Enhanced Oil Recovery Techniques for Indian Reservoirs

N. Sakthipriya, Mukesh Doble and Jitendra S. Sangwai

Abstract The overall oil production worldwide has declined due to the increase in maturity of the oil reservoirs. In developing countries like India, the oil production and demand plays a crucial role for the development of economy of the country. However, the domestic crude oil production is insufficient to meet the requirement for energy. Thus, there is a big challenge to minimize the gap between the demand and supply for crude oil. Several methods to enhance oil recovery have been developed to increase the production from matured reservoirs and are referred to as enhanced oil recovery (EOR) methods. This chapter discusses in detail about the various EOR methods, their applicability, and the screening criteria for various reservoir types. The EOR methods are further discussed in Indian contexts. This chapter also summarizes the details of various oilfields in India. The chapter will in general, help to understand the recent trends and the need of EOR for Indian oil reservoirs.

1 Introduction

Oil and natural gas have been an important source of energy for the mankind. The total energy requirement of the world has increased drastically in the past decade due to the increased demand from the developing countries like India, China and Brazil. According to British Petroleum (BP), statistical review of world energy (2013), India currently imports about 70 % of its total requirement of crude oil and natural gas, thus accounting for about 40 % of the import bills. Crude oil has the weakest global growth rate in terms of production among fossil fuels for the third successive year. The current crude oil production is insufficient to meet the

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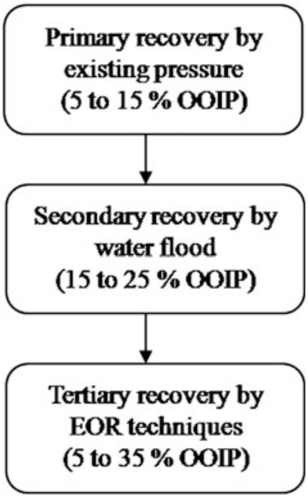
requirement for the energy. Thus, there exists a big gap between the demand and supply of crude oil. The ultimate solution is to increase the recovery of oil from existing reservoirs in addition to the exploration of new reservoirs (Herron et al. 2004). Several methods have been developed to increase the production from mature reservoirs, which are referred to as enhanced oil recovery (EOR) methods. EOR is the process in which external agents in the form of fluids are injected into the reservoir for pressure maintenance and to alter the physiochemical properties of oil, gas, water and reservoir rock, which in turn increase the sweep efficiency (Donaldson et al. 1989). The recovery increases due to an impact of the injected fluids on the reservoir rock properties and fluid properties, like the interfacial tension (IFT), oil swelling, viscosity reduction, wettability modifications, favorable phase behavior, etc.

Oil and gas in the reservoir resides in the porous rock at high pressure and high temperature conditions. The primary recovery of these hydrocarbons is due to the initial reservoir pressure, which is sufficient for the fluid to flow. It is a well-known fact that, during the primary recovery, only 5–20 %, of the oil can be produced from the oilfield due to the existing pressure. To improve the recovery after primary phase, water is injected into the reservoir to displace the oil leading to ~30–50 % additional recovery from the reservoir. The challenge is to recover the residual oil in place, which is ~50 % from the original oil in place (OOIP). Figure 1 shows a schematic of average production resulting from various phases of crude oil recovery from the reservoir. On an average, one third of the OOIP in the reservoir can be recovered through primary and secondary recovery techniques (Blunt et al. 1993). This calls for further development of enhanced oil recovery (EOR) techniques to target the residual oil remaining in the reservoir at the end of secondary recovery.

Fig. 1 Various oil recovery techniques



1.1 Need for Enhanced Oil Recovery

Table 1 shows the proved global crude oil reserves. Here, the proved reserves means reserves from which crude oil can be produced economically using available technology. According to BP statistical review of world energy (2010), worldwide oil production has decreased more rapidly by 2 million bpd, which is the largest drop since 1982. In 2008, oil production and exporting countries (OPEC) executed the production cut agreement to reduce the output of OPEC countries. This agreement is maintained throughout the year 2009, resulted in ~7.3 % decline of production out of which 75 % of the decline was from the Middle Eastern countries.

Ageing of oil wells is an everlasting and crucial alarm faced by the global oil and gas industry. In India, 75 % of oil and Natural Gas's (ONGC) production is coming just from 15 oilfields. In addition, oilfield in Ankleshwar, Rudrasagar and Bombay high wells started declining recent past. Most of the oil wells are either unproductive or produces insignificant oil. An oil well becomes less productive when ~30 % of oil in place has been recovered, which may be due to the reduced reservoir pressure, and developed compositional gradient. This produces lighter hydrocarbon component from the reservoirs in early phase leaving the higher end hydrocarbons (waxes) within the reservoir. These reserves tend to produce more waxy- and asphaltic crude oil, thus shows challenges in EOR. The production of the latter pose serious threat for the recovery of oil since waxes and asphaltene tends to deposit near the well bore, surface facilities and offshore and onshore production pipelines. Low permeability of the reservoir rock and the high viscosity makes crude oil immobile and hinder oil recovery in the existing wells (Bordoloi and Konwar 2008). In addition, high IFT between water and oil increases the capillary forces, which in turn retains the oil in reservoir rock (Banat 1995). The decreased gas trapping in the reservoir, responsible for pushing the oil upto the well, results in decreased production.

However, these reservoirs and the oil wells still show potential for increased production through reservoir management using improved recovery methods. Using typical EOR methods, an additional 5–35 % of OOIP can be extracted from an oil field. After the primary- and secondary recovery techniques, ~7000 BBL of crude oil is expected to stay back in the existing reservoirs. Hence, the target for

Table 1 Worldwide proved crude oil reserves (BP Energy Outlook 2030 2013)

S. No	Country	Thousand million barrels			
		1992	2002	2011	2012
1	North America	122.1	228.3	221.0	220.2
2	South and Central America	78.8	100.3	326.9	328.4
3	Europe and Eurasia	78.3	109.3	140.3	140.8
4	Middle East	661.6	741.3	797.9	807.7
5	Africa	61.1	101.6	126.6	130.3
6	Asia Pacific	37.6	40.6	41.4	41.5
7	World	1039.3	1321.5	1654.1	1668.9

EOR techniques is to recover the remaining oil effectively (Wu et al. 2012; Wang et al. 2013). According to the International Energy Agency, enhancing the oil recovery possibly will release ~300 BBL of trapped oil (Bassioni and Sanders 2013). As per the report by Senergy world magazine (2011), at the end of 2005 the global market for EOR was estimated to be 3.1 billion dollars (for barrels of crude oil), and rapidly increased to 62.5 billion dollars in 2009.

In most of the cases, the primary and secondary recovery methods produce very less crude oil than that estimated (one third of the OOIP), and this case is evidenced by X-ray tomographs (Lake et al. 1992; Iglauer et al. 2010; Al-dousari and Garrouch 2013). EOR can also be applied at the primary stage of an oilfield where available pressure in the reservoir is insufficient to induce the flow of oil through the producing wells. In the secondary stage, EOR is used to promote production rates by improving flow and suitable recovery conditions. Generally, EOR methods are engaged regularly during the tertiary stage where oilfields have high water cut and low productivity (Adasani and Bai 2011). EOR also involves major financial risks due to various suspicions. Pilot studies on EOR methods for the suitability for given reservoirs should be done before implementing at commercial scale. If the pilot study works technically and financially, the process can be expanded at oilfield scale.

2 Methods of EOR

There are several types of hydrocarbon reservoirs ranging from dry gas, wet gas, gas condensate, light oil, brown oil, heavy oil and extra heavy oil reservoirs. In addition, the in situ reservoir properties vary in different oilfields. EOR methods are classified broadly as, chemical injection; gas flooding; microbial and thermal injection (see Fig. 2). The EOR methods target the oil and rock reservoir properties by several mechanisms. In addition, cold heavy oil production (CHOP), cold heavy oil

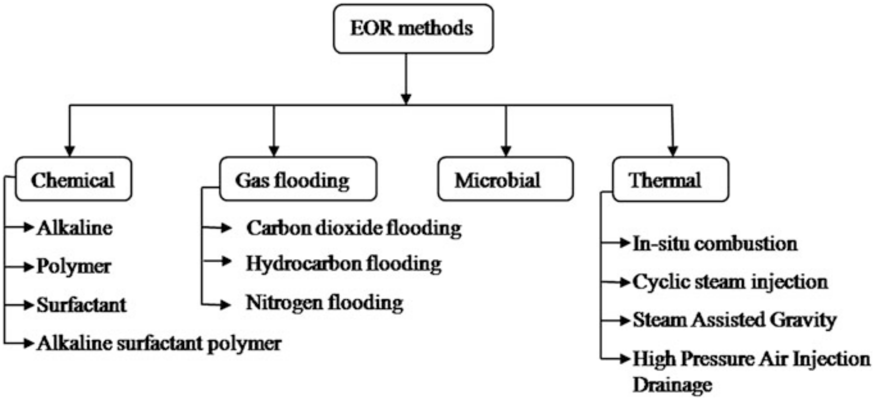


Fig. 2 Various techniques used for enhanced oil recovery

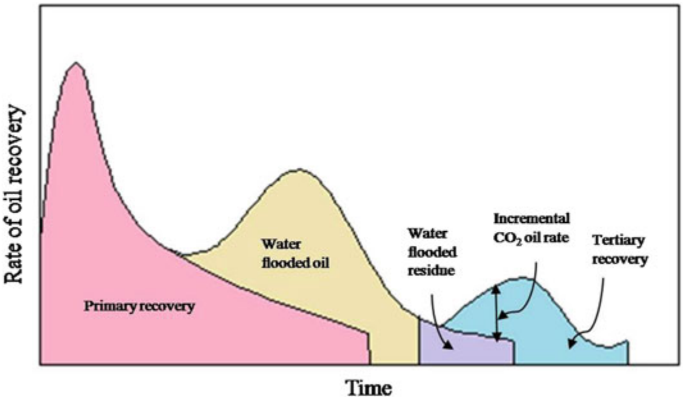


Fig. 3 Expected oil recovery through various EOR techniques (Taglia 2010)

production with sands (CHOPS), microwave technique, surface mining, solvent injection and ultrasound are other techniques employed to enhance the recovery of crude oil (Jiang et al. 2014). Surface mining is suitable for reservoirs with depth less than 70 m and recovers ~5 % of OOIP. On the other hand, CHOP/CHOPS recover ~5–10 % of OOIP (Ivory et al. 2010; Jiang et al. 2014). The largest percentage of OOIP is produced during primary recovery and over the period of time the decline starts when the reservoir is no longer productive, water flooding is done to augment the oil recovery and further enhancement is done through various enhancement methods (see Fig. 3).

