

# Conventional versus electrical enhanced oil recovery: a review

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**Abstract** This paper presents a critical and an analytical view of some unconventional EOR techniques. This includes microwave heating, ultrasonic stimulations, direct current heating and induction heating. It also demonstrates that for some specific reservoirs scenarios, some of these unconventional techniques may provide more efficient results, in terms of recovery rate, over conventional techniques in some specific reservoir scenarios. It also discusses two widely investigated electrical techniques, i.e. microwave heating and ultrasonic stimulations and provides two practical setups for field scale implementation. Different conventional and electrical EOR techniques are also compared in terms of their application suitability and limitations.

**Keywords** Enhanced oil recovery · EOR · Conventional EOR · Electrical heating · Microwaves EOR

## Introduction

Oil and Gas constitute the main resources for the development of many countries in the world (Butt 2001). On the other hand, because of the industrialization, oil consumption is increasing which motivated oil producing countries to optimize their production. However, most of easy oil has been already extracted, leaving a non-negligible quantity of highly viscous trapped oil in the reservoirs. This requires the usage of what is commonly known by enhanced oil recovery (EOR) techniques. More specifically, when a well

is drilled in a hydrocarbon depleted area for primary recovery, the oil starts flowing towards the producing well because of the pressure difference between the bottom of the producing well and the reservoir leading to oil recovery of 5–25 % of the original oil in place. Pumps are installed to maintain the production when the pressure of the reservoir is reduced (Andrei and Simoni 2010). After passing this stage, hydrocarbon gases are injected in the reservoirs so as to raise the pressure but these gases are a huge economic burden on oil companies. After the primary recovery, some other methods to increase the pressure inside the reservoirs are adopted including Hydrocarbon Gas injection, Water flooding, CO<sub>2</sub> injection, Chemical Flooding, etc. This stage of oil recovery is termed as Secondary Recovery (Green and Willhite 1998). For instance, currently in United Arab Emirates (UAE), Abu Dhabi Company for Onshore Oil Operations (ADCO) is using Hydrocarbon gases in Abu Dhabi oil reservoirs. On receiving successful results from the pilot project of CO<sub>2</sub> injection, the company plans to use CO<sub>2</sub> injection as a replacement for hydrocarbon gas injection into the reservoirs to increase the pressure (Saadawi et al. 2011). Besides these conventional EOR methods, some non-conventional, e.g. electrical techniques are also being investigated to enhance the production of oil with high efficiency, low cost and in less time. Electrical heating methods are better in terms of the depth of the reservoir and controlling the heat loss (Acar 2007). In addition, they can achieve higher efficiency in heterogeneous reservoir environment as compared with conventional steam flooding (Carrizales and Lake 2009). Another benefit of using electrical heating is that the energy can be applied directly into the area of interest (Chakma and Jha 1992). Workman was the first to propose electro-EOR as a suitable candidate (Workman 1930). The use of high-density DC electric current for EOR

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has also been proposed by many researchers (Bruninga 1957; Sarapu 1957). In addition, alternating current was demonstrated to a good candidate to heat oil reservoirs and in turn decrease their viscosity resulting in improved oil production (Gill 1970; Crowson 1971). Numerous lab experiments have been conducted by many researchers on the use of electro osmosis and suggesting it as a good candidate for EOR (Amba et al. 1964; Chilingar et al. 1968; George et al. 1997).

Electromagnetic heating has been investigated and proposed as a potential candidate for near-well bore heating (George et al. 1997). These techniques, especially microwave heating, can also be applied to the shallow reservoirs which are not suitable for chemical or gas injection processes.

This paper explores the technical feasibility and economic potential of employing the electrically EOR schemes. Following the introduction is the section discussing briefly the conventional EOR techniques which are actually being employed. Next section elaborates the term electrical heating with its types followed by some discussions on few related setups commonly used in electrical-based EOR. In addition, ultrasonic stimulation technique is also briefly discussed. The next section outlines the differences between the electrical and conventional-based EOR techniques. Finally, the future of the unconventional EOR and some related research areas are discussed.

### Conventional EOR techniques

EOR can be applied in one of the three following methods:

- Primary technique
- Secondary technique
- Tertiary recovery

After oil discovery, a primary recovery undergoes a period of oil production based on natural reservoir energy or pressure. EOR as a secondary recovery technique is used at the stage when oil cannot be extracted if the extraction relies solely on the natural reservoir pressure. Consequently, an introduction of energy into the reservoir is usually required at this stage of recovery. In conventional oil recovery, the most popular method used for secondary recovery is water flooding. Hence, the water is flooded through the reservoir so that it may push the remaining oil towards the production well. Nevertheless, this method may induce some serious limitations as well. For instance, formation damage may take place based on the reaction between the injected water and the formation water. In addition, this technique may induce a corrosion of the sub-

surface electro-mechanic devices (e.g. pumps, valves, and sensors). In addition, the heterogeneous reservoir rocks sometimes make it hard for water to exert pressure on oil. This triggers the need to use a more powerful recovery technique, namely the tertiary recovery technique, which is referred in this paper as EOR. Commonly, the following EOR techniques are employed in the oil fields (Stevens et al. 1998):

