Heavy Oil Production, Review Paper

Mohamed Abd El-Moniem

Cairo University, Egypt, Mohamed.aly.j@eng-st.cu.edu.eg

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HEAVY OIL PRODUCTION, REVIEW PAPER

Mohamed Aly Abd El-Moniem

Ph.D. Student, Cairo University, Egypt

Mohamed.aly.j@eng-st.cu.edu.eg

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Abstract

Petroleum represents an important source of energy. The different resources for energy are classified into renewable and non-renewable. Petroleum is the main source of the non-renewable energy where it is found in conventional and non-conventional reservoirs. Conventional oil production is started since the last century with a high oil and gas production using primary and secondary recovery. Now, the global demand is high compared to the supply from the existing produced fields. The production is declining from the conventional resources, so the production from the unconventional reservoirs is essential to cover the market demand. The unconventional resources are classified as shale oil, shale gas, heavy oil, extra-heavy oil and bitumen. The challenge is to find the best production method that will lead to high production with low cost. The reserves for unconventional resources are estimated by trillions of oil barrels. In this paper, we will review the heavy oil origin, classification, the different production methods and the challenges in the different phases of the upstream (subsurface reservoirs) and downstream (refineries & transportation) to recover the heavy oil economically.

Keywords – Heavy Oil, Bitumen, Enhanced Oil Recovery, Steam Flooding, In Situ Combustion, Steam Stimulation

1. INTRODUCTION

Energy is essential for human life. Different industries are depending on the power supplies by the different energy resources that can be classified into renewable resources “Wind, solar cell, …etc.” and non-renewable resources “Petroleum Hydrocarbons”. Currently oil and gas are considered the most important source for energy.

The global demand for energy supply is increasing and that requires a continuous development for the existing oil and gas reserves and explore another. There are two types of reserves conventional and unconventional. The production from the conventional reservoirs reached the maximum volumes and is following a decline that requires discoveries for both types of reserves to cover the global energy demand. The unconventional oil represents a significant share of the total oil reserves but it requires special efforts to be produced economically. It composed of highly viscous oil, so the challenge will be in finding the best method for the production and transportation of these heavy oils from the subsurface reservoirs to refineries and finally to the tankers after the excluding the different products from the crude itself. The unconventional oil is classified into heavy oil, extra-heavy oil and bitumen.
Figure 1 shows the regional distribution of proven and recoverable reserves of unconventional oils.

To differ between the conventional and unconventional oils, different fluid samples should be collected since the chemical composition is used for preliminarily oil characterization. The unconventional oil presents higher density, higher content of oxygen, nitrogen, sulfur, and heavier oil fractions [2].

The origin of heavy oil formations is related to both biological and physical means. The biological method in which microorganisms degrade light and medium carbons making the reserves riches in resins, asphaltenes, and polyaromatic. This called the biodegradation process in which a decrease in Gas oil ratio (GOR) and an increase in density at a temperature below 80°C [2]. The physical method is raised from water washing and phase fractionation [2].

The different hydrocarbon types from refiners can be classified into:

- **Aromatic” Arene”** is containing one or more benzene rings. Monoaromatic with chemical formula CnH2n-6 like benzene, Toluene, and Xylene. Polyaromatic contains several rings with two or more carbon atoms shared between rings [2]-[3].

- **Asphaltenes** are components of crude oil that are soluble in carbon disulfide but insoluble in n-pentane [2]-[3].

- **Bitumen** is either natural bitumen which formed in the subsurface reservoirs or refined bitumen that obtained as a residue of the distillation of crude oil. It is a dense substance and highly viscous hydrocarbon, in some areas, is called asphalt [2]-[3].

- **Paraffin “Alkane”** is a hydrocarbon with chemical formula CnH2n+2 such as methane, Ethane [2]-[3].

- **Resins** are the fraction of residuum that is insoluble in liquid propane and soluble in normal pentane [2]-[3].

Generally, heavy oil is more easily produced than bitumen which requires advanced development. There are different heavy oil fields all over the world such as:

- China, heavy oil reservoir located in Shengli Liaohe and Xinjiang oil regions where in-situ combustion technique is generally used.