2.1 Chemical EOR

Chemical methods are generally used to decrease the IFT between oil and used water, and after water flooding to increase the oil recovery (Yang et al. 2005). Chemical recovery methods include polymer flooding, surfactant flooding, alkaline flooding, and the composite, alkali-surfactant-polymer (ASP) flooding. These methods involve mixing of the above chemicals in carrier fluid (primarily water) prior to the injection. Figure 4 shows the process of chemical flooding schematically.

Polymer flooding, introduced in 1960, is a widespread chemical EOR practice (Wang et al. 2013). Water soluble polymers increases the viscosity of the injected water thereby making the viscous oils to move efficiently. This is suitable mainly for heterogeneous reservoirs. Polymer flooding is employed efficiently for the oil with high water saturation during the initial period of water flooding with high mobile oil saturation (Wang et al. 2013). The viscoelastic property of the polymer solution helps to displace the oil remaining in micro-pores that cannot be displaced by water flooding alone (Needham and Hoe 1987). When water displaces oil, the mobility ratio of oil and water is so high that the injected water enters the reservoirs,

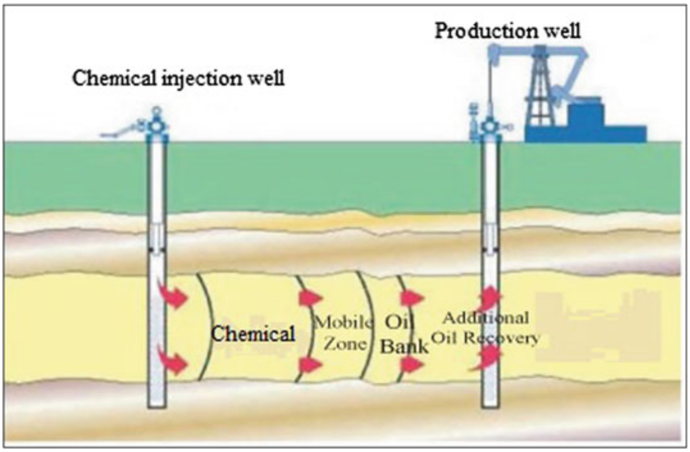


Fig. 4 Schematic of chemical EOR method

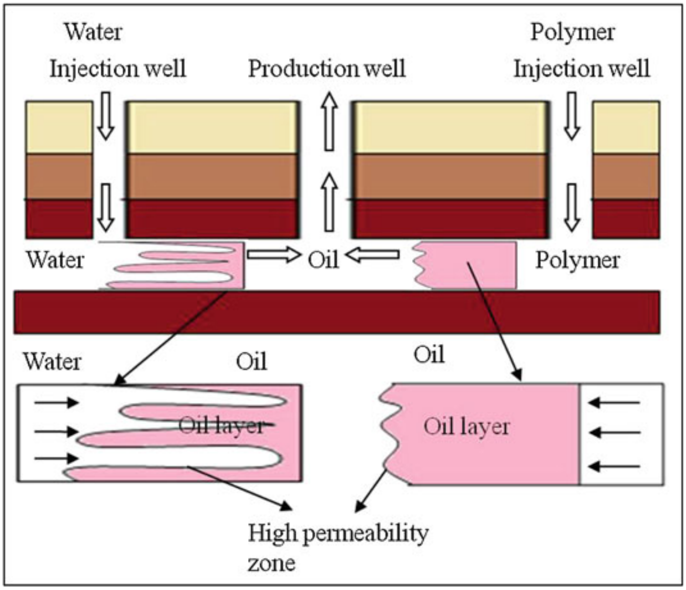
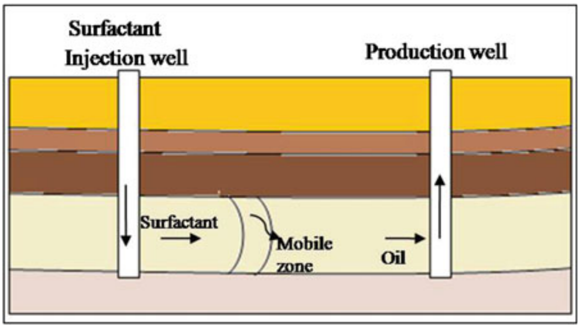


Fig. 5 Mobility control using polymer flood

which is termed as viscous fingering. Injection of polymer solution into the reservoir decreases the oil-water mobility ratio and displacement happens evenly to sweep a huge volume as shown in Fig. 5. Though the polymers control the mobility effectively, they are not suitable for reservoirs having temperature greater than 194 °F (Sabhapondit et al. 2002). After polymer flooding process, more than half of the OOIP remains behind due to the entrapment of oil in the pores of the reservoir rock.

Fig. 6 Schematic of surfactant flood



Figures 6 and 7 show the injection of surfactant into the reservoir and elongation of oil drop. The surfactant reduces the IFT between oil and water by getting adsorbed at the interface between the crude oil and water and makes spherical oil droplets to deform and elongate to overcome the capillary forces persuading a huge raise in the capillary number (Mokhatab and Towler 2009; Wu et al. 2012; Al-dousari and Garrouch 2013). These surfactants also helps to reverse the rock wettability by changing the oil-wet rock to water-wet, emulsify the oil and help the oil to come out of the rock and mobilize the entrapped oil in porous rock (Taylor and Nasr-El-din 1996; Li et al. 2000; Nedjhioui et al. 2005; Mandal and Ohja 2008). Explicitly, surfactants of specific structure and high purity are required (Yang et al. 2005). Due to versatility, currently Gemini surfactants have acquired more attention. Micelles formed by anionic geminis significantly lowers the surface tension than other anionic surfactants (Gao and Sharma 2013).However, there is still a scope in developing the surfactant systems, which help to reduce the IFT between oil and water at high salinity and high reservoir temperature conditions (Hezave et al. 2013).

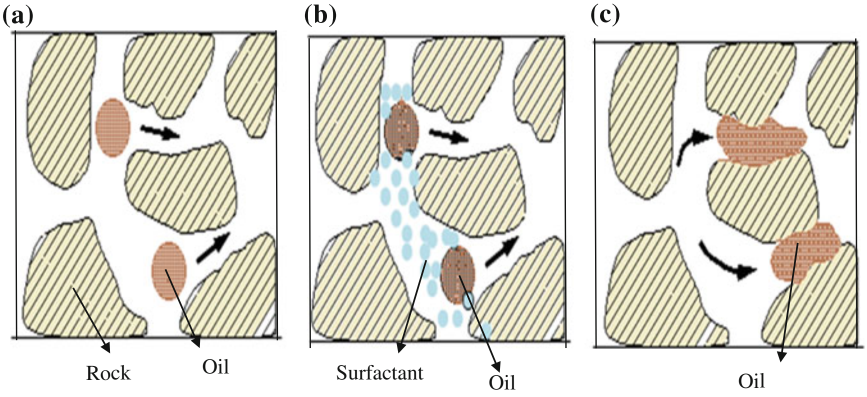


Fig. 7 Deformation of rock and elongation of oil; **a** oil between the reservoir rock; **b** addition of surfactant; **c** elongation of oil between the reservoir rocks

Alkali flooding is typically employed alone or along with surfactant and polymer flooding. It is applied in the areas with relatively poor physical properties, such as ST, rock wettability, etc., and low permeability reservoirs. It involves the addition of NaOH to the injection water to enhance the recovery. Generally, acidic compounds in the crude oil are drifted to the interface by the injected alkali and reacts with aqueous phase hydroxide to form surfactant in situ (Wang et al. 2009). Since this kind of flooding procedure is simple and inexpensive, it continues to receive much attention for EOR (Wanli et al. 2000). Alkali Surfactant Polymer (ASP) flooding gathers the benefits of all three types of chemicals and develop the volumetric sweep efficiency. The alkali component reacts with organic acids present in the crude oil forming petroleum emulsion, which in turn interacts with surfactant to create very low IFT and alters wettability (Gao et al. 1995). It is well suited for carbonate formations since the alkali added with the surfactant can significantly reduce the anionic surfactants adsorbed on calcite and dolomite rock (Hirasaki et al. 2008). This mixture can produce molecular interactions affecting the physico-chemical and rheological properties of the crude oil (Smitter et al. 2001). The molecular interactions exhibit some properties that depend on the electrical charge, hydrophobicity, non-polar tail, flexibility and additives of the polymer and the surfactant (Qi et al. 2013). Generally, the hydrophobic nature of polymer and surfactant induce molecular interactions in situ (Dubin et al. 1992; Iglesias et al. 2003).