- Thermal EOR
- CO<sub>2</sub>-EOR
- Other gas EOR
- Chemical EOR

In thermal EOR, steam is injected into the reservoir to reduce the viscosity of the heavy oil and/or vaporize the oil so that it may flow and can be extracted easily. Thermal-based EOR also involves the in-situ combustion entailing heat generation within the reservoir containing low-gravity oil. Increased heat within the reservoir reduces the surface tension and increases the permeability of oil. Thermal EOR is usually applied in case of Shallow reservoirs (which are less than 3,000 feet deep) of heavy crude oil. In addition, this technique is also mainly applied to large fields which can provide high return on investment. CO<sub>2</sub>-based EOR is being used widely and also depends upon economic availability of CO<sub>2</sub> from natural and/or industrial resources. This method has worldwide demonstrated its efficiency, where for instance in 2006, about 37 % of oil production in the US was contributed by CO<sub>2</sub>-based EOR.

Other Gas-based EOR includes the insertion of hydrocarbon or Nitrogen gases into oil reservoirs. This technique is widely used in oil fields for gas cycling, reservoir pressure maintenance and gas lift. Financially, it is normally cheaper than CO<sub>2</sub>-based EOR with the added advantage that it is non corrosive as well (Stevens et al. 1998).

Usually gas-based EOR have two types of injections:

- Miscible injection, in which the injected gas is dissolved in the oil inside the reservoir and the underlying oil/gas solution starts flowing towards the production well as a result of a decrease in the viscosity of oil. Mainly miscible method is adopted to reduce the interfacial tension for improvement in displacement efficiency. But miscibility can only be achieved at specified temperature and pressure conditions in the presence of a specific chemical composition. It is economically expensive and can only be carried out with justified reasons. Safety issues are also of paramount nature in this case.
- Immiscible injection, in which the injected fluid does not mix up with the oil and water completely because of the characterization of oil. It is just absorbed inside

the oil and water and starts building pressure which in turn tends to the movement of oil blobs lying at different places. These oil blobs are mixed with each other and start flowing towards the production well.

It is worth noting that the main consideration in the two aforementioned injection methods is that miscible injection is usually carried out for fractured reservoirs while immiscible injection is done for non-fractured or limited fracture reservoirs. For instance, for a reservoir having 1,000 psi fracture pressure, miscible injection of 1,200 psi cannot be performed as it will fracture the reservoir. Instead, immiscible fluid would be better in this case.

A liquid-based tertiary recovery technique consists of injecting  $\text{CO}_2$  intermittently (e.g. days or months, depending upon the reservoir geology) with water into the reservoir. This process is termed as Water Alternating Gas (WAG) flooding as shown in Fig. 1. Brine is injected in the formation to push the supercritical  $\text{CO}_2$  further into the depth of reservoir in oil-rich zones. In this processes, supercritical  $\text{CO}_2$  and brine are injected alternately. Although it is one of the best available conventional EOR techniques, it is suffers from the low viscosity of  $\text{CO}_2$ . This is because  $\text{CO}_2$  forms viscous fingering inside the reservoir resulting in reduced recovery.

In some situations, chemical injection is also used in oil fields to enhance oil production by reducing the surface tension of the formation liquid. However, it is technologically complex to implement since it requires relatively

complex and expensive equipment, though it may be a good alternative in case there is much oil trapped in the reservoir, within which the acid content is high.

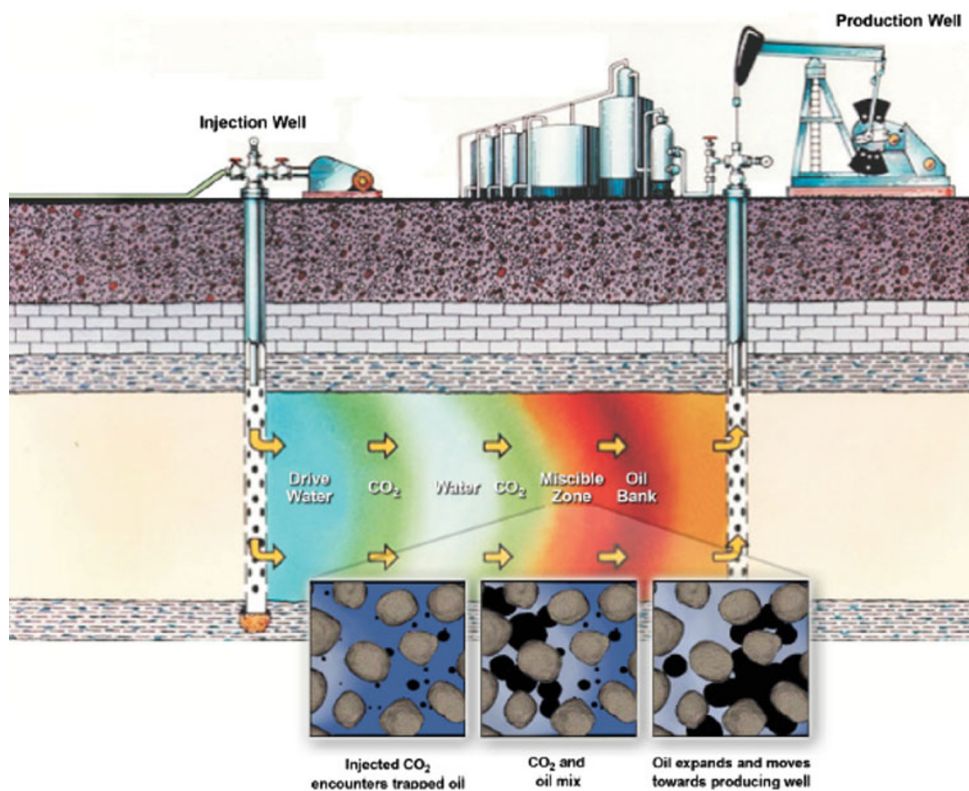
Alkaline flooding is limited in application scope as it can only be done for the reservoir in which acid content is high; alcoholic flooding has not been field tested yet. Surfactant flooding is used to reduce the surface tension of the formation liquid, which results in high chemical losses.

