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Various Techniques for Enhanced Oil Recovery: A review

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Abstract

Crude oil can be extracted from the reservoirs by three mechanisms with different amounts of oil depending on the natural conditions of the reservoir. When the reservoir has an enough pressure, the amount of the produced oil is about 20% to 30% through primary recovery mechanism, and this amount can extend up to about 40% using secondary recovery. Because of the massive amount of the oil left behind the two mechanisms, enhanced oil recovery technique (EOR), the third mechanism, is designed to reduce the residual oil, in which, up to 70% of original oil in place can be recovered. Almost 3.0 trillion cubic meter of light oil and 8.0 trillion cubic meter of unconventional oil will be left underground after primary and secondary stages. Therefore, EOR techniques are applied to improve the oil production and extract much of the oil left in the reservoirs. Economics and technology have to be taken into account to choose the appropriate method in the recovery processes. Mainly, this study discusses various EOR techniques used in the enhancement of the oil recovery, including miscible, immiscible, polymer, surfactants, surfactants-polymer flooding as well as thermal methods.

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1. **Introduction**

Generally, crude oil is produced worldwide from mature fields [1]. Researchers have been paid massive efforts to increase the oil recovery from the aging oil reservoirs. Because of the decline occurring in the natural forces that drive the oil out to the surface through the primary recovery stage, secondary recovery, the second stage, is used to maintain the pressure inside the reservoir to displace the oil toward the production well. The amount of the oil produced by primary and secondary stages represents about 20 to 40 % of the original oil in place [2]. Moreover, there is still about 60 to 70 % of crude oil as a residual oil remaining underground. Therefore, tertiary recovery stage, enhanced oil recovery (EOR), is applied to further boost in the recovery of the oil left behind. The three recovery stages are illustrated in Figure 1 [3].

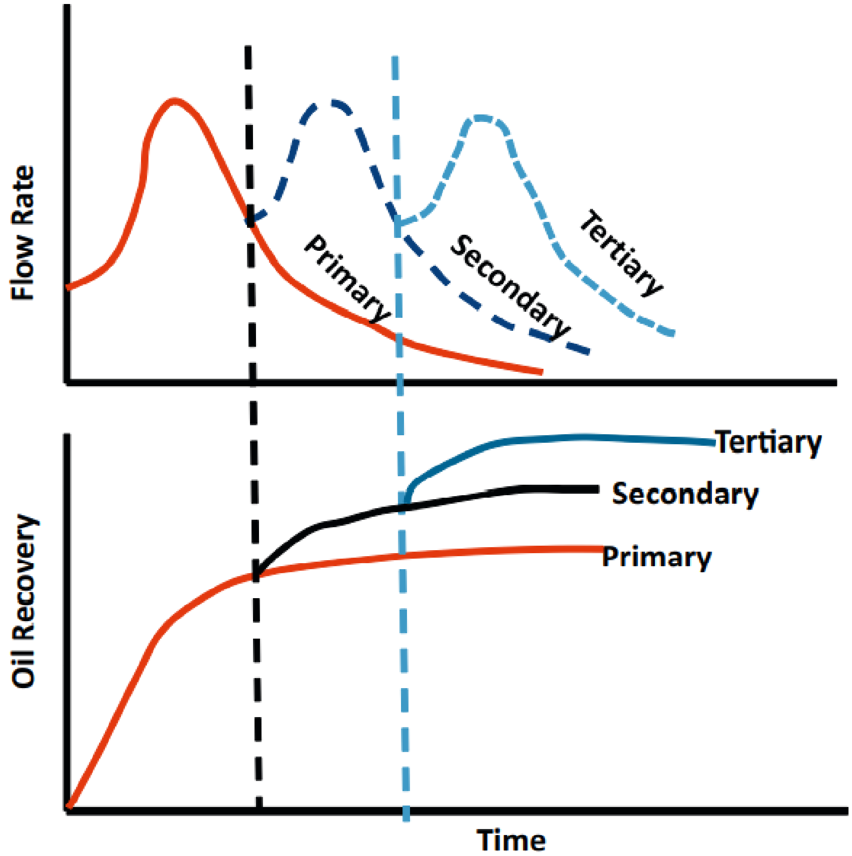

Figure 1: Oil recovery stages [3].

Fluids confined in the reservoir are composed of different hydrocarbon components with enormous-ranging properties, these features have a crucial role in the design and operation of efficient recovery processes. Figure 2 displays the fluid saturations and the EOR target for different types of crude oil. For reservoirs having light oil, primary and secondary are preferably applied first followed by EOR methods which can recover about 45% IOIP. In contrast, primary and secondary are not effective for reservoirs having heavy oil and tar sand, where the EOR is commonly applicable for such kind of reservoirs [4].