- Colombia, heavy oil belt, the southwest portion of the middle Magdelena basin, west of Bogata, where Cyclic Steam Stimulation (CSS) is widely used.

- Egypt, Asran field in the eastern desert where Huff and Puff is generally used.

2. **HEAVY OIL CLASSIFICATION AND CHARACTERIZATION**

Different types of crude oil like heavy-oil, extra heavy oil and bitumen can be classified according to the density (API Gravity). Table-1 shows the API values for the different crude oil.

<table>
<thead>
<tr>
<th>Crude Oil Type</th>
<th>API</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light</td>
<td>&gt; 31</td>
</tr>
<tr>
<td>Medium Heavy</td>
<td>21 - 31</td>
</tr>
<tr>
<td>Heavy</td>
<td>14 - 21</td>
</tr>
<tr>
<td>Extra Heavy</td>
<td>10 - 14</td>
</tr>
<tr>
<td>Bitumen</td>
<td>&lt; 10</td>
</tr>
</tbody>
</table>

Heavy oil is characterized by high density, viscosity, asphaltene and resin content with low H/C ratio and dark black color [2]. A critical aspect of the heavy oil production separation system design is the
accuracy and reliability of the fluid characterization data upon which the design is based and it is a fact that some important parameters are often either overlooked or misinterpreted. During the appraisal phase of a new heavy oil field development, when appraisal well tests occur and fluid samples are being collected for other issues such as Pressure Volume Temperature relationships (PVT) studies for oil assay analysis, however, the fluid properties and rheology may have unusual characteristics during the production and processing of the heavy oil. Good fluid modeling is essential to predict the performance of the heavy oil with the reduction in pressure and temperature.

### 3. HEAVY OIL PRODUCTION

After the primary and secondary recovery methods, enhanced oil recovery (EOR) is applied to reduce the residual oil saturation by working on changing either the fluid or the rock properties. The success of any EOR project depends on the amount of additional oil that can be recovered economically. Table 2 shows the effect of some parameters used for the selection of the enhanced recovery method.

<table>
<thead>
<tr>
<th>Screening Parameters</th>
<th>Steam Injection</th>
<th>In Situ Combustion</th>
<th>CO2 Flood</th>
<th>Surfactant Polymer</th>
<th>Polymer</th>
<th>Alkaline Water Flood</th>
<th>Hydrocarbon Miscible</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oil Viscosity, cp</td>
<td>nc</td>
<td>nc</td>
<td>&lt; 12</td>
<td>&lt; 20</td>
<td>&lt; 200</td>
<td>&lt; 200</td>
<td>&lt; 5</td>
</tr>
<tr>
<td>Oil Gravity, API</td>
<td>10 – 25</td>
<td>10 – 45</td>
<td>&gt; 30</td>
<td>&lt; 25</td>
<td>&gt; 18</td>
<td>15 – 35</td>
<td>&gt; 30</td>
</tr>
<tr>
<td>Depth, ft</td>
<td>200 – 5000</td>
<td>&gt; 500</td>
<td>&gt; 2300</td>
<td>&lt; 8500</td>
<td>&lt; 8500</td>
<td>nc</td>
<td>nc</td>
</tr>
<tr>
<td>Reservoir Temperature, °F</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>&lt; 250</td>
<td>&lt; 200</td>
<td>&lt; 200</td>
<td>nc</td>
</tr>
<tr>
<td>Initial Reservoir Pressure, Psi</td>
<td>nc</td>
<td>nc</td>
<td>&gt; 1200</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
</tr>
<tr>
<td>Net Pay, ft</td>
<td>&gt; 20</td>
<td>&gt; 10</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
</tr>
<tr>
<td>Permeability, md</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>&gt; 20</td>
<td>&gt; 20</td>
<td>&gt; 50</td>
<td>nc</td>
</tr>
<tr>
<td>Residual Oil Saturation, %</td>
<td>50</td>
<td>50</td>
<td>25</td>
<td>&gt; 25</td>
<td>&gt; 50</td>
<td>&gt; 25</td>
<td>&gt; 25</td>
</tr>
<tr>
<td>Transmissibility, md ft/cp</td>
<td>&gt; 100</td>
<td>&gt; 20</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
</tr>
<tr>
<td>Porosity, %</td>
<td>&gt; 10</td>
<td>&gt; 10</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
</tr>
<tr>
<td>Salinity (TDS), ppm</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>&lt; 5000</td>
<td>nc</td>
<td>&lt; 2500</td>
<td>nc</td>
</tr>
<tr>
<td>Hardness (Ca and Mg)</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>&lt; 1000</td>
<td>nc</td>
<td>-</td>
<td>nc</td>
</tr>
<tr>
<td>Operating Pressure, Psi</td>
<td>&lt; 2500</td>
<td>nc</td>
<td>&gt; 1100</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>&gt; 1300</td>
</tr>
<tr>
<td>Target Oil, bbl/acre-ft</td>
<td>&gt; 500</td>
<td>&gt; 400</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
</tr>
<tr>
<td>Lithology</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>Sandstone</td>
<td>nc</td>
<td>Sandstone</td>
<td>nc</td>
</tr>
<tr>
<td>Well Spacing</td>
<td>&lt; 10</td>
<td>&lt; 20</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
<td>nc</td>
</tr>
</tbody>
</table>