2.2 Microbial EOR (MEOR)

This method is used to enhance the production from the mature brown and heavy oil reservoirs. Strains of microbes are injected into the crude oil reservoir. These microbes digest the long chain hydrocarbon molecules to shorter chains and generate bio-surfactants, acids and gases, raise the API gravity and decrease the cloud point (Etoumi 2007). Microbes can either be cultivated at the surface, injected into the reservoir downhole; or they can be directly cultivated in the reservoir by providing the nutrients at the wellbore. MEOR is effective for reservoirs of temperature range ~158–248 °F. Crude oil from shallower and cooler reservoirs are more biodegradable than the oil in the deeper and hotter reservoirs (Wenger et al. 2001; Larter et al. 2012). Generally, microbes are non-carcinogenic, non-combustible, non-pathogenic and environment friendly (Mokhatab and Towler 2009). Use of microbes to enhance oil production appears to be a viable and cost effective when compared to other conventional methods because they occur naturally. MEOR intends to target the drainage of oil into the well and, at the same time, degrades the waxes and asphaltenes of waxy crude oil or heavy oil (Brown 2010). The bio-surfactants, fatty acids, alcohols and solvents produced in situ by the microbes solubilize the hydrocarbons and eliminates damage caused by paraffin from well bores

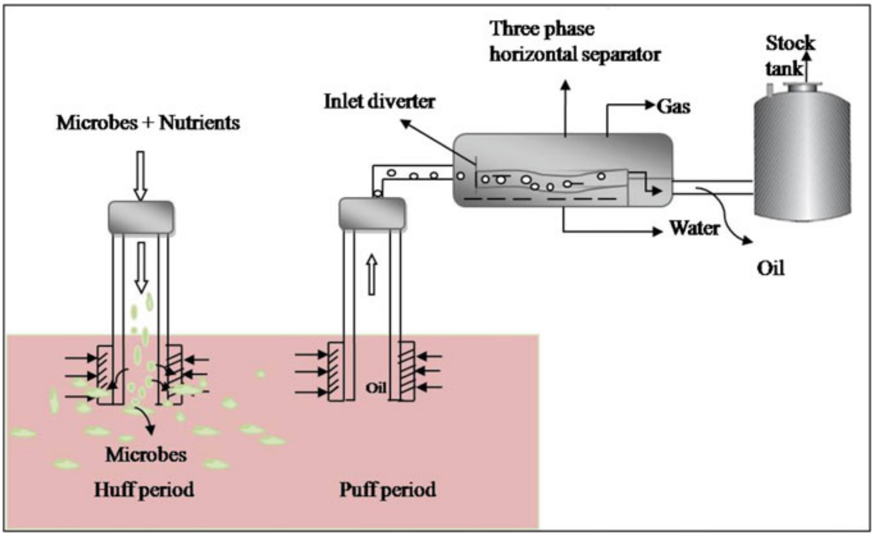


Fig. 8 Illustration of huff and puff microbial EOR

(Sadeghazad and Ghaemi 2003). The bio-surfactant that are surface-active agents are less toxic, highly biodegradable, effective at extreme temperature, salinity and pH conditions and increases the bioavailability of hydrophobic substrates (Pereira et al. 2013). Gas solubility of the hydrocarbons can be increased by creating hydrophobic cavities of micelles, which are due to bio-surfactants (Miller and Zhang 1997). In the matured oil reservoirs, the bio-surfactants come in contact with a small drop of the oil struck in the pores of the reservoir rock, reduce the IFT, and mobilize the trapped oil by reducing the viscous forces (Ramakrishna 2008). Figure 8 shows the schematic of huff and puff microbial enhanced oil recovery. In this method, the microbe and the nutrient enter into the well, and the well is kept shut in for some period. During this time span, microbes produce various metabolites to squeeze out the oil from the reservoir rock. Table 2 shows the various metabolites produced from the microbes and their role in enhancing the oil recovery.

Table 2 Role of byproducts produced during microbial EOR method (Ramakrishna 2008)

S. No	Bioproducts	Role in EOR
1	Acids	Increase in permeability, emulsification
2	Biomass	Selective plugging, wettability alteration
3	Biosurfactant	Emulsification, de emulsification, IFT reduction
4	Gases	Increased pressure, IFT and viscosity reduction, oil swelling
5	Polymers	Selective plugging, viscosity reduction
6	Solvents	Rock dissolution, viscosity reduction

2.3 Gas Injection Methods

These methods are classified into immiscible and miscible gas injection method. In immiscible gas injection, the gas is injected at lower pressure region of the reservoir. The former is further classified into gas injection and dispersed gas injection according to the injection area. In crestal gas injection technique, gas is injected at the gas cap on the top of the oil bearing zone, and in the case of dispersed method, gas is injected at the oil bearing zone. Miscible gas injection techniques categorized as enriched gas miscible displacement method, high pressure dry gas miscible displacement method and miscible slug flooding (Bhatia et al. 2014). In high pressure dry miscible gas displacement, component of the light oil get evaporated and make a homogeneous mixture of gas and oil at interfaces, which helps to move the residual oil from the reservoir. Volatile hydrocarbons (propane and butane) are used in this method. In miscible slug flooding, intermediate hydrocarbon gases are injected before the dry gas injection start. This creates a slug at the front which get displaced by the gas reducing the total cost of the project and increases the oil recovery. Gas injection methods are most widely used for light oil, gas condensate and volatile oil reservoirs (Alvarado and Manrique 2010).

CO_2 flooding is more appropriate when the reservoir pressure is depleted through primary and secondary production. It is particularly effective in reservoirs having low-density crude oil and depth of >2000 ft. CO_2 injection reduces the greenhouse gas and ultimately terminates in CO_2 sequestration (Srivastava et al. 2012). When the injected CO_2 become miscible with the residual oil the physical forces, making the two phases away from each other vanishes, thereby enabling the CO_2 to move the crude oil from the rock pores and thrusting it into production tubing (Fig. 9). According to the US Energy Information Administration (USEIA) (2013), CO_2 floods involve the injection of CO_2 alternated with water (as in case, water-alternating-gas or WAG floods). This help to reduce the trend of low viscous CO_2 to escape through the displaced oil due to gravity segregation. If the injected CO_2 breaks through from the production well, any gas injected afterwards will follow the way, thereby reducing the overall efficiency (Fig. 10).

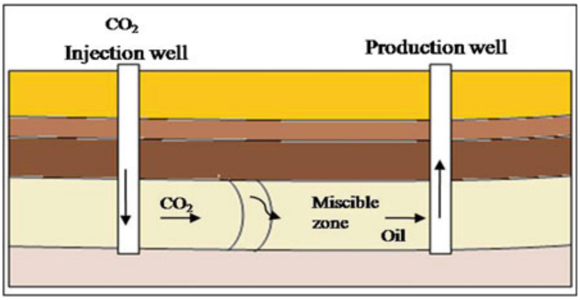


Fig. 9 Schematic of carbon dioxide flood (Shah et al. 2009)

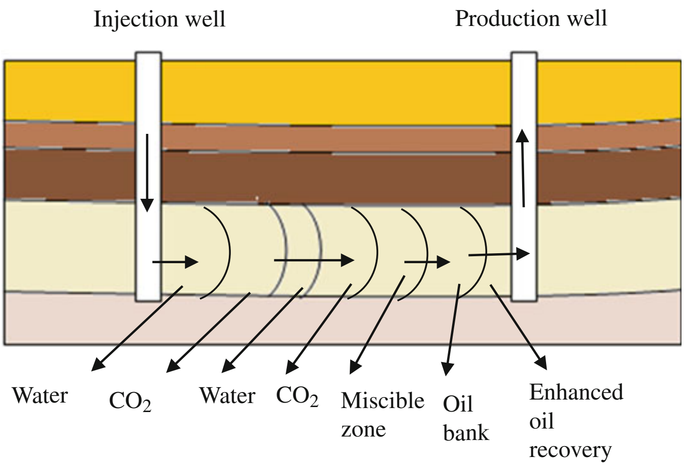


Fig. 10 WAG- carbon dioxide flood

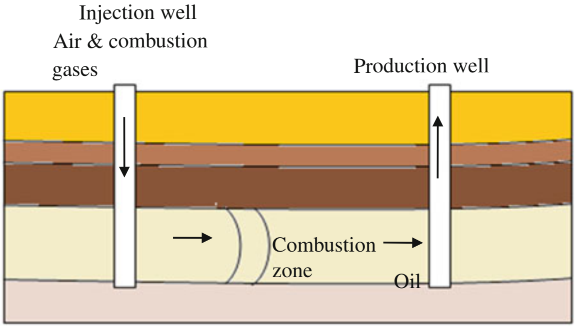
Hydrocarbon flooding engages the injection of hydrocarbon gas into the reservoir. Inside the reservoir, the gas dissolves with the oil, raises the sweep efficiency, and decreases the viscosity in the presence of water (Bhatia et al. 2014). It can also be generated in situ from the impulsive ignition of oil when air is injected into the reservoir. However, this shows the poor mobility ratio compared to other conventional methods. Hydrocarbon gas injection is mostly implemented where the gas supply cannot be monetized.