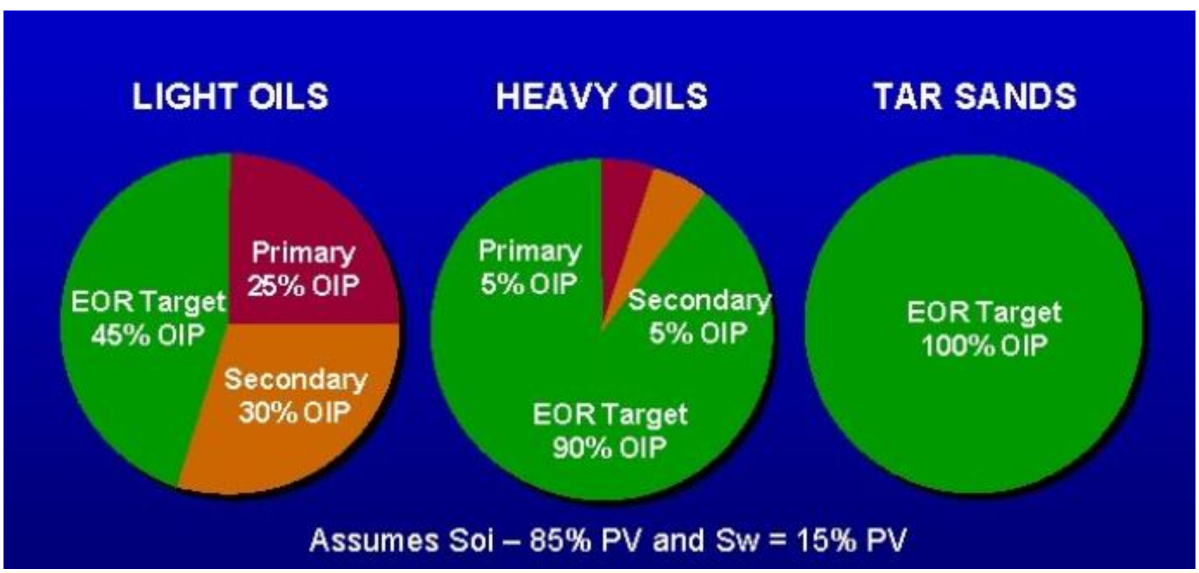

Figure 2: EOR target for different hydrocarbons [5].

2. Reservoir lithology

Reservoir formation is considered one of the substantial screening for EOR methods, often limiting the applicability of specific EOR methods [6,7]. Figure 3 illustrates that most EOR applications have been in sandstone reservoirs, as derived from a collection of 1,507 international EOR projects in a database consolidated by the authors during the last decade. From Figure 3, it is clear that EOR thermal and chemical projects are the most frequently used in sandstone reservoirs compared to other lithologies (for instance, carbonates and turbiditic formations) [8].

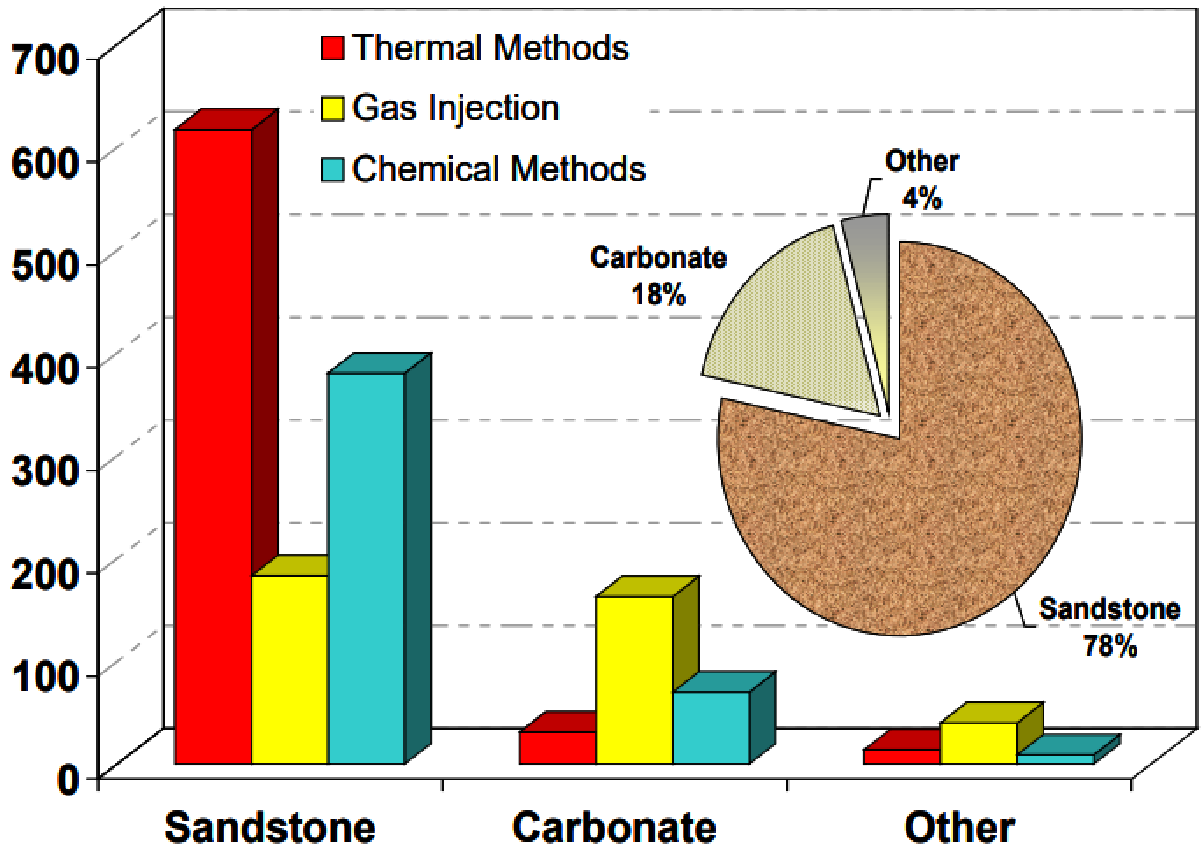

Figure 3: EOR depending on the reservoir formation (Based on a total of 1,507 projects).

3. EOR techniques

Many EOR methods have been used in the past, with varying degrees of success, for the recovery of light and heavy oils, as well as tar sands. A general classification of these methods is shown in Figure 4. Thermal methods are primarily intended for heavy oils and tar sands, although they are applicable to light oils in special cases [9]. Non-thermal methods are normally used for light oils. Some of these methods have been tested for heavy oils, however, have had limited success in the field. Above all, reservoir geology and fluid properties determine the suitability of a process for a given reservoir. Among thermal methods, steam-based methods have been more successful commercially than others. Among non-thermal methods, miscible flooding has been remarkably successful, however applicability is limited by the availability and cost of solvents on a commercial scale. Chemical methods have generally been uneconomic in the past, but they hold promise for the future. Among immiscible gas injection methods, CO_2 floods have been relatively more successful than others for heavy oil [4].