As for the recovery time, the effectiveness of using one or another conventional EOR technique depends upon the heterogeneity of the reservoir. For instance, in case the formation is permeable and contains a low viscous crude oil, the recovery time will also be faster than in case of less permeable reservoir containing high-viscosity crude oil. Since it is difficult to generalize the recovery efficiency of a particular EOR technique, a comparison of different techniques is provided based on 117 oil field experiments. Distribution of the type of EOR techniques employed is as follows (Hammershaimb et al. 1983; Kuuskraa and Stosur 1983; Teknica 2001):

### Electrical EOR techniques

In the literature, it has been found that the usage of the aforementioned conventional techniques for long-term production of heavy oil usually damages the formation

**Fig. 1**  $\text{CO}_2$  flooding (WAG)  
(Carter 2011)



(Baptist 1960; Zhou et al. 1996). This is mainly due to the deposition of paraffin near the well bore and incursion of outside liquids and solids for various types of production operations. Paraffin deposition may also reduce the formation permeability. In addition, these thermal oil recovery techniques may also force the deposited paraffin into the formation resulting in pore throat plugging which may lead to production loss (Bailey et al. 2001).

Another alternative/complementary technique to the conventional EOR techniques is the Electrical-based EOR (EEOR). Hence, using some electrical means (e.g. sound waves, RF waves, Inductive heating, DC Heating, etc.), oil can be recovered from the reservoirs at much lower cost and with enhanced efficiency as compared with the aforementioned conventional EOR methods. The basic function of EEOR process is to increase the mobility of the oil by reducing its viscosity which in turn would help the oil to easily move towards the production well. This is because the electrical energy supplied to the reservoir will either raise the temperature of the oil or create vibrations in the hydrocarbon molecules.

Based on the frequency of electrical current being used, the electric heating methods can be divided into three main categories. Low-frequency electric current is best suited for Ohmic or Resistive heating while high-frequency electric current can be used for Microwaves heating methods. On the contrary, for inductive heating, a range of low- and medium-frequency electric currents can be used depending on the energy availability (Hascakir et al. 2008).

#### Low-frequency heating

Low-frequency electric reservoir heating is also called Ohmic/Joule heating because in this method the electric current passes through the formation and due to power dissipation, heat is produced which in turn heats up the reservoir. This method can be employed using two oil wells: one as anode and the other as cathode; a potential difference is provided between these two electrodes, and a current is allowed to pass through the formation which is having salty water and can conduct electricity fairly (Sierra et al. 2001). It can suitably be employed in different types of reservoirs having different formation depth, formation porosity and permeability, temperature, pressure and thickness, etc. (Oliveira et al. 2009).

The electrical conductivity in the formation can be found by the following expression, which shows how far the heating effect will reach and is also called as Archie and Humble's relation (Sierra et al. 2001) and (Islam and Chilingarian 1995):

$$R = 0.62R_w / \Phi^{2.15} S_w^2 \quad (1)$$

where  $\Phi$  is porosity of the reservoir,  $S_w$  is the proportion of reservoir containing water or water saturation and  $R_w$  is the

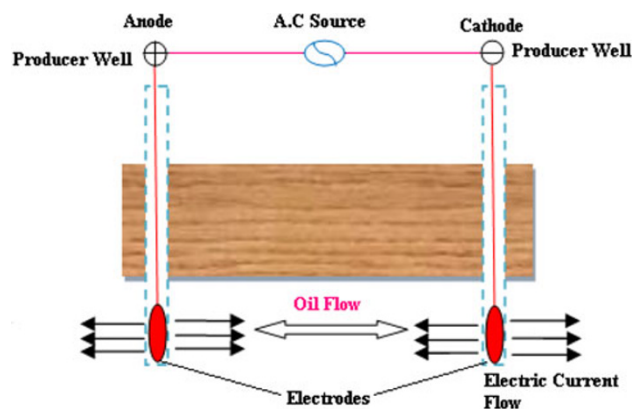


Fig. 2 Low-frequency heating (ohmic heating)

resistivity of brine and is given in ohm-meters and shows the dependence of water resistivity on temperature and is defined as