Though the gas injection can recover the oil effectively, it has poor sweep efficiency. This poor sweep efficiency is due to the unstable viscosity, permeability variation and segregation of the injected gas under gravity. To overcome these problems, foam injection is introduced in 1980. This is a promising technique to increase the gas injection conformance at the well bore and to increase the sweep efficiency in miscible and immiscible gas EOR (Ocampo et al. 2013). Foam has the ability to reduce the gas mobility to overcome the permeability variations (Ashoori and Rossen 2010). There are several types of foam injection techniques such as CO_2 foam, steam foam, surfactant alternating gas (SAG) foam. Strong foam can be produced if there exist a high critical pressure gradient (Feng et al. 2008). Surfactant is added alternating to the gas injection and can be applied to the field, which contains the constraining injection pressure (Shan and Rossen 2004). However, if straight-line relative permeability occurs, this SAG process should not be applied to naturally fractured reservoirs though strong foams can be developed in the fractures (Ashoori and Rossen 2010). In high permeability areas, foam acts as a high viscous liquid and diverts the injected fluid to low permeability rocks, thus it can be a better alternative to polymer flooding in the case of high permeability rocks (Nguyen et al. 2000).

2.4 Thermal EOR

Thermal EOR methods use the form of thermal energy, which is injected into the reservoirs to decrease the viscosity of oil and degrade hydrocarbon in situ, thereby improving the oil recovery. Four common recovery methods involving thermal injection are: in situ combustion (ISC); cyclic steam stimulation (huff and puff/CSS); steam-assisted gravity drainage (SAGD) and high pressure air injection (HPAI). Figure 11 shows schematically the ISC, which employs the injection of air to ignite the small fraction of oil, generates heat internally, and produces the combustion gases to enhance the oil recovery especially for heavy oil sandstone reservoirs (Yazdani and Maini 2005; Alvarado and Manrique 2010; Capper et al. 2011; Knorr and Imran, 2011). Figure 12 shows schematically the CSS. CSS and SAG Dare performed to recover bitumen and heavy oil from reservoirs (Jiang et al. 2014). SAGD is most popular in the oil sands and extra heavy crude reservoirs of Alberta, and tested in Venezuela with some degree of accomplishment. An interesting study could be the use of solar power to generate steam and drive enhanced oil recovery. The steam generated by solar energy can be used as an alternative to steam injection derived from natural gas. Recently, solar EOR projects are running in California. Solar EOR may be a real alternative to conventional thermal EOR in regions with plentiful sunshine as the economics start to become viable with higher oil prices (Naderi and Babadgli 2010). In the current decade, HPAI is receiving the popularity due to its economic feasibility. It is applicable for light crude oil reservoirs, particularly for in light oil and low permeability carbonate reservoirs (Alvarado and Manrique 2010). As per the report by SAOGL (2013), thermal methods minimize the physical damage and provide an option where other EOR techniques cannot be applied. However, these methods are lengthy, leaves residue in the reservoirs decreasing permeability, porosity, and alter wettability. Significant heat losses do happen in the case of reservoirs with thin formations and high water saturation present in the pay zone (Jiang et al. 2014).

Fig. 11 Schematic of In-situ combustion (Shah et al. 2009)



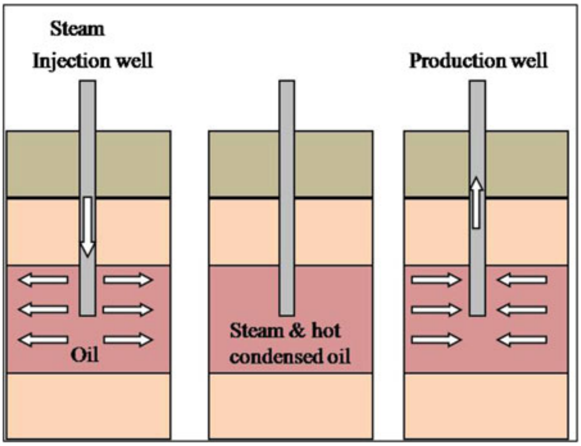


Fig. 12 Cyclic steam stimulation (Shah et al. 2009)

2.5 Ultrasonic and Microwave EOR

Ultrasound is swinging sound pressure wave with a frequency higher than the maximum value of the normal human hearing range. Power ultrasounds in the 20–100 kHz ranges enhance the reaction and at higher power values. Ultrasound changes the properties, such as solubility, mobility, etc. Transducers produce and sense ultrasonic waves in water and break the strong bonded molecules into several parts (Alhomadhi et al. 2013). Application of high frequency sound waves into the reservoir enhances the oil recovery unconventionally. Acoustic waves with high intensity is generated inside the well bore by sending an acoustic emitter and these waves then pass through the porous media and mechanically stimulate the fluids (Hamida 2006). This ultrasound is used to stimulate the water flooding and improves recovery by ~16 %. However, the influencing mechanisms are not fully researched (Mohammadian et al. 2011). The awareness about this field is rather less. Another method, such as microwave heating is the thermal stimulation method performed by microwave irradiation. This depends on various parameters, such as heating period, amount of matter, etc. (Datta and Anantheshwaran 2001). Oil and water has both positive and negative particles, which behaves as microscopic magnets. As the positive particles move towards the porous medium, the negative particles get repelled and, thus the heat transfers leading to improved oil recovery (Hascakir et al. 2008).

2.6 Nanotechnology in EOR

Nanotechnology is gaining attention in upstream oil and gas industries. Until now, nanoparticles have become an attractive means for EOR only at laboratory-scale, and ultimately many researchers at lab scale have observed oil recovery for various permeability sandstone rocks (Hendraningrat et al. 2013). Nano EOR is performed by injecting 1–100 nm nano-particles into the reservoir to reduce the viscosity and alter the mobility (Ayatollahi and Zerafat, 2012). These particles alter the chemical interactions responsible for IFT, phase behaviour and contact angle of fluids (Ogolo and Onyekonwu 2012). Recently, nano-emulsions have also gained attention to recover the residual oil. It contains the emulsion made of 5–500 nm particles (Sharma et al. 2014). The success of these nano-emulsions depends on the preparation of the emulsion. Figure 13 represents the schematic of nano-particles in contact with the oil. It illustrates that, a thin film forms at the oil droplet surface and it alters the contact angle of the trapped oil and the rock, which, in turn, reduces the IFT. Implementation of nano-EOR on the reservoir is based on several physical properties of the reservoir, e.g. porosity, permeability, depth of the reservoir, viscosity of the oil, API gravity of the oil, etc.

2.7 Screening Criterion for EOR Methods

The oilfield shows varying characteristics of rock- and fluid properties. It is therefore essential to know the applicability of EOR methods for specific reservoir conditions. Figures 14, 15 and 16 show the screening criteria of EOR based on permeability, oil viscosity and reservoir depth. Table 3 shows the applicability of EOR for various reservoir conditions.

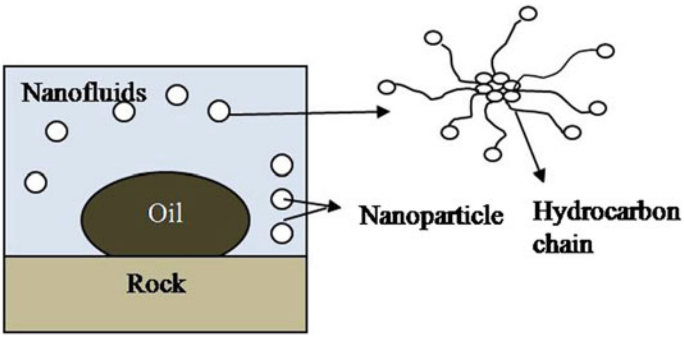


Fig. 13 Illustration of a nanoparticle assisted oil recovery (Das et al. 2008)

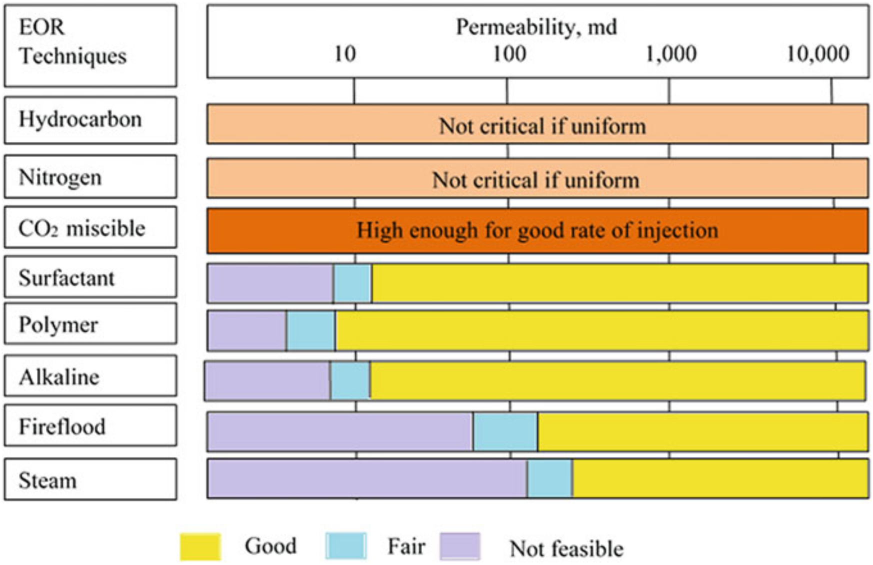


Fig. 14 Screening criteria for EOR methods by permeability (Taber and Martin 1983)