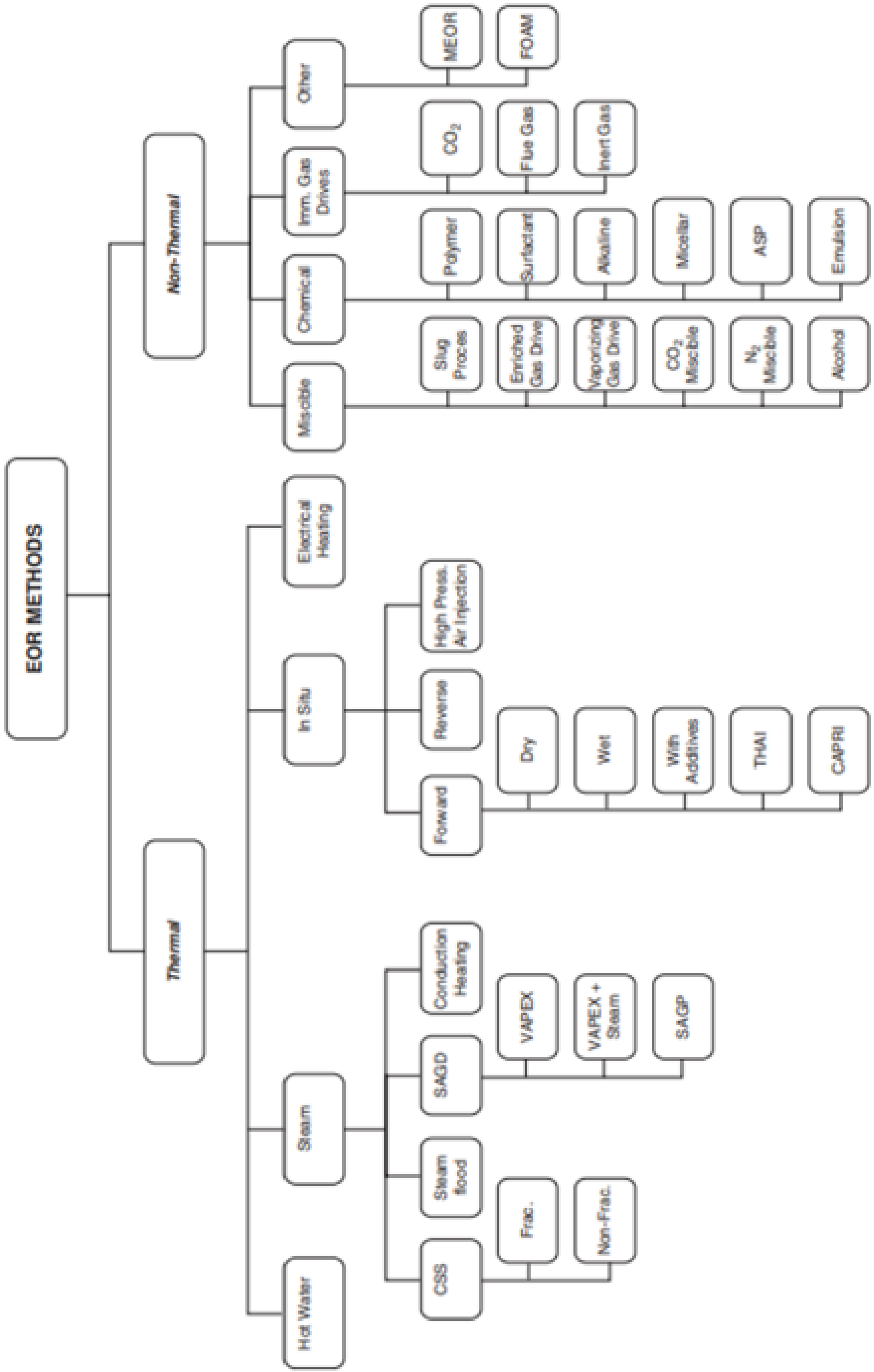

Figure 4: Classification of enhanced oil recovery (EOR) methods [4].

3.1 Non-Thermal Methods

Non-thermal methods are best suited for light oils (<100 cp). In a few cases, they are applicable to moderately viscous oils2000 cp), which are unsuitable for thermal methods. The two major objectives in non-thermal methods are:

– lowering the interfacial tension,

– improving the mobility ratio.

Most non-thermal methods require considerable laboratory studies for process selection and optimization. The three major classes under non-thermal methods are: miscible, chemical and immiscible gas injection methods as clarified in Figure 4. A number of miscible methods have been commercially successful. A few chemical methods are also notable. Among immiscible gas drive processes, CO_2 immiscible method has been more successful than others [10,11].

3.1.1 Miscible gas injection

Miscible gas injection is an EOR process that improves microscopic displacement efficiency by reducing or removing the IFT between the oil and the displacing fluid (the miscible gas). When used after a water flood this has the effect of re-establishing a pathway for the remaining oil to flow through and results in a very low residual oil saturation (2% has been measured in reservoir cores recovered from gas swept zones [12]. The drawback of this process is that the gas is both less viscous and less dense than the oil. As a result, these schemes often have a lower macroscopic sweep efficiency as they are adversely affected by viscous fingering, heterogeneity and gravity [13,14]. The injected gas may be hydrocarbon gas, carbon dioxide or nitrogen depending on what is available and the reservoir conditions. CO_2 is miscible with oil at a relatively low pressure and temperature but obviously requires a source of CO_2. Past applications were in fields near natural sources of CO_2 [8]. It can result in problems with corrosion of steel pipe unless care is taken in the design of wells, flow lines and facilities as well as provision for the separation of the CO_2 from the hydrocarbon gas when produced. Nitrogen requires a relatively high reservoir pressure for miscibility and involves the use of additional equipment to separate it from the air.