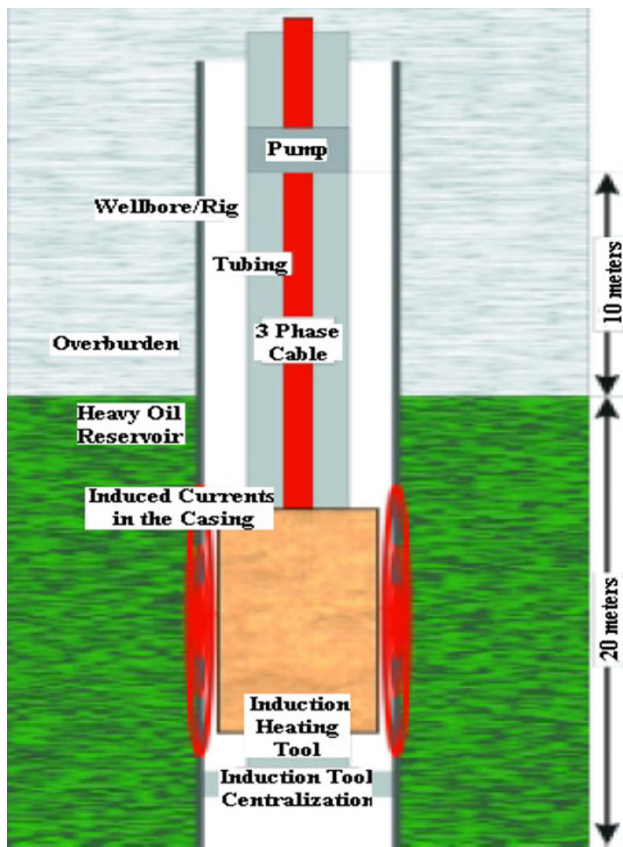
$$R_w = R_{wt}(T_r - 251.65)/(T - 251.65) \quad (2)$$

In the aforementioned expression,  $T$  is the initial temperature of reservoir in Kelvin while  $T_r$  is the reservoir temperature after passage of electric current through it. A view of the Low-frequency heating procedure is shown in Fig. 2.

One limitation of this method is that the amount of heat dissipated is reduced as the quantity of water decreases and in case the majority of water is converted into steam as a result of heating. One suggestion is to use water injection along with this method (Harvey et al. 1979). According to Akfhampour (1985), commercially available mineral insulated (MI) cables can be used for producing heat. In this method brine is not needed to conduct electricity; instead, two conductors insulated with graphite and polymer are used for the purpose. With the rise of temperature, the mineral resistance also increases which in turn increases the temperature even more. A self-regulating mechanism is achieved which prevents from overheating. These heater wires are available in lengths ranging from 300 to 1,000 m and are suitable for use in horizontal and shallow reservoirs for heating purpose. The source required for this purpose is 480 V AC.

#### Inductive heating

Electric source impressed upon at its edges produces alternating electric and magnetic fields causing eddy as well as displacement currents to flow through the surrounding materials. Eddy currents flow through the metallic materials producing heat and raising temperature while displacement currents, also called RF (Radio Frequency) Waves, are involved more in the dielectric materials. Both of these eddy currents as well as displacement



**Fig. 3** Configuration of wellbore for induction heating (Vermeulen and McGee 2000)

currents flow depend upon the dielectric loss factor and resistivity distribution of the reservoir.

A study conducted by Fisher (2007) on some specific reservoirs showed that in oil shale the desired temperature was 550 °C (for this case) and the input heat required was 153 kWh/ton, and in oil sand the maximum temperature required was 300 °C and input heat requirement was 123 kWh/ton.

In case of induction heating, a number of inductors are normally installed at the bottom of production tubing

facing the production zone. Production tubing acts as inductively heated source to radiate heat inside the production zone as shown in the Fig. 3 below. Mostly inductive heating is employed for near-well bore heating in vertical wells. The inductive tool can be installed near the heavy formation resulting in increased oil recovery because of reduction of viscosity of formation oil. A proposed configuration for induction heating is shown in Fig. 3 (Vermeulen and McGee 2000) (Fig. 4).

An inductor is attached to the production tubing opposing the production zone. Production casing is utilized as the inductively heated element to heat the surrounding of well bore. Bahrain Petroleum Company conducted the Induction heating with a power of 5–8 kW at Bahrain oil fields in 1998–2001 and as a result, the production output was tripled (Sierra et al. 2001). In addition, Inductive heating also raises the temperature of rocks and other inorganic materials present in the reservoir. The heat transfer from electromagnetic energy source to the porous rock media can be given by the energy equation. Increase in temperature can be calculated as follows (Hascakir et al. 2008):

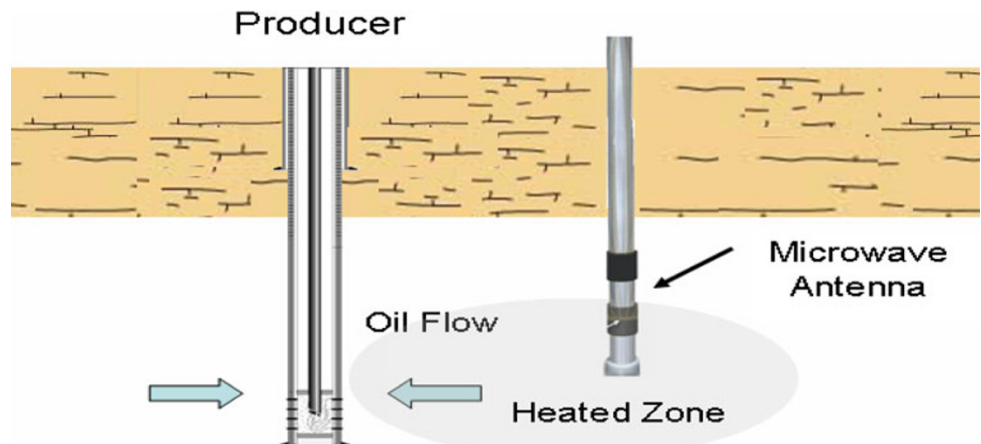
$$\rho c_p \frac{\partial T}{\partial t} + \rho_f c_{pf} \vec{v}_f \nabla T = \nabla \cdot (\lambda_c \nabla T) + P \quad (3)$$

