revealed that emulsification could be one of the most important oil recovery mechanisms happening in porous media when ultrasound is applied for a short time. Furthermore, the ultrasound radiation time increase causes an increase in size and decrease in the dispersed phase droplets stability. Mullakaev et al. (2017) conducted field experiments in Western Siberia and developed the ultrasonic automated oil well complex. The result of tests showed a noticeable boost in the oil production rate and average well productivity. Arabzadeh and Amani (2017) assessed the effect of ultrasonic wave on the oil permeability of three samples with different average bead sizes and its influence on oil recovery in terms of free fall gravity drainage. They found that using sonication, bigger bead sizes result in more oil recovery in nonasphaltenic samples and reduce the gravity drainage in the asphaltenic samples. Furthermore, their results reveal that sonication enhances the recovery in the gravity drainage process, while it has a negative impact on asphaltenic samples by means of oil viscosity increment. Shi et al. (2017) experimentally studied the effect of the ultrasonic application on reducing the viscosity of crude oil samples from the Daqing oil field. They found that the ultrasonic technique is beneficial to depolymerizing and breaking the long chains of large molecules (resin and asphaltene), and it has a considerable influence on decreasing the thermal energy consumption in the process. He et al. (2018b) explored the effectiveness of different soil types, oil components, and ultrasonic operation factors on oil recovery from heavy oil-containing sludge. Their results state that ultrasonic power and hydrophilicity of sludge are the most significant factors affecting the efficiency of heavy oil recovery. Abdulfatah (2018) implemented ultrasound waves in reservoirs, and the result of his experiments yielded up to 50% increase in oil recovery. The summary of previous studies on ultrasonic-based EOR from 2000 onward is mentioned in Table 5.

Discussion

This study reviewed the application of conventional EOR techniques as well as EEOR methods with more focus on ultrasonic-assisted oil recovery. The following discusses the most suitable/efficient techniques for the ultrasonic-based EOR. The ultrasonic stimulation can highly assist in waterflooding method to increase the recovery rate. Using low-viscous high-API fluid such as kerosene causes low mobility ration and high sweep efficiency, and consequently, the recovery rate of ultrasonic-stimulated waterflooding will be high. Similarly, CO_2 flooding under both controlled and uncontrolled temperature conditions can be aided by ultrasonic stimulation. In fact, in ultrasound-assisted CO_2 flooding technique, the parameters such as viscosity, capillary pressure, and interfacial tension will be reduced to improve the oil recovery. The ultrasonic downhole stimulation can be used to revitalize the failing oil wells and increase their production rate. Ultrasonic treatment is highly effective on wells with permeability above 20 mD and porosity higher than 15%. In the case of wells with lower permeability and porosity, ultrasound should be combined with chemicals to boost the production rate of the well. The wettability of rocks influences the effectiveness of ultrasonic radiation. Employing ultrasound waves can boost oil recovery in both water-wet and oil-wet cases. However, water-wet cases show a slight increase in ultimate recovery, while oil-wet cases experience high rate of ultimate recovery. Thus, oil-wet cases are more suitable than water-wet cases for ultrasound application.