Hydrocarbon gas is usually readily available from the field itself or adjacent fields and is thus most widely used, especially in fields where there is no ready market for the [15]. In most cases, however, the produced gas that was originally associated with the oil has to be artificially enriched with heavier components in order to make it miscible or nearly miscible with the oil. It may also have to be supplemented with gas from other sources or water injection because the volume of produced gas, when re-injected, may not be sufficient to maintain reservoir pressure above the minimum miscibility pressure (MMP). It is more usual for the injected hydrocarbon gas to be nearly miscible with the oil rather than miscible on first contact. Miscibility then develops between the fluids through the exchange of components, commonly referred to as multi-contact miscibility, resulting in the gas becoming heavier as it passes through the oil and/or the oil becoming lighter [16]. However, even if the gas does not achieve full miscibility with the oil there are likely to be pore-scale displacement benefits compared with a water flood as gas components may dissolve in the oil, causing its volume to increase and its viscosity to reduce. As a result, it is possible for an immiscible gas flood to result in a lower residual saturation than a water–oil displacement.

3.1.2 Water-alternating-gas injection (WAG)

WAG injection is an EOR process that was developed to mitigate the technical and economic disadvantages of gas injection. It is the most widely applied and most successful traditional EOR process [15,17]. It involves the injection of slugs of water alternately with gas although sometimes the two fluids are injected simultaneously (termed SWAG). Usually the gas is first contact miscible or multi-contact miscible with the oil but this is not always the case. Injecting water alternately with the gas reduces the volume of gas required to maintain reservoir pressure. It also reduces the tendency for the gas to finger or channel through the oil as the presence of mobile water in the pore space reduces the gas mobility through relative permeability effects. Vertical sweep efficiency is also improved as water, being heavier than oil, tends to slump towards the bottom of the reservoir while the gas, being lighter, rises to the top. Although the majority of WAG applications in the field have been successful, the incremental recovery achieved is generally less than that predicted. Early gas breakthrough and a reduced macroscopic sweep, owing to channeling or gravity over-ride, are common. In addition, there are often operational problems. In particular, injectivity can be lower than expected owing to a reduced total fluid mobility near the well as a result of three-phase relative permeability effects and/or a reduced hydrostatic head in the injection well during gas injection [14].

3.1.3 Chemical EOR techniques

It is a well-known fact that flooding alone cannot mobilize the oil entrapped in the porous rock structures due to the capillary forces. Too much of residual oil remains stagnant in the porous rock structure. Other techniques that were thought of is to alter the interfacial tension between the water and oil with the addition of certain chemicals such as surfactants or alkaline substances, a method called chemical EOR [18]. Recent studies on EOR is very encourageous with chemical methods that greatly after the wettability properties and improved recovery rates compared to the traditional thermal methods. Many chemicals have been tried to analyze the chemical EOR methods in the form of alkaline, surfactant, polymer and combined flooding methods [19,20].

Chemical methods for enhanced oil recovery (EOR) consist of the injection of a displacing fluid in oil reservoirs to mobilize the crude oil trapped in the porous rocks. The displacing fluid generally is a water solution containing various additives. Typically, the mixture contains a water soluble polymer (this technique usually is referred to as polymer flooding), alone or in combination with a surfactant (surfactant-polymer flooding, or simply SP flooding) and/or an inorganic base (alkali-surfactant-polymer flooding, ASP) [21].

- **Polymer flooding**.

Polymer flooding is by and large viewed as an improved water flooding technique, since it does not ordinarily recover residual oil that has been trapped in pore spaces and isolated by water and is often referred as polymer augmented water flooding. The injection of dilute water-soluble polymers, such as polyacrylamides and polysaccharides, can produce additional oil compared with that obtained by ordinary water flooding by improving the displacement efficiency and increasing the volume of reservoir that is contacted by increasing the viscosity of the water. This reduces the probability of the flood breaking through to the production well while also producing oil at a higher rate. In most cases, polymer flooding is applied as a slug process and is driven using dilute brine [22]. Reservoir permeability needs to be higher than for gas displacement techniques although can be lower than that necessary for thermal methods [23]. Recovery levels, however, are only a little higher than that achieved with just water and so thorough understanding of the reservoir is necessary to make the process profitable. Loss of polymer to the porous medium, particularly in reservoirs with high clay content, is particularly problematic as can be polymer degradation [24].

- **Surfactant Flooding**

Surfactant flooding, sometimes called detergent flooding, can be described in much the same way as a detergent is used in removing oil or grime from fabric. The surface-active agent reduces the interfacial tension between the oil and water, allowing the water to remove the oil from the material. In surfactant flooding applications, a dilute aqueous surfactant solution is injected into the reservoir [25]. Mechanistically, the injected surfactant migrates to the oil- water interface reduces the interfacial tension (IFT) between oil and water and essentially increases the miscibility of these phases [26]. To put this into perspective, in a typical waterflooding process, IFT is approximately 30 mN/m; the addition of small concentrations of surfactant (in the range of 0.1–5.0 wt%) to the injected water can significantly reduce IFT to values of 0.01 mN/m or lower. The critical micelle concentration (CMC), phase behaviour and oil solubilisation ratio are key parameters for the characterisation of the efficiency of the surfactant formulation. For effective oil displacement:

- Dilute aqueous surfactant solutions are injected in slugs.

- The injected slugs must attain ultra- low IFT.
- This leads to the mobilisation of the residual oil and creation of oil banks, which allows the continuous phase flow of oil and water [27,28].

➢ **Surfactant and polymer (SP) flooding**

In surfactant and polymer flooding, separate surfactant and polymer slugs are injected into the reservoir. The alternate injections of surfactant and polymer slugs have the potential to sweep larger reservoir volumes and to increase oil displacement efficiency. The mobility control is established during SP flooding by injecting the chemical slugs according to the following injection scheme: surfactant slug, polymer slug [29], polymer buffer (to protect the integrity of the polymer slug) and chase water [30]. Accurate formulation of the surfactant-polymer (SP) mixture can promote capillary number increase (due to the presence of surfactants through IFT reduction) and reduction in mobility ratio. However, an incompatible SP formulation can cause surfactant and polymer phase separation even when oil is not present. Two essential factors for consideration during SP flooding are: (a) IFT reduction and (b) viscosity increase. In addition, the effective permeability to water is reduced due to polymer retention in the formation rock. Therefore, an overall improvement of mobility ratio and sweep efficiency is achieved rendering incremental oil recovery [28,31].