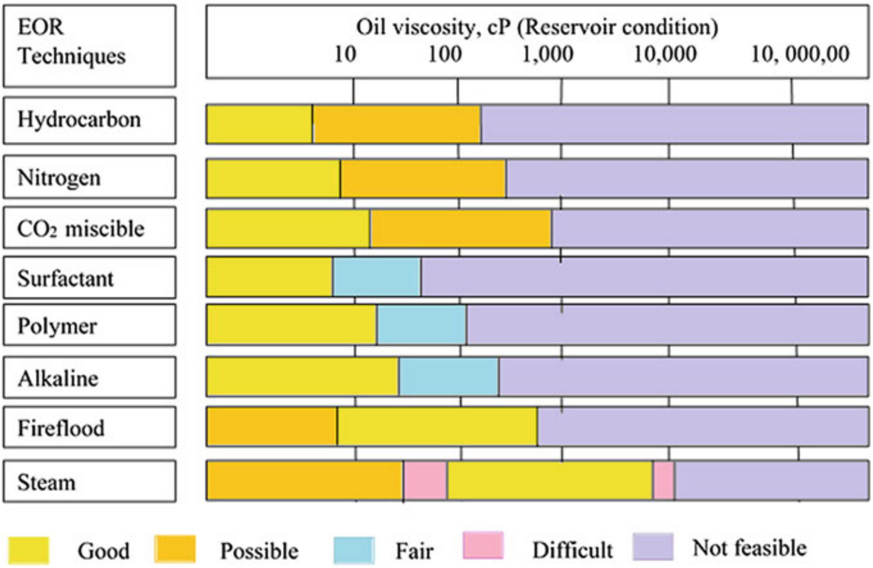


Fig. 15 Screening criteria for EOR methods by viscosity of oil (Taber and Martin 1983)

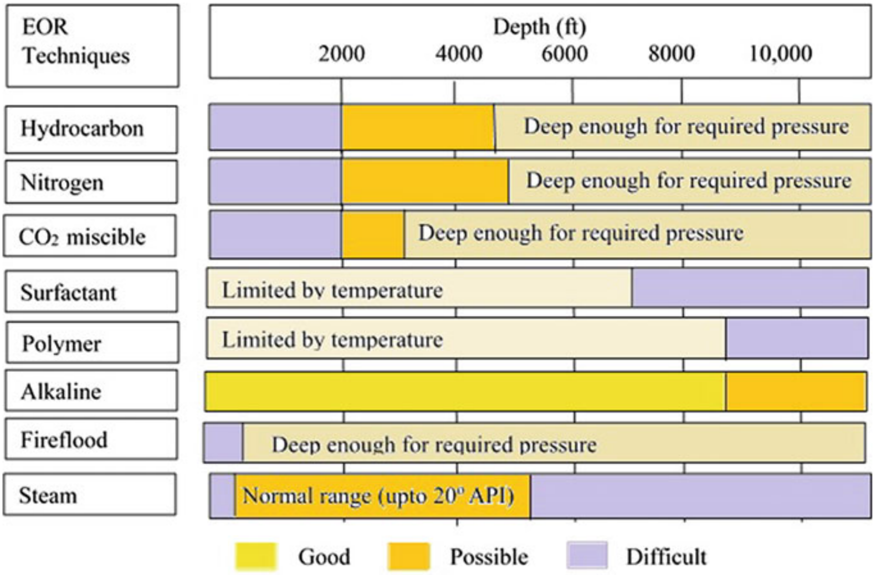


Fig. 16 Screening criteria for EOR methods by depth (Taber and Martin 1983)

3 EOR Techniques: Global Scale

Proved reserves of oil and gas estimates have increased slightly all over the world. Currently oil reserves are estimated to be 1.64 trillion bbl and gas reserves to be 7.02 quadrillion cf, which is 0.4 and 2 % higher compared to the last year. OPEC share has also declined for both the resources. Worldwide oil production is edged up ~1 % in 2013 (Xu and Bell 2013). The total world oil production from EOR is ~3 million bpd. It has remained relatively at a lower level over the years. Figure 17 shows the worldwide EOR production rate. Using thermal EOR techniques, ~2 million bpd oil has been obtained in the recent past. Brazil, China, Canada, California, Indonesia, Oman, Trinidad, Tobago and Venezuela are the countries, which implemented the steam injection for heavy oil sand reservoirs (Kokal and Al-Kaabi 2010). CSS has been effectively executed in Issaran oil field (Egypt), one of the first heavy oil carbonate fields. Steam injection is also followed in Bahrain oil field.

When compared with the total worldwide production, China plays the major role in attempting the EOR technique to maximize the total oil production, which involves mostly the chemical EOR. Daqing oil field in China, which plays the largest role in EOR, employed polymer flooding in most of the wells to increase the sweep efficiency and oil displacement efficiency (Wang et al. 2013). In Saudi Arabia, chemical EOR is implemented in Safania reservoir resulting significant improvement in recovery (Almalik et al. 1997).

Table 3 Applicability of EOR for various oil reservoirs (Adapted from Taber and Martin 1983; Shah et al. 2009)

S. No	EOR methods	API gravity	Reservoir fluid composition	Depth (ft)	Permeability (md)	Viscosity (cP)	Requirements	Limits
1	Alkaline	13–35	Organic acids	<8400	>20	<200	Naphthenic acids, asphaltenes	Salinity
2	CO_2 injection	25–48	C2-C12	>3000	Not critical	<15	Steep dip, anisotropic	Salinity, fissuring
3	Hydrocarbon flood	30–52	C2-C7	>5000	Not critical	<10	Hydrocarbon intermediate	Low reservoir pressure
4	ISC	8–38	C30+	>500	>100	<1000	Asphaltenes, paraffin	Fissuring
5	N_2 flood	37–55	High % of C1-C7	>5000	Not critical	<10	Steep dip, anisotropic	Fissuring
6	Polymer flood	15–39	Not critical	<8400	>10	<150	High permeability	Fissuring
7	Steam flood	8–32	C30+	300-5000	>600	>20	Low salinity, asphaltenes, paraffin	Hydrophobicity, water saturation
8	Surfactant flood	25–45	Light intermediates	<7800	>20	<30	Low water-cut sand content	Clay content fissuring
9	SAGD	>15	C30+	>3280	>100	<1000	Thick reservoir	Depth more than 1000 m
10	THAI	6–20	Not critical	>300	Not critical	>300	Thick reservoir	Fissuring
11	VAPEX	>15	Not critical-	>3280	Not critical	<500–	Thick reservoir	Depth more than 1000 m

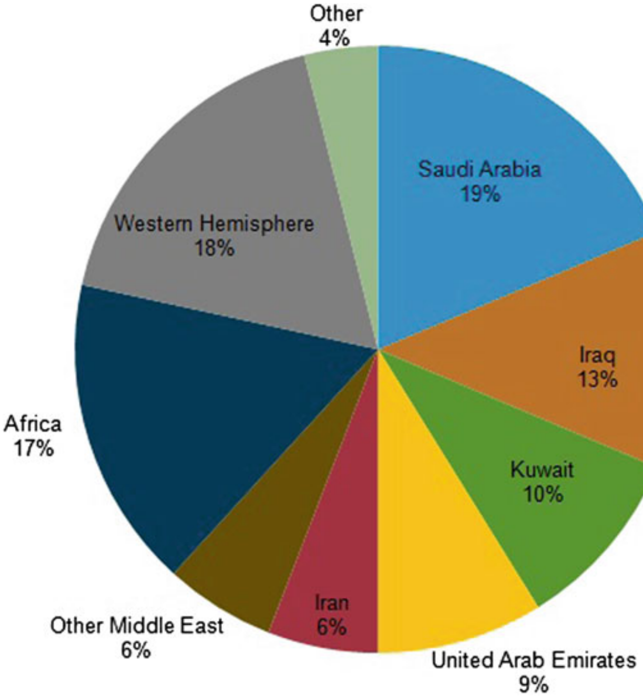


Fig. 17 Worldwide EOR production rate (Kokal and Al-Kaabi 2010)

Microbial EOR at the commercial scale are performed in many oilfields in China. Two different microbes are used to degrade wax and bitumen in the Sha-3 reservoir in Zhuangxi oilfield, China. This reservoir consists of low permeability and highly waxy oil, with temperature of 197.6–239 °F. The microbial degradation process has created 24.6 % of increase in oil recovery. In addition, the percentage of light oil is increased from 3.6 to 6.22 % due to wax degradation (Chen et al. 1999). In China, single strain F-2 and hybrid strain F-23 are used to reduce the viscosity of heavy oil at 113 °F in 6 days using nitrogen and phosphorous as nutrient resulting in 99.15 % reduction in the viscosity of the crude oil (Zhang et al. 2012). In an another case, *Brevibacillus brevis* and *Bacillus cereus* isolated from produced water are used to degrade the long-chain alkanes enhancing the oil recovery in Chaoyanggou Daqing low permeability oilfield in China. The viscosity of the waxy crude oil is reduced by 40 % and accumulative oil increment is observed to be 14,500 tons (Xiaolin et al. 2012). The light oil reservoirs of Gulf region (UAE), Masjed-I Soleyman field (Iran), The Prudhoe Bay oilfield (Alaska, US), Piedras Coloradas field, (Argentina), etc., are some the oilfields in world utilizing the microbes for EOR (Ferguson et al. 1996; Aimaghrabi et al. 1998; Maure et al. 1999).