where  $c_p$  and  $\lambda_c$  represent the density, specific heat capacity and thermal conductivity of the medium, respectively.  $\rho_f c_{pf}$  and  $\vec{v}_f$  are the density, specific heat capacity and superficial velocity of the fluid phase.  $P$  is the electromagnetic power dissipated per unit of volume and is a function of the electric field,  $\vec{E}$  and the effective conductivity  $\sigma$  of the medium, and it is given by

$$P = \frac{\sigma + \omega \epsilon \tan \delta}{2} |\vec{E}|^2 \quad (4)$$

A comparison of steam injection and inductive heating is shown in Table 1 (Acar 2007).

**Fig. 4** Schematic view of microwaves (Acar 2007)



**Table 1** Comparative analysis of conventional EOR techniques

EOR type	No. of experiments	Oil recovery % of ROIP	Basic principle
Steam drive	26	30–60	Improvement in sweep and displacement efficiency
In situ combustion	34	15–25	Improvement in sweep and displacement efficiency
CO <sub>2</sub> injection	14	20–30	Improvement in displacement efficiency
Surfactant flooding	20	15–40	Improvement in sweep and displacement efficiency
Polymer flooding	15	2–10	Improvement in sweep and displacement efficiency
Alkaline flooding	8	2–5	Improvement in sweep and displacement efficiency

Comparison of the widely used Steam Injection with the novel technique of inductive heating indicates that inductive heating method is more energy efficient and more economic as opposed to its rival. The energy consumed for heating the oil is much less as compared with the crude oil recovered from the earth.

### Microwave heating

Microwaves are high-frequency waves ranging between 300 and 300,000 MHz and are called Microwaves because of their shorter wavelength. Microwaves can also be used for heating the reservoir for EOR (Sahni et al. 2000). Normally microwaves are either transmitted by a material, absorbed or reflected. In majority of the cases microwaves interact with the water molecules as they are polar in nature. Hence, when microwaves are applied these polar water molecules are set into circulatory motion and they collide speedily with other molecules with the frequency collisions equal to the frequency of applied micro waves which in result produces much heat (Okassa et al. 2010). This rise in temperature reduces the viscosity of oil and hence causes it to flow towards the production well from where it can be extracted.

Microwaves produce heat more efficiently in case of absorption inside the material but crude is not a good absorber of microwaves. To enhance the absorption power of crude oil, microwave receptors (activated carbon, iron oxide and methanol) are used which stimulate the heating process. Microwave heating is affected by the design of the microwave source and the dielectric properties. Dielectric properties of material mainly depend upon the frequency of operation, temperature of the reservoir, etc. Hydrocarbons mixed with sand can absorb huge amounts of microwaves and hydrocarbons may get heated to achieve temperatures as high as 300–400 °C centigrade rapidly (Acar 2007). A schematic diagram for microwaves' employment is provided below (Fig. 5).

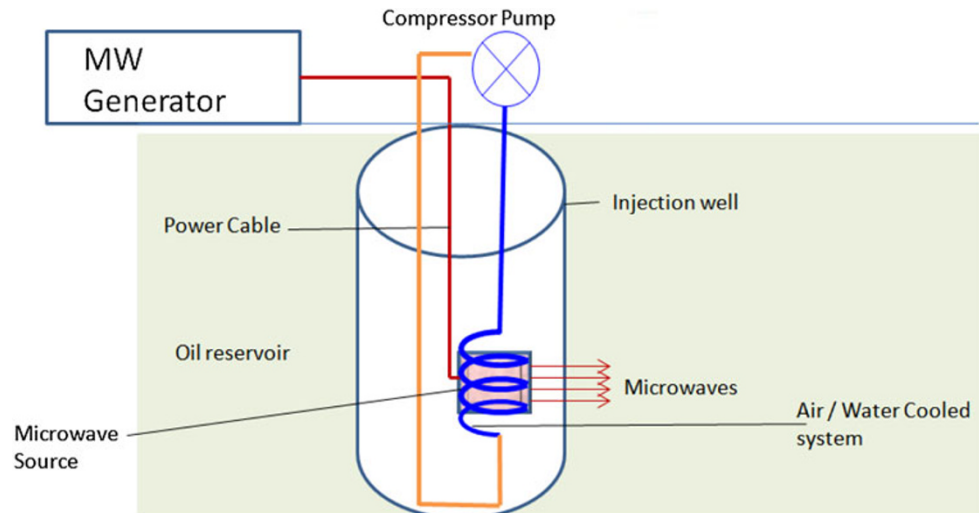
Studies mainly focused on three different types of reservoirs consisting of medium crude oil, shallow Lake Maracaibo heavy oil and extra heavy crude oil (Ovalles