3.2 Thermal Methods

Thermal methods are considered the most sophisticated amongst the techniques which are used to improve oil production, and they were used for the first time in 1950. These techniques have been successfully applied in many countries especially in Canada, Indonesia and Venezuela, and they are quite appropriate for heavy oil and bitumen which have API gravity between 10 to 20°, and tar sand with API gravity less than 10°. Technically, thermal methods provide heat to the oil reservoir, which causes vaporization of some of the oil. This process leads to a great reduction in the viscosity, thereby moving oil toward the producer will be easier [32,33].

3.2.1Cyclic Steam Stimulation (CSS)

Cyclic Steam Injection is an efficient method to increase the production of heavy oil. This technique is also named "Huff and Puff", which includes three stages, steam injection, steam soaking and finally producing oil. Figure 5 shows these stages and it is clear that the process, which used one well for both injector and producer, is repeated to improve the rate of oil production. In cyclic steam injection, oil originally in place is heated by injecting steam for a period of time and the steam is left to soak in for several weeks [34]. The amount of injected steam must be sufficient for this process, and during this time the well should be closed. As a result of oil heating, the viscosity of oil will be reduced. After that, the reservoir is opened. Initially, the oil will be produced by normal flow, and then by pumps. High production rates are reached quickly in the production process, and this rate can be kept constant for a short time, before gradually dropping over several months. Once the rate of the oil production becomes uneconomic, the steam injection is repeated and the process continues with increasing ratio of steam to oil from 3:1 to 4:1 during the process [24].

3.2.2 Steam Assisted Gravity Drainage (SAGD):

Steam-assisted gravity drainage (SAGD), which is a familiar form of steam flooding, is an effective method to enhance oil recovery with low API [36]. Butler and Stephens (1981) [37] developed SAGD to improve bitumen recovery in the fields in Alberta. The typical SAGD configuration is presented in Figure 6. Two horizontal wells are used in parallel in this process; the separation of oil from the sand by steam utilising gravity force is the main principle of this technique. Steam is injected through the injector which is located towards the top of the reservoir, and the producer will be towards the bottom of the reservoir. A steam chamber will be created as a consequence of steam rising to the top of the reservoir. The produced temperature due to this steam causes a large reduction in the oil viscosity, making the heavy oil more mobile, and by gravity, the mobilized oil is drained to the producer well. A high value for vertical permeability represents the vital part needed for the success of the process. The rate of production is affected by many parameters like the pressure of steam, and oil properties such as density, viscosity, and heat combustion, in addition to the distance between injector and producer and other properties.

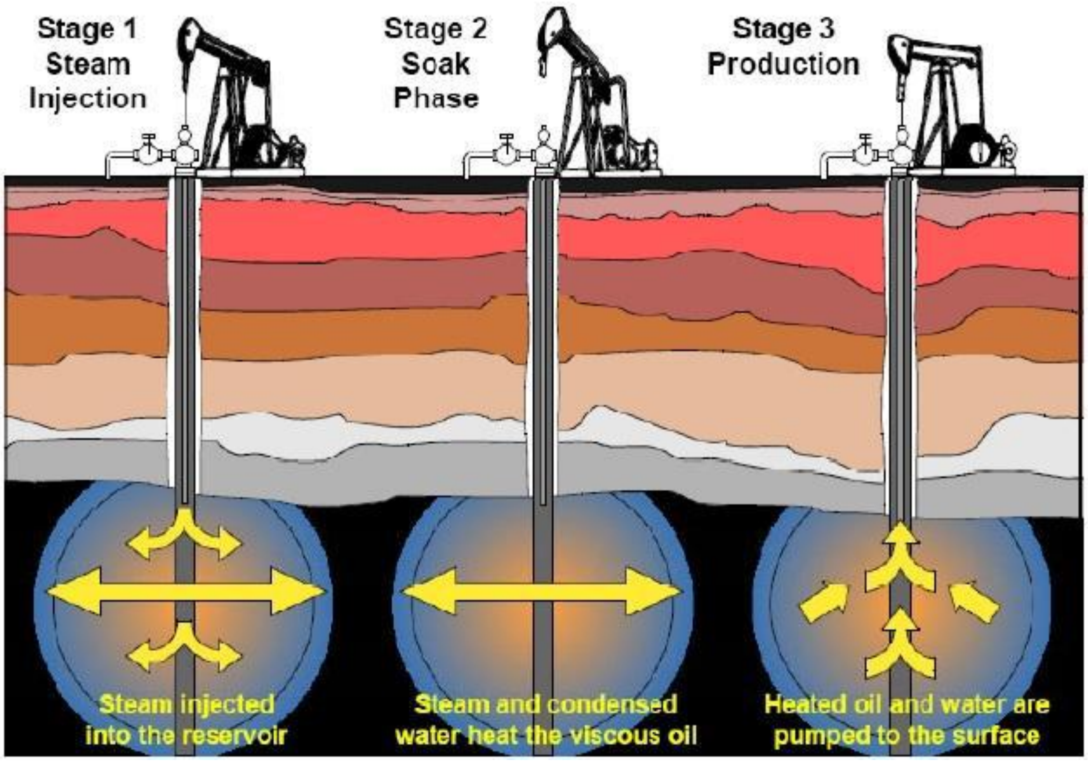

Figure 5: Cyclic Stem Injection [35].