Table 5 Ultrasonic-based EOR studies from the year of 2000

Researchers/year	Title	Findings	Method/experiment/material/development
Gunal and Islam (2000)	Alteration of asphaltic crude rheology with electromagnetic and ultrasonic irradiation	Ultrasonic treatments do not alter crude oil rheology as a function of temperature	*Three series of tests were performed *The stock tank was the crude oil sample *Used a domestic generator with a fixed frequency of 2450 MHz and commercial generator (MEGA LP 320).
Guo et al. (2004)	High-frequency vibration Recovery enhancement technology in the heavy oil fields of China	*High-frequency vibration has many advantages comparing with conventional thermal EOR *High-frequency vibration can improve heavy oil production efficiency and ultimate oil recovery	Used the sonic generator with hydropower as ultrasonic generator; its working power is supplied with water pump
Hamida and Babadagli (2005a, b, c)	Effect of ultrasonic waves on the capillary imbibition recovery of oil	*Ultrasonic energy enhances the capillary imbibition recovery of oil for different fluid pairs *Ultrasound does not appear to be highly effective on wettability	*Conducted Laboratory tests using cylindrical Berea sandstone and Indiana limestone samples with all sides (co-current imbibition) and only one side (countercurrent imbibition) open to flow contacting with the aqueous phase *An ultrasonic bath was used as a place for the oil-saturated cores and brought into contact with the aqueous phase.
Hamida and Babadagli (2005a)	Capillary interaction of different oleic and aqueous phases between matrix and fracture under ultrasonic waves	*In all cases, except countercurrent kerosene water imbibition, ultrasound showed significant improvements in oil recovery *Ultimate recovery increase for mineral oil–brine imbibition under ultrasound *Ultrasound has a profound effect on polymer rheology	*Selected nonionic and anionic surfactant solutions above and below the CMC *Used xanthan gum solutions as an aqueous phase *An ultrasonic reaction chamber was used as a place for the oil-saturated cores (crude and processed oil) and brought into contact with the aqueous phase
Hamida and Babadagli (2005b)	Effects of ultrasonic waves on immiscible and miscible displacement in porous media	*The interface between immiscible liquids affected obviously when ultrasound implemented *Decrease in the interfacial tension by raising the intensity of ultrasound *At low injection rates, molecular diffusion increased when the ultrasonic radiated	*Conducted experiments on Hele-Shaw models Immiscible displacement tests for mineral oil–brine and mineral oil–surfactant pairs Miscible displacement tests for mineral oil–pentane, mineral oil–kerosene and mineral oil—2-propanol pairs *Implemented fractal methods to analyze the changes and correlate them with the intensity of ultrasonic waves

Table 5 (continued)

Researchers/year	Title	Findings	Method/experiment/material/development
Hamida and Babadagli (2007a, b, c)	Immiscible displacement of oil by water in consolidated porous media due to capillary imbibition under ultrasonic waves	*Spontaneous imbibition of water into dry sandstone and limestone cores: the recovery rate is relatively unchanged under ultrasound, and for co-current flow (all sides open), the final recovery considerably decreased. The opposite is true for countercurrent flow with all sides closed except the bottom end *Totally dissimilar results were observed when spontaneous imbibition of water into Berea sandstone saturated with kerosene and light mineral oil compared to air *Recovery increased substantially when brine was used as an aqueous phase in comparison with water	*Performed the capillary (spontaneous) imbibition of an aqueous phase into oil (on air)-saturated Berea sandstone and Indiana limestone samples experiment. *Prepared solutions of water, brine (15,000 and 150,000 ppm NaCl), anionic surfactant (sodium dodecyl diphenyloxide disulfonate), nonionic surfactant (alcohol ethoxylate) and polymer (xanthan gum) as the aqueous phase. *Tested both countercurrent and co-current geometries
Hamida and Babadagli (2007a)	Analysis of capillary interaction and oil recovery under ultrasonic waves	Ultrasonic irradiation enhances capillary imbibition recovery of oil for various fluid pairs, and such process is dependent on the interfacial tension and density of the fluids	*Conducted Laboratory experiments using cylindrical Berea sandstone and Indiana limestone samples with all sides (quasi-co-current imbibition), and only one side (countercurrent imbibition) contacting with the aqueous phase *An ultrasonic bath was used as a place for the oil-saturated cores and brought into contact with the aqueous phase. *Conducted tests such as air–water, mineral oil–brine, mineral oil–surfactant solution and mineral oil–polymer solution to investigate a separate physical process governing acoustic stimulation.
Amro et al. (2007)	Improved oil recovery by application of ultrasound waves to waterflooding	*Higher oil recovery can be achieved when stimulating the wave compared to stimulation at original oil in place *suggested performing wave stimulation on core sample with a compressive strength higher than 150 psi (unconsolidated)	*Conducted horizontal and vertical core flooding tests *After initial waterflooding, wave stimulation was applied at both residual oil saturation and at original oil in place *Water fractional flow curves were considered to determine the average water saturation after breakthrough with and without ultrasound waves
Hamida and Babadagli (2007b)	Fluid–fluid interaction during miscible and immiscible displacement under ultrasonic waves	Ultrasound waves stabilize the interfacial front, especially at low viscosity ratios	*An extensive set of Hele-Shaw-type experiments were performed for several viscosity ratios, and interfacial tension *Fractal analysis techniques were applied to quantify the degree of fingering and branching