nc: not critical

For heavy oils, thermal methods are the most successful methods, while non-thermal have restricted accomplishment in real field tests. Electrical heating and thermal methods are used to supply the reservoir with heat. An improvement in the heavy oil mobility will be achieved by the reduction of the viscosity. Thermal methods will supply heat by injecting steam or hot water using different methods, however, the selection of the best method that
helps in recovering more oil economically is differing in each case.

3.1 THERMAL METHODS

3.1.1 HOT WATER INJECTION
Hot water can be injected into the reservoir sand to reduce the viscosity of the heavy oil and allow the flow and consequently increase the oil [6] production by the heat transfer between hot water and heavy oil. The disadvantage of this method is the less heat content compared to other steam injection methods [7]-[8].

3.1.2 CYCLIC STEAM STIMULATION (CSS)
This method is considered one of the effective thermal methods to recover heavy, extra heavy oil and bitumen. This technique is also known as “Huff and Puff” as shown in Figure 2 where steam is injected into the reservoir under high pressure and temperature for a long time that can reach to a month, and then the injection is stopped allowing the heat to be distributed along the formation and consequently reduce the oil viscosity. After that the well is reversed to be a producer well. This process is repeated by cycles, but the disadvantage represents the low recovery factor (RF) since it reaches (20-40%) with steam/oil ratio of 3 to 5 but it is more efficient with lower emission intensities than other thermal injection methods [7], [9].

CSS is considered the main method for producing heavy oil in China, since 75 % of the heavy oil production is from the different CSS projects [10-13]. Nehring et al. [14] reviewed that there are 41 pools qualified for the CSS process in United States [10].


In Alberta, Canada, CSS started from more than 45 years in Athabasca, Cold Lake, Peace River and Grosmont [10,18–20]. It is applied since 1980s by Canadian Natural Resources at Primrose and Wolf Lake and by Shell Canada at Peace River [10,20,21].

In Venezuela, a successful project started in 1971 until 1995 was applied in the Lake Maracaibo area. 325 wells have been stimulated with 860 cycles [10,15,22].

In China, A CSS started in 1960s in Karamay oilfield (CNPC, Xinjiang). A pilot tests started and then the technique applied to Liaohe, Shengli and Henan oil fields [10].

Different projects have been applied in Russia [10,23], Indonesia, Colombia [10,24-25], Oman and Mexico [10,26–28].

3.1.3 STEAM ASSISTED GRAVITY DRAINAGE (SAGD)
It is one of the preferable thermal methods for producing heavy oil. As shown in figure 3, it depends on steam injection into horizontal well above a parallel another horizontal producer well. The steam is injected in the upper injector while the oil flows down by gravity and be produced from the lower well.
There are two types of placing the used wells [7], [31]:

1. Vertical well and a combination of horizontal wells.
2. Dual horizontal well “Common used” SAGD received attention in Canada, Venezuela with its large resources of heavy and extra-heavy oil [2]. The RF can reach up to 55%. The disadvantage of this method is the high cost of installation of the steam injection system [7], [32-34].