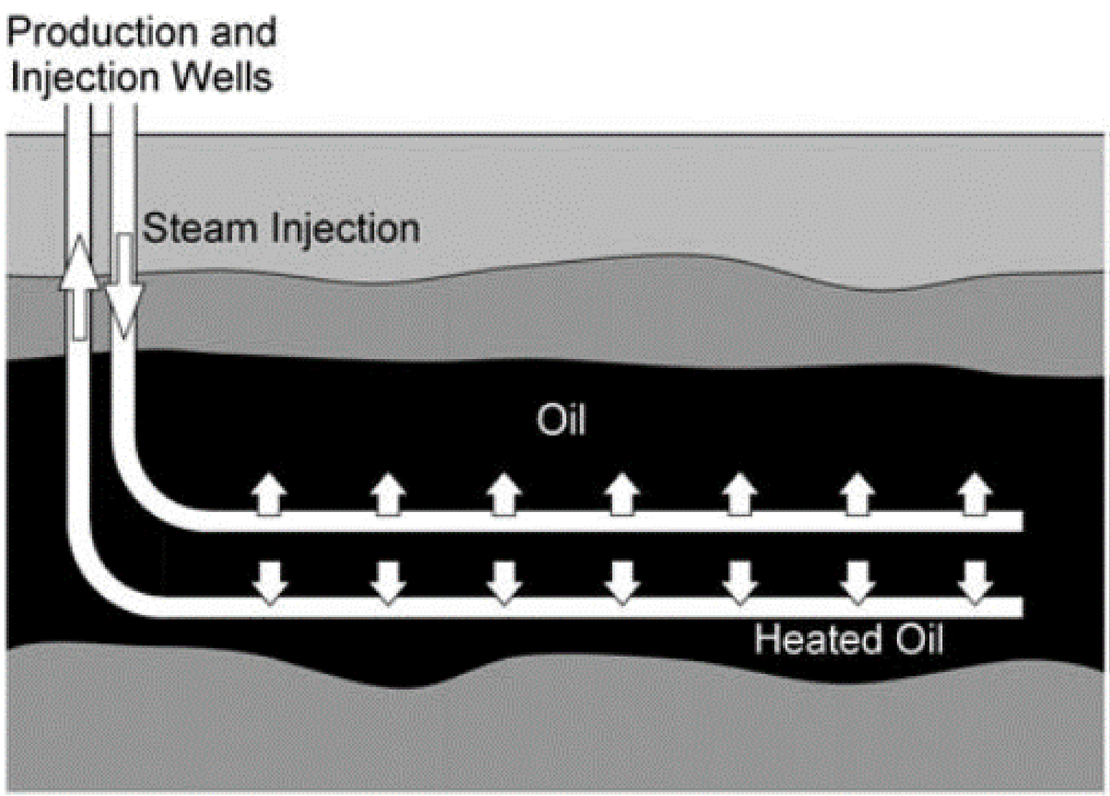

Figure 6: Steam Assisted Gravity Drainage [24].

3.2.3 In-Situ Combustion (ISC)

Another thermal method is the in-situ combustion technique, in which gas, usually air or oxygen impregnated air, is injected through a vertical injector to the reservoir [38] as represented in Figure 7. This injected oxygen and the presence of a heater cause ignition inside the well, where part of hydrocarbons is burned, resulting in generation of the heat required to reduce the oil viscosity. However, the amount of the air injected into the reservoir controls the burn direction. Once the surrounding rock is heated, the heater is turned off, but keeping the injection of air, to sustain the propagation of the combustion front [9]. The cracking process for hydrocarbons will be occurring as

a result of high temperatures, as well as evaporation of light oil and water in place, in addition to the coke formation as a solid phase. The created fire front will be in continuous movement forward which drives the component mixture of burning gas, steam and hot water ahead. Consequently, the oil viscosity will be reduced ahead of the front, and the component mixture displaces the oil in the direction of the producer.

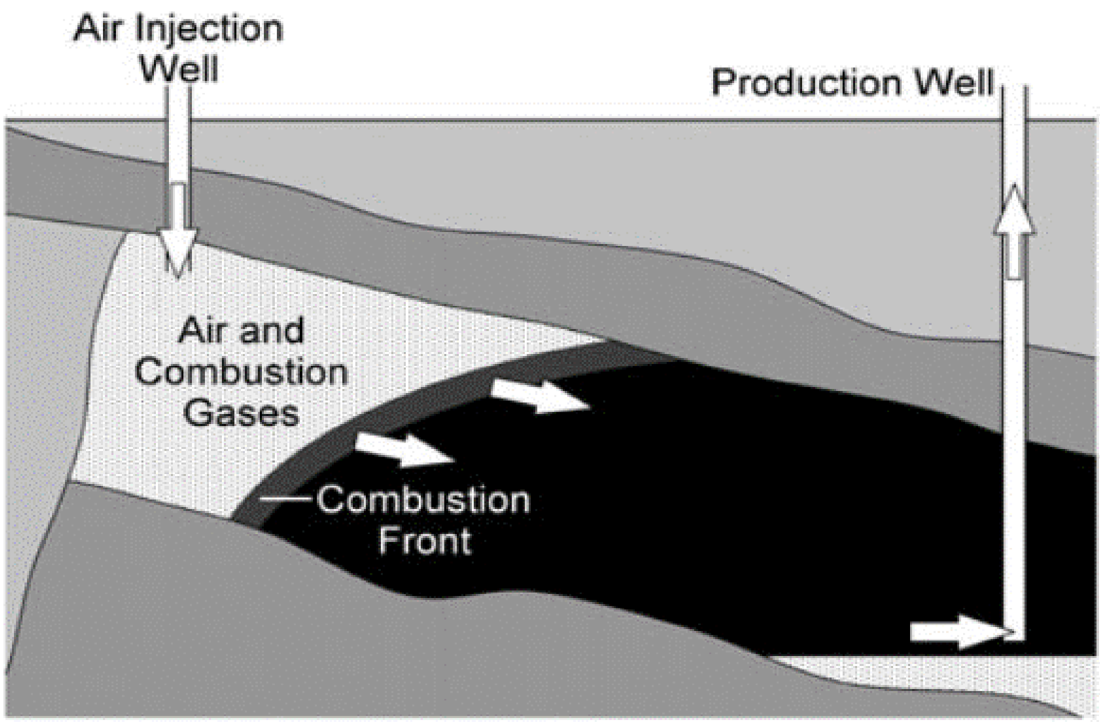

Figure 7: In-Situ Combustion Method [24].