Table 5 (continued)

Researchers/year	Title	Findings	Method/experiment/material/development
Hamida and Babadagli (2008a, b)	Effects of ultrasonic waves on the interfacial forces between oil and water	Application of ultrasonic waves significantly changes the interfacial forces between oil and water which causes oil recovery improvement	*Used the pendant drop method. Water was injected into a 0.1 mm Hastelloy C-276 capillary tube submersed into several mineral oils with different viscosities, and kerosene *The average drop rate per minute was measured at several ultrasonic intensities
Hamida and Babadagli (2008a)	Displacement of oil by different interfacial tension fluids under ultrasonic waves	*Based on miscible experiments, the ultrasonic radiation improves molecular diffusion at low injection rates, while it may only cause little change in both fractal dimension and lacunarity at higher injection rates	*Experiments were performed on Hele-Shaw models *Conducted immiscible (for mineral oil–brine and mineral oil–surfactant pairs) and miscible (for mineral oil–pentane, mineral oil–kerosene and mineral oil–2-propanol pairs) displacement experiments *Fractal techniques were used to analyze the changes and correlate them with the intensity of ultrasonic waves
Naderi and Babadagli (2008b)	Clarifications on oil/heavy oil recovery under ultrasonic radiation through core and 2-D visualization experiments	*Reduction in influence of ultrasonic waves on the recovery when oil viscosity increased *Initial water saturation facilitated oil recovery in oil-wet cores using ultrasound waves causing higher ultimate recovery compared to the water-wet case *The effect of ultrasonic radiation on oil recovery for oil-wet samples is so high	*Capillary imbibition experiments conducted on cylindrical Berea sandstone core samples under ultrasonic radiation *The cores were placed into imbibition cells where they were contacted with an aqueous phase *Every experiment was conducted with and without ultrasonic radiation for comparison. Different intensities of ultrasonic waves were tested as well.
Naderi and Babadagli (2008a)	Effect of ultrasonic intensity and frequency on heavy-oil recovery from different wettability rocks.	*Ultrasonic radiation increases the recovery *The recovery rate in oil wet cases extremely influenced by radiation of ultrasonic *The recovery rate increased in higher frequency *The wave loss in air and water cases was much lower than in the slurry medium	*Performed each experiment in the presence and absence of ultrasonic radiation while all other conditions and parameters were kept constant *Initial water saturation was considered as Swi = 0 to 40% and oil viscosities considered from 35 to 1600 cp *The influence of wettability measured for the samples tendered oil-wet by treating with dry film *The ultrasonic intensity (45 to 84 W/sq cm) and frequency (22 and 40 kHz) were also changed
Naderi and Babadagli (2010)	Influence of intensity and frequency of ultrasonic waves on capillary interaction and oil recovery from different rock types	*Ultrasonic radiation increases recovery *Ultrasonic radiation is highly effective on recovery of oil-wet cases	*Experiments were conducted for different initial water saturations, oil viscosities and wettabilities *The ultrasonic intensity (45–84 W/sq cm) and frequency (22 and 40 kHz) were also changed *Designed a setup to measure the ultrasonic energy penetration capacity in different media

Table 5 (continued)