Different SAGD techniques have been applied Alberta [10,35–39] and more than 15 projects are still in operation in Canada, mainly in Athabasca, Cold Lake and Lloydminster [10,40–42]. In China, different projects are located in Xinjiang oilfield in Karamay and Liaohe oilfield in Panjin [10,43–46].

![Steam injection process](image)

**Figure 3 Steam assisted gravity drainage (After Markham Hislop, 2017[30],[47])**

### 3.1.4 STEAM FLOODING (SF)

Fixed well patterns are used to produce the oil after the continuous injection of steam. Figure 4 clarified the mechanism that is based on creating a hot zone that moves across the reservoir. The RF is about (50-60%) [2], [30-31].

Nehring et al. [14] reviewed that there are 101 pools qualified for the steam flooding process in the United States. Different projects were conducted in different regions like the projects of Kern River in USA and Cold Lake in Alberta are the two successful steam flooding cases in North America [10,48-49]; Imperial [50].

In China, Different projects are applied to different reservoirs like Qi40, Jin45 and Wa38 reservoirs in Liaohe oilfield, Shan83 and the Shan56 reservoirs in Shengli oilfield, and the BQ10 reservoir in Henan Oilfield [10,12,51-52].
3.1.5 IN-SITU COMBUSTION (ISC)

It is a thermal method targeting a downhole combustion for a portion of the oil to provide heat and mobilize it. Air “gas containing oxygen” is injected through a central vertical well into the reservoir and when contact with oil, ignition is initiated creating a combustion front that propagates through the reservoir as shown in figure 5. A group of produced wells are used to produce the oil after reducing its viscosity by heating and shows an increase of API 2 to 6 [30, 54-58].

Figure 4 Schematic of steam flooding (After Alhakiki, 2012 [30, 53])

Figure 5 In situ combustion process schematic (After Rob Kendall, 2009) [30, 59]

Figure 6 shows that the reservoir can be divided into six zones [60]:
- Post-Combustion zone,
- Combustion zone,
- Cooking zone,
- Steam zone,
- Light oil zone and
disadvantage of this method is the combustion front may not advance uniformly in the vertical direction due to the gravity override the injected gases and this may decrease the sweep efficiency \[60\].

There are different types of the in-situ combustion processes. It includes forward combustion (Dry and wet) and Reverse combustion.

The forward combustion starts from the air injection in the injector well where the combustion front moves from the injector well in the same direction of the air flow and this is called the dry combustion. Water with a certain amount can be added to the injected gas and this process is called wet combustion. Reverse combustion is occurred when the combustion front moves in the opposite direction of the injected air since the combustion zone is initiated at the production well and it is very efficient in the low permeability reservoirs \[10,13,61\].

Nehring et al. \[14\] showed that 32 pools qualified for the ISC process in the United States.

Different field applications are applied globally. In Canada, a pilot test project was conducted in 1978 using the combination of the two methods of CSS and ISC in the Cold Lake area by BP Resources Canada Ltd. \[10,62-63\]. Another project was carried out such as the Husky Oil’s Tangleflag combustion and Amoco Canada’s Morgan fireflood projects \[10,63\].

In Romania the largest dry ISC process was applied \[10,64\]. The ISC project at Suplacu de Barcau consists of more than 2700 wells since 1970 \[10,65\].

Two wet combustion projects in India (The Balol and Santhal projects) have been in operations for more than seven years \[10,64\].

In USA in Bellevue, Louisiana, another dry combustion project was applied 34 years ago. It is operated by Bayou State Oil Corporation (BSOC) with 15 air injectors and 90 producers \[10,64\].

Different projects were conducted in China, there are more than 20 field pilots in Xinjiang, Liaohé (Du 48, Du 66 oil fields), Shengli (Jinjia and Le’an oil fields) and Jilin oilfields \[10,66-69\].