The in-situ combustion method has been applied for more than eight decades. In the past, the process was mostly used in heavy oil with sandstone reservoirs. The in-situ combustion technique is appropriate to apply for a wide range of different oil properties. In this technique, also called fire flooding, the high temperature is created in a limited area and may reach to 600 ℃. There is no loss in the wellbore or surface heat, and a slight loss in the amount of heat to the overburden and underburden. Therefore, thermal efficiency is quite high in this process. In some cases, water is injected with air to increase the steam formation which promotes heat recovery and also reduces the required air during the injection process.

Although in-situ combustion is employed in a wide range of reservoirs, many problems may appear through the process. The main problems are intense corrosion, production of poisonous gas and gravity override [32].

Overriding is a phenomenon in which the lighter vaporized hydrocarbons, steam and combustion gases rise up into the top of the reservoir to be above the oil zone. This phenomenon causes a decrease in the efficiency of the combustion process. Therefore, water injection with air could help the combustion process to maintain its performance well [9].

High reduction of the oil viscosity takes place due to heat generated, the gas formed from the burning hydrocarbons and the created steam. These phases, collected together, push the displaced oil through a long distance across the thick cold oil region before reaching the producer [39]. During the forward burning front movement inside the reservoir, many types of zones (see below) will be created in the area which is located between the injection well and the production well due to the heat. Several important phenomena also happen through the process, including chemical reactions and mass transfer. Figure 8 explains the positions of the different zones and how temperature is changing from zone to zone.

Also, Figure 8 gives details about the distribution of oil and water saturations through their travels inside the reservoir. These zones can be described briefly as follows [24]:

1- Oil is burned in the first zone by the air flowing from the injector in the direction of the combustion front. As a result of continuous air injection, the temperature increases in this zone but it is likely that small amounts of oil may remain unburned. This zone is called the burned zone.

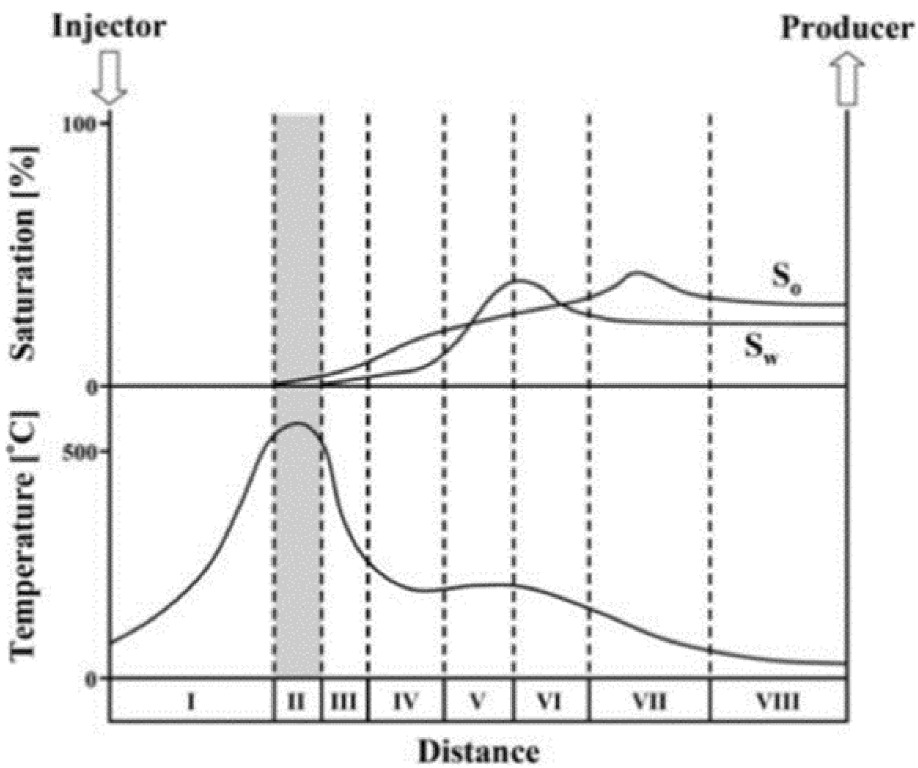

Figure 8: Block Diagram of Forwarding In-Situ Combustion [24].

2- This zone, which is called the combustion front, has the highest temperature among the zones. In this area, the oxidation process takes place for hydrocarbons via mixing them with a certain amount of oxygen. This amount of oxygen can be calculated from the fuel used in this process.

3- and 4- represent the thermal cracking/evaporation region. This zone includes cracking of the crude oil due to the high temperature which leads to upgrading of the oil and evaporation of the lighter hydrocarbons. Then vaporized oil comes back again to the original oil in place after its condensation.

5- In this section, the steam plateau is to come in downstream while most of the oil is travelled ahead of the steam. This feature causes a high reduction in the oil viscosity. Thermal cracking processes for the crude oil take place in varying degrees depending on the temperature; oil which cannot move easily goes through steam distillation and moderate cracking takes place for the remaining oil.

6- At the border of the steam hill, where the temperature is less than the temperature of steam saturation, water accumulates that reduces in temperature and saturation as one looks downstream, with a resulting rise in oil saturation.

7- Most of the oil light ends, which were a result of cracking processes of the heavy oil, reach this region by travelling with the oil moved from upstream.

8- Beyond lays the undisturbed original reservoir.

3.2.4 Toe-to-Heel Air Injection (THAI)

The reduction of the viscosity of the oil is the main aim for processes of enhanced heavy oil recovery. To help the immobile oil to be capable of motion easily inside the reservoir, air is the most commonly utilized material through In-Situ Combustion method for generating the heat which is the key factor in the process. Although the ISC technique has potential benefits, this process is facing significant challenges to its success in many cases because controls on combustion fronts are limited and there is difficulty in the travel of oil toward the production well. Stability under gravity is a vital part of a conventional ISC process. Thus, gravity segregation between the hot region, which represents burning gases, and the cold region, which represent cold oil, may lead to further decrease the effectiveness of the reservoir sweep [40].