et al. 2002). Simulation results presented that Microwave heating caused the temperature of the crude oil to rise and hence the viscosity of the oil to fall, which facilitates its extraction and enhances the production of oil. Moreover, the dielectric heating can produce 10 times more heat as compared with the electricity of same power level. Microwave heating is advantageous as compared with other thermal methods because heat loss can be reduced through controlled use of microwaves heating (Ovalles et al. 2002). Therefore, microwave heating can be employed for EOR. Nevertheless, the penetration power of microwaves is relatively limited and depends mainly on the frequency of operation as well as the inner shape and composition of the well. A microwave cable could be a good solution for providing maximum power to the magnetron placed in specific areas of reservoir with minimum losses and attenuation (Tomberlin 1964).

### Use of sonic waves for EOR

Several studies have been reported for the use of ultrasonic waves for EOR (Westermarck and Brett 2001; Xiao and Zhimin 2004; Amro et al. 2007; Hamida and Babadagli 2008; Luces 2010; Mohammadian et al. 2011). Different authors have addressed different parameters of EOR, e.g. change in viscosity, permeability, pressure, temperature and interfacial tension while considering different type of fluids and ultrasonic sources and concluded that use of ultrasonic waves is very well suited for EOR. It has been found that ultrasonic waves may increase the solubility of surfactants in oil which in turn will lead to decrease in interfacial tension (Hamida and Babadagli 2005; Hamida and Babadagli 2006). Miscible experiments have also been conducted and found that ultrasonic waves enhance the molecular diffusion at low water injection rates leading to EOR (Hamida and Babadagli 2008). (Gadiev 1977) performed experimental studies of ultrasound application to oil-saturated unconsolidated sand packs proving the improvement in cumulative oil recovery as well as oil production. Many field tests have also been performed with the application of ultrasonic waves to oil fields resulting in

**Fig. 5** A microwave based EOR setup



improved oil recovery in Texas, Siberia and California (Naderi and Babadagli 2010). From these studies, it has been concluded that ultrasonic-based EOR can be applied to any type of reservoir and may also be useful in heterogeneous environment (Chen and Fairbanks 1969; Amro and Al-Homadhi 2006; Kurawle and Kaul 2009).

According to some authors, small oil droplets, which usually are found in the reservoir after primary recovery, may coalesce to form larger ones leading to the flow of oil which results in oil recovery (Beckham 2009; Jeong et al. 2011). Ultrasonic energy is usually dissipated at the location of cracks and defects causing temperature distributions at these locations which in turn contribute towards the oil recovery. It has been found that high ultrasonic frequency is better as compared with low ultrasonic frequency as long as velocity of waves and their thermo sonic effects are concerned (Han 2003). In addition to frequency, intensity of applied ultrasound waves has also major effect on the EOR (Westermarck and Brett 2001).

Different type of oil reservoirs contain crude oils of different rheology which is a critical parameter to be taken care of during oil recovery. Experiments have also been conducted to verify that ultrasonic waves have no effect on rheology of crude oil with different asphaltene levels proving that they can be suitably used for EOR (Gizem Gunal and Islam 2000). From these studies, it has been concluded that ultrasonic-based EOR can be applied to any type of reservoir and may also be useful in heterogeneous environment (Chen and Fairbanks 1969; Amro and Al-Homadhi 2006; Kurawle and Kaul 2009).

Sound waves are advantageous to the conventional recovery methods in many ways. Some of them are (Amro et al. 2007) as follows:

1. There is no need for chemical stimulation which is not suitable in some cases for the reservoir rocks.

2. It can be used while the initial recovery is in progress.
3. It can also be employed to remove the filter cake, especially in the horizontal wells. Filter cake formation of all the impurities being filtered from the extracted oil and these impurities accumulate on the filter.

Usually, ultrasonic-based EOR comprises the hardware parts consisting of power supply, rectifier, power amplifier, inverter, control circuitry and piezoelectric transducer. Piezoelectric transducer is used to convert the high-frequency electrical signal to mechanical vibrations of the same frequency as that of applied electrical signal. A stack of piezoelectric transducers can be suitably employed to increase the amplitude of the ultrasonic stimulations created (Tables 2, 3).

### Application of specific electrical techniques

Different types of reservoirs exist on the earth depending upon their shape, characteristics of rocks and formation, etc. Different types of electrical techniques can be applied based on characterizations of different oil reservoirs. Two different models are presented for microwave heating and ultrasonic stimulations.

### Microwave-based EOR model

Figure 6 presents a specific case of oil reservoir with a microwave source installed inside an injection well. Microwave generator is placed on the ground surface and provides power to the microwave antenna installed down hole. A suitable air/water cooled system is also installed inside the injection well which is supplied with cold water or cool air from the compressor pump installed on the

**Table 2** Comparison of inductive heating and steam injection (Acar 2007)

Characteristics compared	Inductive heating	Steam injection
Water vaporization	34 kWh/t	34 kWh/t
Heat value of the deposits not utilized	27 kWh/t	675 kWh/t
Heat value of recovered oil	97 kWh/t	2295 kWh/t
Energy return rate	70 %	30.6 %
Heating the formation	62 kWh/t	40 kWh/t
Total heat energy required	123 kWh/t	749 kWh/t

ground surface. This is done to prevent the source from getting damaged because of excessive heat near the source. The main advantage of the microwave-based EOR is that source can suitably be employed near the target area.