Researchers/year	Title	Findings	Method/experiment/material/development
Najafi (2010)	A mathematical analysis of the mechanism of ultrasonic-induced fluid percolation in porous media	*The permeability of porous medium is independent of the wave parameters *The radiation acts in opposition to capillary pressure effect	*Glass beads ranging from 70 to 100 mesh sizes were used *The working fluids consist of distilled water, kerosene and Doroud and Paidar crude oil as wetting and air as nonwetting phase
Mohammadian et al. (2011)	Enhancing oil recovery through application of ultrasonic-assisted waterflooding	Ultrasonic stimulation increased the recovery of waterflooding from 2 to 16%	Series of straight and ultrasonic-stimulated waterflooding experiments on a long unconsolidated sand pack
Mohammadian et al. (2013)	Effects of sonication radiation on oil recovery by ultrasonic waves stimulated waterflooding	*sonication for all the case studies resulted in waterflooding recovery from 3 to 16% *The recovery of ultrasonic-assisted waterflooding was higher for less viscous fluid being kerosene.	*Two types of ultrasonic transducers were employed. *For dynamic experiments, the ultrasonic transducers were specially installed surrounding the column test section *Crest ultrasonic generator with frequency of 40 kHz and power outputs of 100–500 W was used *Kerosene, Vaseline, and SAE-10 (engine oil) were used as nonwet phase in the system
Abramov et al. (2013)	Ultrasonic technology for enhanced oil recovery from failing oil wells and the equipment for its implementation	Ultrasonic technology can significantly enhance oil recovery by 30–50% or more on wells with permeability higher than 20 mD and porosity higher than 15%	Ultrasonic and combined ultrasound with chemical treatment of the bottomhole zone of oil wells were performed by equipment such as generator and a downhole ultrasonic tool (SP-42/1300 or SP-102/1270)
Alhomadhi et al. (2014)	Experimental application of ultrasound waves to improved oil recovery during waterflooding	*Increase in the rate of oil displacement as a result of various identified mechanisms *Changes in relative permeability and in water breakthrough because of interaction of the generated waves with the fluids in porous media	The core flooding was performed horizontally and vertically, and the wave stimulation was applied at original oil in place and at residual oil saturation after performing initial waterflooding
Abramova et al. (2014)	Ultrasonic technology for enhanced oil recovery	*The success rate of the method reaches 90% *The range of increase in oil production is between 40 and 100%	*Developed ultrasonic equipment *Upgraded ultrasonic generator TS10W with the power of 10 kW, and a sonotrode PSMS-42 (with the diameter 42 mm) and a registrator of geophysical data
Keshavarzi et al. (2014)	Investigating the role of ultrasonic wave on two-phase relative permeability in a free gravity drainage process.	*The recovery factor of the free gravity drainage process noticeably increased by using ultrasound *The relative permeability of both wetting and nonwetting phases increases under exposure to ultrasonic waves.	*The tests were performed with and without ultrasonic waves, and the recovery data were recorded versus time under both conditions *Based on the Hagoort backward methodology, the wetting phase relative permeability curves were obtained by using the recovery data versus time. Subsequently, the relative permeability of nonwetting phases was calculated by performing history matching to the experimental production data

Table 5 (continued)

Researchers/year	Title	Findings	Method/experiment/material/development
Mohsin and Meribout (2015)	An extended model for ultrasonic-based enhanced oil recovery with experimental validation	*Ultrasonic-based EOR showed a good recovery rate of around 88.2% of original oil in place *Multiple ultrasonic actuators have been found as good alternative to increase the efficiency of ultrasonic-based EOR	The model is modular and consists of an acoustic module and a heat transfer module, where the heat distribution is updated when the temperature rise exceeds 1 °C, and it is considered geophysical and acoustical properties of the wells
Hamidi et al. (2015)	Effect of ultrasound radiation duration on emulsification and demulsification of paraffin oil and surfactant solution/brine using Hele-Shaw models	*Emulsification could be one of the significant oil recovery mechanisms happening in porous media under short period of application of ultrasound *Emulsification becomes dominant over demulsification when short period of ultrasound application is used *When ultrasound radiation time increased, the size and stability of the dispersed phase droplets were increased and decreased, respectively	*The 2D glass Hele-Shaw models were placed inside the ultrasonic bath under long and short periods of ultrasound radiation *Used a microscope on top of the model for microscopic investigations on the water and oil interface *At the beginning of ultrasound radiation, diffusion of phases and formation of emulsion were observed in both long and short periods of the ultrasound implementation.
Gao et al. (2015)	Influence of ultrasonic waves on the removal of different oil components from oily sludge	The ultrasonic with respective frequency, intensity, and ratio of sludge/water of 25 kHz, 0.33 W/cm^2, and ½(in volume) is an optimal conditions for oil elimination from oily sludge	*Oily sludge samples components: oil (54.5%, by mass), water (25%), and sand (20.5%) *All chemical used were of reagent grade *Ultrasonic with 25, 50, and 100 kHz generated for the experiment *Used infrared oil content analyzer, carbon tetrachloride, and a thin-layer chromatograph for Oil content in oily sludge, oil extraction, and oil components analysis, respectively
Mullakaev et al. (2017)	Ultrasonic automated oil well complex and technology for enhancing marginal well productivity and heavy oil recovery	*Daily average oil production rate increased 5.2 tons *107% increase in the average well productivity index is attained (from 0.14 to 0.29)	The developed complex includes an ultrasonic oil well module MSUM based on magnetostrictive transducers, an ultrasonic oil well module MSUP based on piezoceramic transducers, and a workstation
Arabzadeh and Amani (2017)	Application of a novel ultrasonic technology to improve oil recovery with an environmental viewpoint	*Ultrasonic application has positive impact on oil recovery of nonasphaltenic samples. Conversely, it causes negative influence on asphaltenic samples	*Followed the methodology of Keshavarzi et al. (2014) *For the experiment, equipment, such as Plexiglas cylinder, gradual cylinder, ultrasonic generator with frequency of 22 kHz, and three samples with average bead sizes of 80–100 µm, 170–200 µm, and 240–270 µm were used