Toe-To-Heel Air Injection (THAI) method is a relatively new process, which was invented to solve the problems that gave rise to the failure of classical ISC processes. In the THAI process, a horizontal producer is used instead of a vertical producer as in ISC process as shown in Figure 9. Unlike the conventional ISC process, in which the phenomenon of gas override occurs which is considered a negative feature, the arrangement of the injector and the producer in THAI process effectively reduces or prevents this phenomenon [41]. Furthermore, coke formation, as well as the fire front propagation through the horizontal well, effectively close the ‘‘toe’’ and preventing gas bypass. This property arises from the huge extension of the combustion front which covers all of the distance along the producer from toe to heel [42]. Therefore, THAI is quite stable and robust compared to the conventional in situ combustion process.

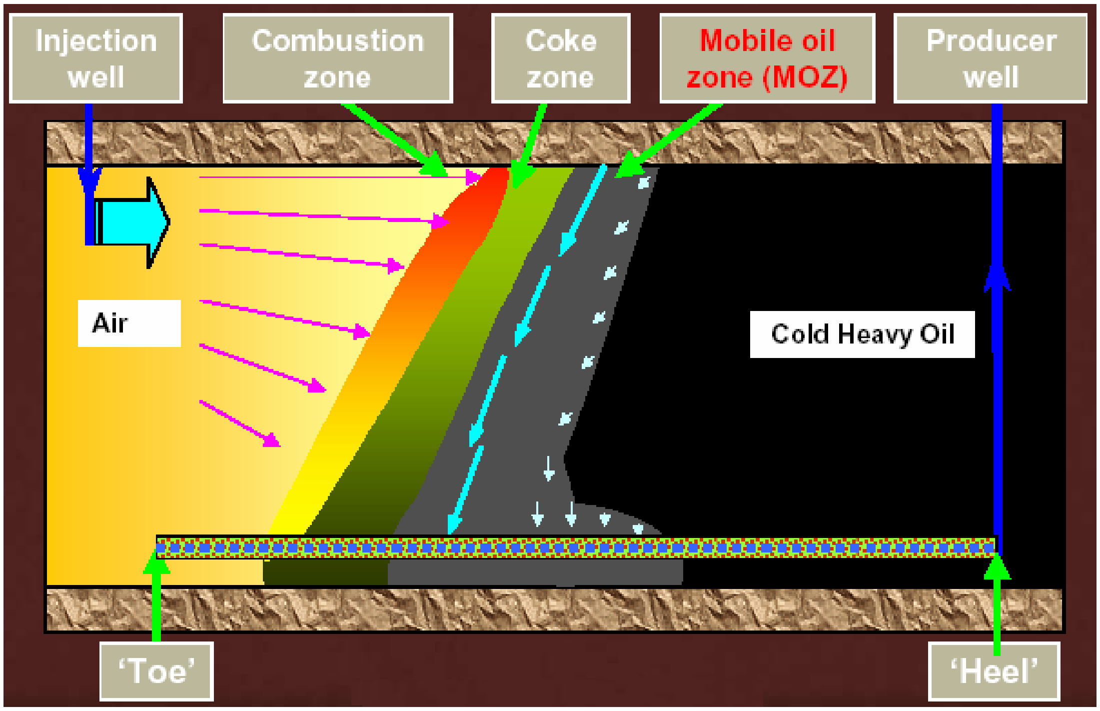

Figure 9: Schematic configuration in THAI (Kulkarni1 and Rao, 2004).

In the THAI process, the region around the injection well is heated prior to air injection, to create communication between the injection and the production wells. This also results in generating some coke as a fuel for initiation the combustion front and to sustain its propagation along the reservoir [43]. The combustion front progresses forward inside the reservoir and generates a quite high temperature, which reaches over 600 ℃. This rise in the temperature is accompanied by a reduction in the viscosity of the oil and then the immobile oil sweeps through a narrow zone, named a mobile oil zone (MOZ), toward the reservoir ahead. In addition to the MOZ, which is in contact with the cold oil region, combustion and coke zones are created upstream of the MOZ. Moreover, the hydrocarbons with high molecular weight, due to the high temperature created in the combustion zone, are subject to the thermal cracking producing lighter oil. The thermal reactions take place in the coke and the MOZ zone. Oil produced with other products proceed in a short distance through the MOZ toward the horizontal producer, resulting in higher levels of recovery in the THAI. On the other hand, oil produced in the conventional ISC needs

to travel a long distance, passing in the cold oil region, resulting in low rate production control problem. In this process, the amount of gas injected is maintained without loss, unlike in the classical ISC method where a considerable amount of air is lost. This is because the displaced oil is produced from the mobile oil zone immediately rather than having to go through the cold oil zone. In addition, because the oxidation process is taking place at high temperatures, the gas is completely prevented from getting to the cold oil zone.

4. Conclusion

Enhanced oil recovery methods are a sophisticated technique applied in the aging oil fields to improve the mobility of the crude oil to be easily extracted. Enhanced oil recovery comprises different flooding types called miscible, immiscible, polymer, surfactants, surfactants-polymer flooding, in addition to the thermal methods in which heating is used to reduce the oil viscosity. Reservoir formation, type of oil, rock properties and many parameters are taken into account to choose the appropriate method for enhanced oil recovery.

Among all types of EOR techniques, the many of these methods have not been commercially successful. Moreover, Moreover, the selection of the convenient applied method mainly depends on the reservoir kind and the hydrocarbons composition in addition to other several parameters. For instance, recovery methods based on the heat generation such as Cyclic Steam Stimulation (CSS) and steam flooding have been very effective for heavy oil and bitumen. Light oil can be extracted by gas injection including miscible and immiscible gas flooding. EOR techniques based on chemicals methods involving polymer flooding, surfactant flooding and surfactant-polymer flooding are promising methods to reduce the residual oil left in the crude oil reservoirs. However, these methods suffer from some limitations related to economics due to the high cost of solvents on a commercial scale.

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