#### Ultrasonic-based EOR model

Similarly, Fig. 6 provides an overview of a proposed field-scale ultrasonic-based device for EOR under the constraint to recover a specific quantity of oil from the reservoir. In this setup, electrical part of the setup is placed on the ground surface while ultrasonic part is installed inside the injection well. Rectifier converts the AC voltage to DC which in turn is amplified by the power amplifier. High-frequency inverter chops the high-voltage DC signal

converting it into high-frequency square waves which are then supplied to the piezoelectric transducers installed within the injection well. Ultrasonic transducers generate the ultrasonic stimulations at the frequency of applied square wave signal. Since these mechanical vibrations generated by ultrasonic transducer are low in amplitude, an ultrasonic booster is coupled to the transducer to amplify the mechanical vibrations. Finally, an ultrasonic horn couples these high-frequency and high-amplitude ultrasonic stimulations to the oil reservoir by proper impedance matching. Analog switches are installed inside the injection well and controlled from the control circuit to switch on or switch off a specific arrangement and number of ultrasonic transducers.

#### Electrical EOR versus conventional EOR

Electrical EOR (EEOR) has many advantages over conventional EOR; some of them are listed below:

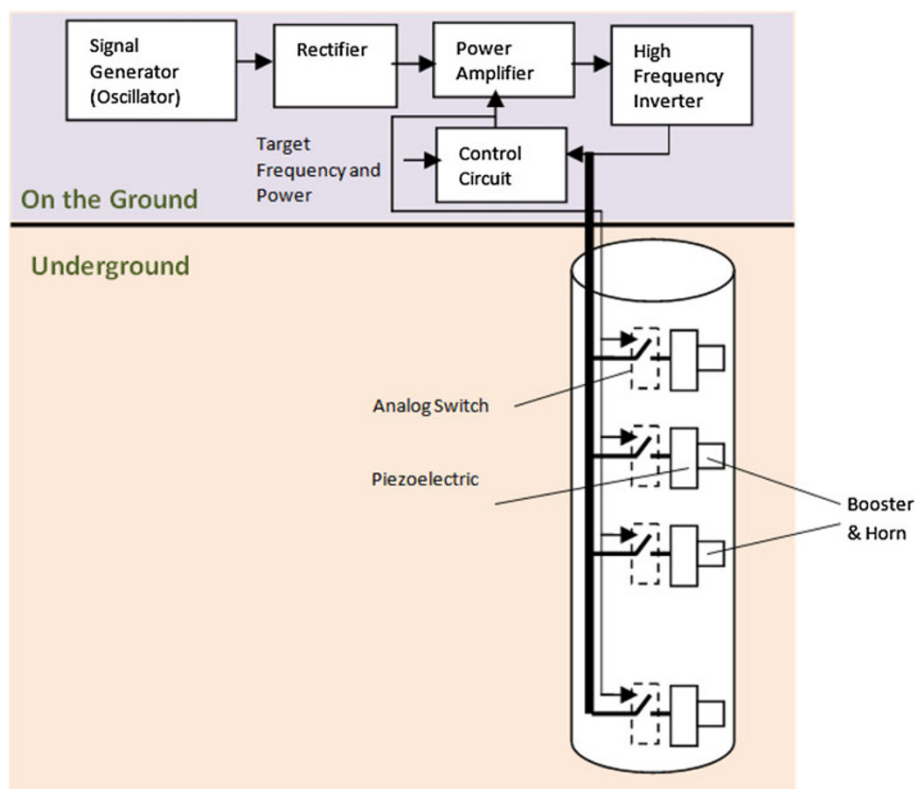
- In conventional EOR, external materials, e.g. chemicals, gases, steam or water is injected into the reservoir while in case of Electrical EOR is purely based upon the voltage and frequency without any requirements for chemical, steam or gas injection.
- Waiting time to see the results for Electrical EOR is much less as compared to conventional EOR techniques.

**Table 3** Comparison between different electrical EOR techniques

EEOR type	Suitability	Limitations
Induction heating	Suitable especially in the presence of thief zones or in the reservoirs not suitable for other thermal EOR techniques Different set of low- and high-frequency electrical currents can be used according to the requirements Reservoirs having low in situ water saturation	Can only be applied to heat the near well bore areas
Low Frequency Electric heating (Joule heating)	Maximum power transfer may get limited in some field applications because of hot spots occurring near the ends of electrodes Based on energy supplied, it can be alternative of steam injection Reservoirs comprising of high permeability streaks or fractures	Temperature should be maintained below the boiling point of water in order to maintain continuity Corrosion may occur on the electrodes in high salt concentration reservoir
Microwave heating	Suitable for reservoirs containing heavy oil Mostly applicable to reservoirs having the target area directly exposed to microwaves without any hurdles	Require shut down of production Penetration depth of high frequency is limited Source may get damaged because of extensive heat production Not applicable to water flooded reservoirs
Ultrasonic stimulations	Suitable for reservoirs with high water saturation or depleted reservoirs Suitable for the reservoir having heavy oil lying behind water	Size of ultrasonic vibrator is limited by the diameter of injection well Not suitable for unconsolidated formations with compressive strength of less than 150 psi Not suitable with a slurry mixture of sand and water