Table 5 (continued)

Researchers/year	Title	Findings	Method/experiment/material/development
Shi et al. (2017)	Application and mechanism of ultrasonic static mixer in heavy oil viscosity reduction	*The ultrasonic power is more effective on viscosity reduction rate than reaction time and temperature. The highest viscosity reduction rate was 57.34% *Using ultrasonic method enables 43.03% of saving energy in comparison with the visbreaking process *Condition of optimal process: ultrasonic power, reaction time, and temperature were 1.8 kW, 45 min, and 360 °C, respectively.	*Autoclave ultrasonic static mixing reactor with horizontal and vertical bidirectional sonic waves was adopted *Heavy oil was added to the reactor in certain amount and then heated to a specific temperature *Used numerical modeling and control equations to investigate heavy oil's flow characteristics due to cavitation effect and energy consumption, respectively
He et al. (2018b)	Effect of ultrasound on oil recovery from crude oil containing sludge	*The maximum rate of oil recovery (92%) was obtained when ultrasonic technique applied with power of 240 W and hydrophilic sludge *Ultrasonic power is the most effective factor among operating factors *The highest oil recovery occurs when the contact angle of water on soil is smallest.	*Used crude oil samples which were taken from Jidong, Xinjiang, and Liaohe oil fields in China *The oily sludge was prepared by mixture of soil samples and pretreated heavy oil (mass ratio: 2:1, microheat temperature: 40 °C, mixing speed: high) and then placed at room temperature for 1–2 days *The experiment was designed based on orthogonal test and used analytical methods
Abdulfatah (2018)	Application of ultrasonic waves in enhancing oil recovery in secondary recovery phase	*Increase in oil recovery by up to 50% *Using ultrasonic wave in porous medium resulted in reduction in the critical oil saturation of 0.09	*The experiments were in twofold without and with ultrasound wave (minimum frequency of 24 kHz and maximum of 54 kHz) *Test A included waterflooding without implementing ultrasound, and Test B included wave stimulation application on core samples at residual oil using minimum and maximum ultrasound frequency

Ultrasound waves influence the interface between immiscible liquids by enhancing momentum and heat transfer across the phase interfaces. When the ultrasound intensity is increased, the interfacial tension decreases.

Conclusions

A review has been executed to investigate the trend of employing ultrasonic waves for enhanced oil recovery. Variety of related experimental studies and field applications in different locations were performed during past decades considering effects of ultrasound waves on influential parameters of enhanced oil recovery. For several reasons, adoption of ultrasonic waves for enhanced oil recovery is beneficial. Firstly, it is an economical and environmentally friendly method. Secondly, it can be implemented in any reservoir type and significantly boost the oil production rate. Thirdly, it will keep the well and its casing is safe and it removes formation damage around the wellbore. Additionally, it allows stimulation for any interval of interest and prevents heat loss. To conclude, employing ultrasonic waves for EOR has shown promising results recently and it provides EOR scientists with an interesting and challenging field of study.

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