CO_2 injection has received increased attention all over the world due to the intention to reduce the emission of greenhouse gases. As the US struggles to reduce the exporting of energy sources and decreasing greenhouse gases emission, CO_2 injection is followed in the Permian Basin in the US and the Weyburn field in Canada. Hydrocarbon gas injection supplies one third of a million bpd from projects in Venezuela, Canada and Libya. In UAE, the Abu Dhabi Company for onshore oil operations started an EOR project in November 2009 to test the injection of CO_2 to increase the oil recovery. Saudi Aramco is currently assessing the use of CO_2 injection and planned a series of pilot studies in mature fields like Ghawar. Pilot scale studies are performed in Abudhabi oilfield containing carbonate cores with a porosity of 10–24 % and permeability 77–149 md and the ultimate recovery factor is increased up to 85 % (Haroun et al. 2012).

4 Indian Scenario for Enhanced Oil Recovery

India is undergoing an emerging trend of economy with other countries like China, Brazil, etc. India's oil and gas industry is intently undergoing exploration opportunities without any major discoveries. In India, crude oil is produced in both onshore and offshore oilfields. According to USEIA report (2012), onshore reserves provide 53 % of oil production and the rest comes from offshore oilfields. Major Indian crude oil reserves are in the western coast (Mumbai High) and in the northeastern parts (Assam, Tripura, etc.). Onshore fields are located in Assam, Andhra Pradesh, Arunachal Pradesh, Gujarat, Nagaland, Rajasthan and Tamil Nadu. Oil India Limited (OIL), Oil and Natural Gas Corporation (ONGC) have the onshore field for the production of crude oil whereas; the offshore production takes place at Bombay High, which is jointly ventured by ONGC and other private companies. Until date, private and foreign firms, such as British Gas, Cairn Energy, Nikko Resources and Reliance Industries control very few oilfields. The operators are struggling to improve the declining production through EOR technologies.

As per the report by USEIA 2012, at the end of 1995, India had 5500 million barrels of reserves. After a decade, it showed only 1 % increase in reserves and at the same time 10 % increase in consumption of crude oil. According to the report by USEIA (2013), the special purpose legal entity, Indian Strategic Petroleum Reserves Limited (ISPRL), possessed by the Oil Industry Development Board, would run the projected amenities. The Indian government planned to start cargo space of 37 million barrels of crude oil at Mangalore, Padur and Visakhapatnam in 2005. In 2006, oil demand in India was 100,000 bpd and during the same year, ONGC accounted for 75 % of country's oil production. The Indian Oil and Gas sector plays the major role in Indian economy and thus falls among the six core industries in India. According to report by the World Energy Council (2013), ONGC plays the foremost role in Indian upstream oil and gas sector. Indian oil sector is mainly conquered by nationalized venture, though the government had taken steps in the past to hold greater foreign connection. Earlier, the foreign companies played a lead role in discovering various offshore openings. For example, in 2009, Cairn India discovered the largest oilfield, Mangala, of the RJ-ON-90/1 block having 130,000 bpd production capacity in Barmer basin. However, foreign venture in India has faded recently since Indian industries have heavy competition and the existence of strict exploration and production laws (Report by USEIA 2013).

According to MoPNG, India had 8803 million barrels of crude oil reserve and 1437 billion cubic meters of natural gas reserve as on 1st April 2010. In late 2011, the government proposed plans to increase the capacity of proved crude oil reserves to 132 million barrels before 2020 and after a year, India had 5.5 billion barrels. In 2011, according to the energy outlook 2030 report by BP, India was the fourth largest crude oil consumer following China, Japan and US. India had 5.5 billion barrels of proved reserves in 2012 with world's sixth largest refining capacity of 2.56 million bpd, representing approximately 3 % of the world capacity (Report by USEIA 2012). In 2013, the demand of crude oil is over 4 million bpd and in 2021, it is expected to be 14 million bpd. This gap can be reduced by the application of EOR on various mature reservoirs across India. It is reported in the India energy portal (2013) that the total crude oil production has been stagnated to around 32–33 MMT for the past 16 years. The government set goals to achieve 132 million barrels of the crude reserves by 2020. In addition, various government organizations have committed to set up an independent support of assets that might help in foreign energy acquirement (Sharma 2010). With the current rate of production, these proven reserves will meet the needs of Indian economy for the next 20 years. Over the past few decades, the gross domestic product (GDP) of India has increased from 36 billion USD to about 1.25 trillion USD. By 2035, India is expected to become the third largest economy next to US and China with the annual growth rate of 6.2 %.

The Rajasthan joint venture of Cairn India (70 %) and ONGC (30 %) is planning to drill 48 infill wells by 2014, which is further targeted to go for EOR application, which may include chemical intervention to sustain plateau production rates for a longer period. According to BP statistical review of energy (2013), India has only 0.4 % of proven oil resources and 0.6 % of world natural gas resources. Due to the increasing oil consumption, the unwavering production rate is not satisfying the demand, thereby making makes India dependent on importing more than 6 % of its crude oil requirement from other countries to overcome the needs (Patra 2013). Figure 18 shows the energy map of India, which depicts various oilfields, gas reservoirs, coalfields, thermal power plant and nuclear power plant present in the country. Figure 19 shows the total oil production in various states and the statistics of imports from other countries. Gujarat plays the key role in oil production followed by Rajasthan and Northeast regions. The oil producing regions in India are Assam, Gujarat, Mumbai and Rajasthan. In Assam, oilfields are located in Dibrugarh, Digboi, Makam, Naharkatia and Surma. In Gujarat the oilfields are located in Ankleshwar, Balol, Jhalora, Kalol, Mehsana, Sanand, Santhal and Viraj (Qazi and Qazi 2007).

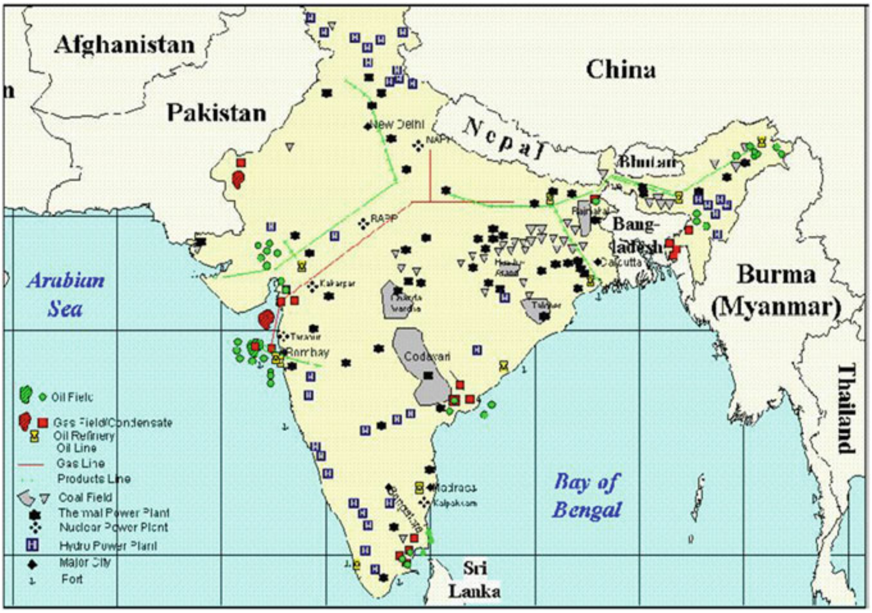


Fig. 18 Energy map of India (Report by USEIA 1997)

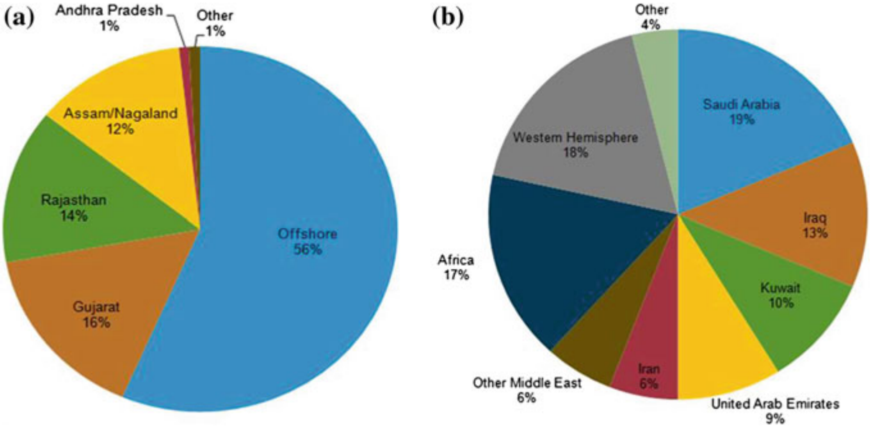


Fig. 19 Oil production and oil import in India; **a** production rate of oil in various states; **b** oil imports from various countries (Report by USEIA 2013)

4.1 Basins in India

Petroleum basins in India are showing immense guarantee for fresh findings with increasing thirst for the country's energy and fuel. Figure 20 shows the various basins in India. Assam-Arakan Basin, (Jorhat), Cauvery Basin (Chennai),