Many different new techniques for in-situ combustion are under evaluation as following:

### 3.1.5.1 IN-SITU TOE-TO-HEEL AIR INJECTION (THAI)

In this technique \[60,70-72\], a horizontal well is used as a producer \[73\], the combustion front spreads from the tip to the heel which creates a flowing oil zone and helps in creating thermal cracking for the heavy oil. The horizontal well helps in decreasing the displacement distance for the conventional in-situ combustion \[74\].

### 3.1.5.2 COMBUSTION OVERRIDE SPLIT PRODUCTION HORIZONTAL WELL (COSH)

It depends on using lateral wells \[60,75-76\] to vent the flowing gas out of the reservoir and producing the heavy oil from the horizontal well. Crude oil viscosity is decreased below the combustion front in the heat-affected zone \[60,77-78\].
3.1.5.3 COMBUSTION ASSISTED GRAVITY DRAINAGE (CAGD)

Same as the SAGD technique but used for the in-situ combustion where two horizontal wells (injector & producer) are used at the top and near the bottom of the formation respectively [60], [79-80].

3.1.6 VAPOR EXTRACTION (VAPEX)

Vapor extraction (VAPEX) is a method used to recover heavy oil and bitumen in case of the non-applicability of SAGD. It depends on using two horizontal wells with an injection of light hydrocarbon vapors like solvents (propane, butane, or a mixture of them) in the upper well. It will help in the dilution of oil deposit in the upper formation and will be dropped by gravity to be produced by the bottom well as shown in figure 7 [81]. VAPEX technique can be used in the reservoirs that are not suitable for the thermal methods due to the low pore voidage, fracture appearance and high water saturation [82]. Recently, CO2 was used instead of solvent and it gives a good result due to its effect on viscosity reduction and increasing of the density [81].

Butler [82] studied the effect of the different parameters on the VAPEX performance, lateral well spacing was found to have a high effect on the oil production.

One of the challenges in using this method is to select the optimum solvent concentration because asphaltene could be deposited and precipitated if this value exceeds the critical value [82].

The recent researches stated that the use of VAPEX has the advantage over SAGD technique due to its low capital cost and the process is environmentally friendly.

Due to the importance role of reservoir pressure and temperature in the selecting of the solvent and to avoid any liquefaction of the solvent at any portion in the reservoir, the reservoir pressure should be lower than the solvent’s vapor pressure [83].

3.2 ELECTRICAL HEATING METHODS

These methods have minor oil recovery compared to the thermal methods and have not been proved to be economically feasible.

In the electrical heating method, a heat transfer system by an electrode will flow an electric current to the reservoir formations from the electricity generator and flows back to the surface as shown in Figure 8 [7]. The amount of required electric current depends on the rate of production. In case of much energy is used, damage for the reservoir will occur [84].
Therefore, oil viscosity can be reduced properly by heating [85]. The advantages of electrical heating are in the production at the same time of heating with no fluids injection and this helps in reducing the heat loss. Due to the ease of the flow of the electric current in low permeability zones, the volumetric sweeping is considered more efficient than thermal injection [7].

Several studies have been done to have an aid for the thermal methods in reducing viscosity not only by the heating of the crude oil but to find a way to accelerate these chemical reactions. Aquathermolythis is the thermal cracking for heavy oil which breaks the larger molecules into smaller ones and consequently reduces the viscosity. These reactions can be accelerated by using catalysts, so this issue is a good area for studying [86-91].

In 2005, China tested the usage of catalysts and hydrogen donors in 20 CSS wells and the production has been increased with high sulfur and asphaltene contents removal [86], [92]. They also tested in 2012 the usage of alkyl ester sulfonate copper (0.1-0.3 wt%) and it gave a good result in the removal of asphaltene and sulfur and consequently an increase in the API gravities have been noted [86], [93].

There are three fundamental heat transfers of the electrical heating method into the formation (heat conduction, heat convection, and radiation heat transfer) [7, 94]. Heat conduction will transfer heat based on vibrations for each molecule contact. Meanwhile, heat convection is heat transferred from the transfer of gas or liquid with the heat contained in the vicinity, and radiation heat transfer is heat energy transferred through electromagnetic waves [7], [95-96].