**Fig. 6** An ultrasonic wave-based EOR setup



- Employing the electrical techniques, electrical or electromagnetic heat energy/mechanical vibrations can be directed precisely towards the target area proving these techniques as efficient and cost effective as opposed to conventional EOR.
- Geology or characterization of the reservoir is not affected by employing electrical techniques.
- No storage and supply of chemicals or other fluids is required for electrical procedures as opposed to conventional techniques. This latest leads to the suitability of electrical methods for both onshore and offshore reservoirs.
- Electrical EOR methods also do not need dumping of any waste material, e.g. chemicals, etc., and hence are environment friendly.

#### Microwave EOR with added advantages

Microwave EOR is the optimum case of EEOR in many cases and helps to extract the best possible quantity of oil within less time as compared with other EEOR methods. It is because of the dielectric heating effect of microwaves, when microwaves are applied to a material medium, it directly interacts with the polar molecules. Since the frequency of applied microwaves is very high, they produce electric and magnetic fields alternating at microwave frequency. When these alternating electric and magnetic fields

interact with the polar molecules, these polar molecules are set into vibrations at the frequency of applied microwaves. Because of this change in polarity, vibrations and collisions with the other molecules at such a high frequency, a great deal of energy is produced which helps in raising the temperature of the environment (Okassa et al. 2010). When microwaves are applied to the hydrocarbons reservoir, this increase in temperature helps in reducing the viscosity of oil and enabling the oil to flow towards the production well from where it can be extracted.

Microwaves produce heat more efficiently in the case of absorption inside the material, but crude is not a good absorber of microwaves. To enhance the absorption power of crude oil, microwave receptors (activated carbon, iron oxide and methanol) can be used which stimulate the heating process. Microwave heating is affected by the design of the microwave source and the dielectric properties. Dielectric properties of material mainly depend upon the frequency of operation, temperature of the reservoir, etc. Hydrocarbons mixed with sand can absorb huge amounts of microwaves and hydrocarbons may get heated to achieve temperatures as high as 300–400 degree centigrades rapidly (Acar 2007).

Ovalles et al. (2002) presented discussions on three different types of reservoirs consisting of medium crude oil, shallow lake Maracaibo heavy oil and extra heavy crude oil. Simulation results presented that microwave

heating causes the temperature of the crude oil to rise and hence the viscosity of the oil to fall which facilitates its extraction and enhances the production of oil. Moreover, the dielectric heating can produce 10 times more heat as compared with the electricity of same power level. Microwave heating is advantageous as compared with other thermal methods because heat loss can be reduced through controlled use of microwave heating. Therefore, microwaves are a good candidate for use in EOR with the only limitation of penetration of microwaves which depends mainly on the operational frequency as well as the inner characterization of the wells. Microwaves cannot pass through water and they can only travel in line of sight. At higher frequency the attenuation of microwaves increases.

A solution to these problems can be employment of microwave source close to the target area to heat it without losing energy and efficiently using all the energy to heat up the reservoir.

## Conclusion

Electrical EOR is a good alternative of conventional EOR in terms of energy efficiency and low cost. It does not have any environmental effects leading to no deterioration of the reservoir geology and surrounding area. In addition, EEOR has no need for production arrangement, transportation and storage of specific reactants. In addition, EEOR provides an increase in the production of oil as compared with its counterpart, the conventional EOR. Switching technique between different EEOR processes can also be employed based on the need. Microwaves are an ideal candidate from EEOR processes in many application areas with reduced cost and focused heating effects. Different schemes of electrical-based EOR are presented and a comparison is also provided in terms of advantages on the conventional EOR techniques. In addition, two basic oil field models have also been presented and discussed for two of the electrical-based techniques named as microwave heating and ultrasonic stimulations.

Electrical EOR has also some limitations as other conventional techniques do. These include non-uniform heating of reservoir especially as most of the energy and heat is concentrated near the well-bore region. Some cases are only applicable in the presence of brine, e.g. resistive or joule heating. Similarly, electrodes also suffer from the corrosion and this issue needs to be resolved. Similarly, microwaves only travel in line of sight, and the presence of any hurdle in between the source and target may attenuate them resulting in energy loss.

Future work may focus on the areas of control feedback for providing the real-time temperature and pressure

conditions inside the reservoir during the heating process and based on the results, the process should be boosted or stopped. Similarly, in terms of switching between different EEOR processes, the conditions of the reservoir should be investigated and based on the results a selection from different available EEOR processes should be done, which can provide an optimum recovery for the conditions of the reservoir. It can also be done using a control feedback loop which can analyze the conditions and can decide about the best suited method and adopt it based on the results. Similarly, the decision regarding location for employment of electrical sources inside the well should be taken for the best possible recovery; a feedback loop should be developed which can calculate the desired position and basing upon the results can adjust the position of the heaters accordingly.

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