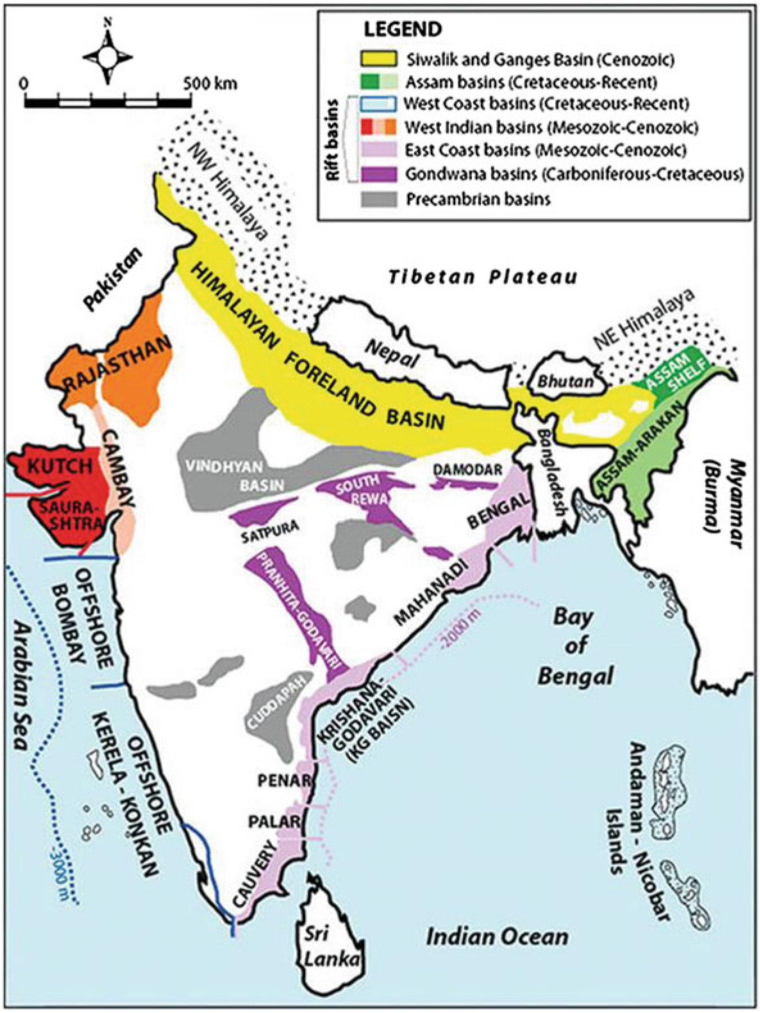


Fig. 20 Various basins in India (Rasoul 2008)

CBM-BPM Basin (Kolkata) and Frontier Basin (Dehradun), Krishna-Godavari Basin (Rajahmundry), Western Offshore Basin (Mumbai) and Western Onshore Basin (Vadodara) are in the control of ONGC. The Assam-Arakan basins in the northeast India hold more than 10 % of the country's crude oil reserves. Recently, Gujarat State Petroleum Corporation and Andhra Pradesh Gas Infrastructure Corporation discovered many new wells in Barmer basin in Rajasthan and the offshore Krishna-Godavari basin and expands the country's production to some extent (Report by USEIA 2013). The Cambay basin is a narrow elongated rift expanding from north to south on the western edge of India (Gupta et al. 2012). It

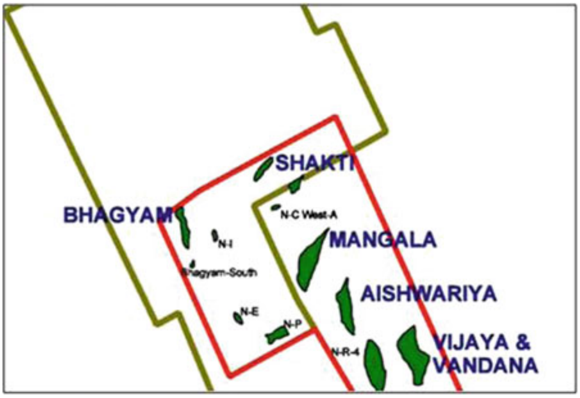


Fig. 21 Various fields in Barmer basin (Sullivan et al. 2007)

contains several small and big hydrocarbon fields in Tertiary sediments (Pratap et al. 2006). The Deccan Trap forms the technical basement of petroliferous Cambay basin. Padra, a small field situated on eastern border of Cambay basin is unique, as here, in addition to Tertiary sediments, the Deccan Trap basaltic rocks are commercial oil producers. The depth to the basement varies from about 400 m in the east to about 800 m in the west towards the basin axis (Kumar et al. 2002). In the matured Cambay basin, 5000 wells have been drilled and 1150 million tons of OOIP has been recovered (Sharma and Kulkarni 2010).

The Mangala Field was discovered in January 2004 in tertiary Barmer Basin (Yashwant et al. 2006). The Mangala oilfield contains sweet waxy crude oil with 20° API and low gas oil ratio (GOR) of about 180 scf/bbl with the viscosity of in situ oil ranging from 9–22 cP (Kumar et al. 2008; Mckenzie et al. 2011). Figure 21 shows the various oilfields in Barmer basin, Rajasthan. The Cauvery, Krishna-Godavari, Mahanadi and Palar are the four sedimentary basins along the east coast of India. Mahanadi Basin covering 18,000 km^2 onshore and 12,500 km^2 offshore is in the northern part along the east coast of India. The Krishna-Godavari Basin covers an area of 15,000 km^2 onshore and extends into the Bay of Bengal. Palar, a smallest basin falls between the Cauvery in the south and the Krishna-Godavari in the north (Talukdar 1982).

4.2 EOR Techniques in Indian Reservoirs

India is the world's fifth largest energy consumer, sixth largest oil consumer and imports more than half of the demand from the overseas. This prevailing scenario involves the need of sufficient and consistent energy to the Indian people in the midst of growing demand of energy and support by economic growth. Secondly, import of oil is the driving force for energy security and vital to meet the India's

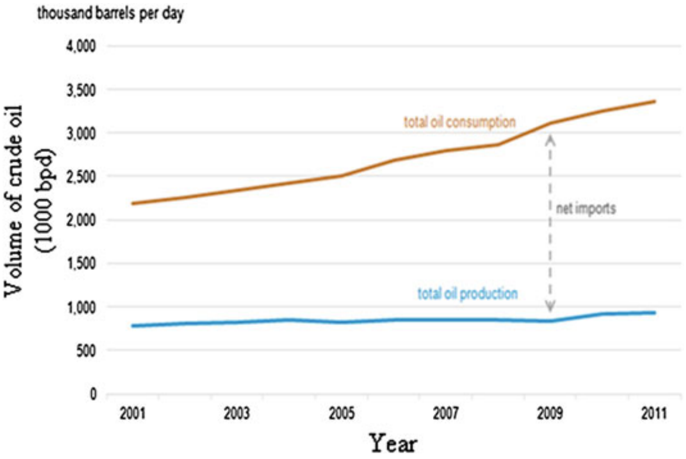


Fig. 22 Demand and supply of oil in India (Report by USEIA 2013)

vast energy requirement. Increase in import leads the nation to larger geopolitical difficulties and international price volatility (Ahn and Graczyk 2012; Patra 2013). Hence, this increasing demand not only affects the consumers, but also plays the key role in political and international level (Rasoul 2008). Figure 22 shows the demand and supply gap. In India, only about 27 % of the OOIP is being produced economically. Recovering the remaining oil and gas resources poses formidable technical and financial challenges. To recover the last drop of oil economically from the reservoir, lot of research work is going on. As the production from many onshore fields is in decline, companies are now looking to implement EOR technologies to boost and maximize domestic production. For instance, Cairn India is finalizing polymer flood on a pilot scale on the Mangala oilfield and with the initial encouraging results, it is now considering a full field wide application of the technique.

Thermal method comprises approximately 70 % of all EOR techniques followed in India, which includes 50 % of in situ combustion (Ramachandran et al. 2010). In many heavy oilfields in onshore assets operated by ONGC, in situ combustion has been used. Balol and Santhal oilfield were discovered in 1971 in the northern part of Gujarat. The production was started in 1971 on Santhal and in 1985 on Balol oilfield (Turta et al. 2007). This project is initiated at Balol field (Gujarat) on pilot scale and later, the project is expanded to commercial scale at Balol and Santhal field, Gujarat (Chattopadhyay et al. 2003; Chattopadhyay et al. 2004). ISC has been implemented in Balol oilfield in 1990 and it is commercialized in Santhal field since 1997 for enhancing the heavy oil recovery. Santhal field is a North-South sloping monocline surrounded by Mehsana Horst towards the west and falling towards the east. Production was started in Mehsana asset on 1968 with the rate of production of about 191 bpd. OOIP has decreased from an average 25, 15 and 9 % on successive three decade. In Santhal field about 15 MMT of trapped oil has been recovered with the aid of in situ combustion process (Panchanan et al. 2006). ISC is implemented technically and commercially in this field and production has improved by 540 tons over the period of 5 years (Chattopadhyay et al. 2004). In addition, the research on ISC projects is being carried at the Institute of Reservoir Studies (IRS), ONGC, Ahmadabad, India (Taglia 2010). In light oil onshore asset of ONGC, air injection technique is followed to enhance the oil recovery. The reservoir temperature is typically 158 °F with a viscosity of around 2–3 cP. Air injection enhanced the oil recovery by about 62 % (Mitra et al. 2010). CO_2-WAG flooding is implemented in an Eocene sandstone reservoir in Cambay basin Gujarat, which is at a temperature of 172 °F and a pressure of 1508 psi. After the implementation, WAG is raised to 11,000 m^3/day from 200 m^3/day and water cut is reduced significantly (Srivastava et al. 2012). Immiscible hydrocarbon WAG is employed in Ankleshwar asset (Gujarat) containing a sandstone reservoir of depth 2800 m. The reservoir contains saturated light oil at 266 °F reservoir temperature with 47 °API and 0.2 cP viscosity. This reservoir is not suitable for miscible flooding due to the requirement of higher miscibility pressure compared to the reservoir pressure of 3500 psi. The enhancement of 30 % in the oil recovery is observed after the implementation of WAG EOR. WAG is also implemented in light oil reservoir with the temperature of 262 °F and pressure of 3271 psi in Gandhar oilfield (Gujarat) and 40 % of improvement in oil recovery has been observed (Srivastava and Mahli 2012).

Sanand oilfield located in Ahmedabad-Mehsana tectonic block of Cambay Basin, Gujarat, was discovered in 1962 and the production was started in 1969 (Pratap and Gauma 2004). Polymer flooding was introduced in the year 1985 through 5 spot injection techniques, thereby 23 % of proved the oil in place has been recovered (Tiwari et al. 2008). In the Ahmedabad asset (Gujarat), ONGC has carried out polymer flooding pilot studies on the Kalol field with some success and are conducting pilot studies in Ankleshwar using miscible gas flooding and CO_2 injection (Panchanan et al. 2006). Jhalora oilfield located in Ahmedabad-Mehsana tectonic block of Cambay Basin, Gujarat, was discovered in 1967 and the production was started in 1978 (Pratap and Gauma 2004). Overall, Jhalora field contains 29 wells and, until now, it has produced 3.41 MMT oil. ASP flooding is implemented in K-IV well in Jhalora field having sandstone rock and 23 % of an incremental displacement efficiency is observed (Jain et al. 2012). ASP flooding is also implemented in Viraj oilfield in Cambay basin and the enhancement of 18 % recovery of OOIP is observed (Pratap and Gauma 2004). Polymer flooding is also applied in Mangala Field of Barmer Basin in pilot scale and the water cut is reduced effectively (Pandey et al. 2012).

Microbial EOR is not implemented in India due to the lack of various studies on the reservoirs suitable for this operation. Mesophilic bacterial consortium (FIB-19) is injected into the surface flow lines of ten wells of Mehsana Asset (Gujarat, India) containing heavy oil and found 67 % wax degradation at 98.6 °F (Biswas et al. 2012). ONGC and TERI developed bacterial strains effective up to 194 °F from formation water samples. Based on encouraging results in ONGC's wells, OIL has implemented MEOR in its fields having wells with a temperature of 158–185 °F, in two phases of 3 and 5 wells in 2005 and 2008, respectively, in Mehsana asset,

Table 4 Oilfields in India

S. No	Oilfield	Operator	State	Year of discovery	Production rate (bpd)	Area (km^2)
1	Aishwarya	Cairn, ONGC	Rajasthan	2013	10,000	–
2	Allora	Heramec, GSPCL	Gujarat	1967	70–80	6.85
3	Ankleshwar	ONGC	Gujarat	1958	21,000	–
4	Asjol	GSPCL, HOEC	Gujarat	1995	75,000	15
5	Balol	HOEC	Gujarat	1971	4400	27.3
6	Bhagyam	Cairn, ONGC	Rajasthan	–	25,000	–
7	Bhandut	GSPCL, NIKO	Gujarat	–	146,795	6
8	Bombay high	ONGC	Mumbai	1965	140	–
9	Dholasan	GNRL	Gujarat	1972	75,000	8.7
10	Dholka	Joshi Technologies	Gujarat	1995	720	–
11	Digboi	IOCL	Assam	–	–	13
12	Gandhar	ONGC	Gujarat	1983	30,000	–
13	Hazira	GSPCL, NIKO	Gujarat	1995	2000	50
14	Jhalora	ONGC	Gujarat	1967	1663	–
15	Jorajan	HOEC	Assam	–	–	–
16	Kalol	ONGC	Gujarat	–	–	–
17	Kusijan	HOEC	Assam			
18	Kosamba	ONGC	–	–	–	–
19	Lakshmi-Gauri	Cairn	Gujarat	2005	–	–
20	Lunej	ONGC	Gujarat	1958	30,122	11.2
21	Kanawara	GNRL	Gujarat	1971	–	6.3
22	Mangala	Cairn, ONGC	Rajasthan	2004	15,000	
23	Moran Hugrijan	HOEC	Assam	1953	–	–
24	Narimanam	ONGC	Tamilnadu	–	4032	–
25	Naharkatia	OIL	Assam	1953	50,203	–
26	Navagam	ONGC	Gujarat	–	–	–
27	North kadi	ONGC	Gujarat	1969	174	
28	North Kathana	GNRL	Gujarat	1975	–	12.2
29	Panna-Mukta	RIL, BG, ONGC	Mumbai	2010	35,000	430
30	Pramoda	HOEC, ONGC	Gujarat	2005	–	–
31	Ravva	Cairn, ONGC, Ravva oil	AP	1987	–	331
32	Raageshwari	Cairn	Rajasthan	2012	500	–
33	Saraswathi	Cairn	Rajasthan	2011		–
34	Sabarmathi	GSPCL, NIKO	Gujarat		74,000	5.8
35	Santhal	ONGC	Gujarat	1985	3958	–
36	Sanand	ONGC	Gujarat	1962	–	–
37	Shanti-Tarajan	HOEC	Assam	–	–	–
38	Sobhasan	ONGC		1960	377	–
39	South kadi		Gujarat		–	–
40	Unawa	GSPCL	Gujarat	1984	111,000	5.7
41	Viraj	ONGC	Gujarat	1977	–	–
42	Wavel	Joshi Technologies	Gujarat	2004	75	–

Table 5 Name of the oilfields in India and their properties

S. No	Field	Reservoir conditions							Existing EOR process	Proposed EOR process	Criteria for applying proposed EOR
		P (Psi)	T (°F)	k (d)	η_{OIL} (cP)	ϕ (%)	D (ft)	°API			
1	Balol	1500	154	3–8	300	28	1049	45	ISC	–	–
2	Dholka	–	–	1.9–8.7		15–50	900–1200	40	Natural depletion	Steam flooding	Since the depth is low from the surface steam flooding can give better recovery
3	Gandhar	3271	262	5–40		18–25	2850	42	WAG	–	–
4	Hazira	–	–	–	–	–	1500		Water drive	–	For low depth water flooding is good
5	Jhalora	1962		1.9–8.7	30–50	25–35	1270	22.3	ASP	–	–
6	Kalol	–	180	1	18–20	20–30	1500	–	Polymer flooding and water injection	–	–
7	Kanawara	–	–	1.4	–	–	3500	–	Natural depletion	ISC	Because of low permeability and high depth
8	Mangala Bhagya Aishwarya	–	180	–	9–22	30	900–1200	27	Polymer flooding	–	–
9	Mangala	–	140	–	5	–	–	27	–	MEOR	Because of high waxy nature
10	Mehsana	1450	154	–	–	50–450	–	–	ISC	Microbial	Because of low temperature and high viscosity
11	Panna	2550	1800	–	–	–	1737	–	Water injection		Since it is near (50–60 m) to sea level, water injection is good
12	RAVVA	–	–	–	–	–	3400	–	Natural depletion	Polymer flooding	Since the temperature and pressure is high. It is preferred
13	Sabarmathi	–	–	–	–	–	659	–	–	–	–
14	Sanand	2059	185	1.5	20–30	20	1325	21.2	Polymer flooding	–	–
15	Santhal	1450	154	3–5	50–200	28		40	–	–	–
16	Sobhasan	426		15–5	13–24						
17	Viraj	1977	178	4.5–9.9	50	30	1300	19	ASP flooding	Polymer flooding	Since the permeability is very low, polymer flooding is preferred

*P-pressure, T-temperature, D-depth, μ- permeability, η-viscosity, ϕ -porosity, °API- API gravity, GSPCL-Gujarat State Petroleum Corporation Limited, GNRL-Gujarat Natural resources Limited, RIL-Reliance Industries Limited, BG-British Gas, HOEC-Hindustan Oil Exploration Corporation Limited, IOCL-Indian Oil Corporation Limited

Gujarat. Recently ONGC and TERI has implemented MEOR jointly in 50 wells at ONGC, Ahmedabad and Gujarat asset and 5 oil wells in Assam asset. The Mangala field discovered in 2004 in Barmer basin (Rajasthan) consists of five reservoirs with 1.3 billion barrels of OOIP (Zalawadia and Pwade 2013). The crude oil in this field is highly waxy in nature with the wax appearance temperature (WAT) of 43 °F. Owing to this waxy nature and temperature of 140 °F, MEOR can be a better option for this field to increase the oil recovery. In general EOR techniques has been implemented in many fields but still more improvement is required to improve the economy and decrease the dependency of importing oil from the foreign countries. Table 4 shows the various oilfields located in India and its operators and Table 5 shows the reservoir conditions of various oilfields and the existing EOR process (Figs. 20, 21 and 22).

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