It is preferred to use this method in heavy oil reservoirs with too low temperature and not too high oil viscosity like Orinoco oil belt in Venezuela. There are three types for the electrical heating methods according to the frequency of the used electrical current. They classified as low frequency electric resistive (ohmic) heating, medium frequency electromagnetic (EM) induction heating and high frequency (radio frequency or microwave) EM heating [10,97–100].

3.2.1 ELECTROMAGNETIC HEATING ASSITED GRAVITY DRAINAGE

This method was tested in a sandbox, an induction loop embedded in the sandstone layer. No field applications till now [7], [101-102].

3.2.2 SOLVENT AND WATER ASSITED ELECTRICAL HEATING

This method depends on the usage of solvent and water for in-situ extraction of bitumen in which the
heat is targeted into the formation using downhole electrical heating with a fluid to heat transfer, then the vapor chamber is created for the project of steam-assisted gravity drainage [7], [103-107].

3.2.3 ELECTROMAGNETIC HEATING

By using the electromagnetic heating (EM) process method, the volume of heat generated is called the eddy current loss. Eddy current is the induction of an electromagnetic field produced by an alternating current (AC) current that is driven through an inductor cable. The inductor cable is placed in a circle in the reservoir [7], [108-109].

3.2.4 ELECTRO THERMAL DYNAMIC STRIPPING PROCESS

An electro-thermal dynamic stripping process (ETDSP) which helps in reducing greenhouse gas emissions and fresh water usage which is considered an environmental friendly method [10,110]. It is used to recover oil deposits whose depth is too shallow for steam injection and too deep for surface mining [10,111].

3.2.5 ULTRA SONIC WAVES

Ultrasonic has frequencies above human hearing that is around 20kHz. Ultrasonic waves will increase capillary strength and consequently the adhesion between rocks and liquids by making vibrations around the reservoir and cause of oil coalescence [7].

3.2.6 RADIO FREQUENCY

Radio Frequency Heating was found more practical than electrical resistive for surface oil sand. The range of recovery was about 50 to 80% [7], [105]. Radio Frequency is electromagnetic radiation from an antenna positioned in a wellbore adjacent to an oil reservoir layer as shown in figure 9 [7], [112-114]. Electromagnetic energy will flow in the carrying oil layer for a considerable distance then will be absorbed or removed and finally it will be converted to thermal energy using forces as low as 5 kW to as high as 100 kW [7], [115].

This Radio-frequency method also has the advantage of a rapid heating speed and relatively small heat loss where this will increase the efficiency of oil production and heat can be transmitted through the casing and into the reservoir by heat conduction [7], [116-117]. Particularly, radiofrequency can reduce heat loss through the seal rock [7], [118]. The cost for this method is high compared to the other methods of the resistive and inductive electrical heating methods [116]. According to the frequency of electrical heating, electrical heating is divided into two parameters, which low frequency is used for ohmic and resistive heating is used for microwave heating method [7].

3.2.6.1 LOW FREQUENCY ELECTRIC RESISTIVE / OHMIC

Low-frequency electric called ohmic or joule heating is a method to heat the reservoir by flowing electrical current through the formation [7], [119-121]. Ohmic occurs when low-frequency from AC flows to the reservoir and the electrical heating is
converted to heat energy. \cite{7,122} Figure 10 shows the idea of this method.

\begin{figure}[h]
\centering
\includegraphics[width=0.6\textwidth]{fig8.png}
\caption{Figure 8 Schematic of low frequency electric resistive (After Sahni, 2000) \cite{122}}
\end{figure}

3.2.6.2 HIGH FREQUENCY MICROWAVE HEATING

Microwave heating is high-frequency heating where the wave range ranges from 300 – 300000 MHz \cite{7}, \cite{123}. Therefore, it is called a microwave due to a short wavelength. Microwave heating is affected by the design of the microwave source and dielectric properties \cite{7,124-125}. Hydrocarbons mixed with sand can absorb large amounts of microwaves, and hydrocarbon can be rapidly heated to temperatures as high as 300-400 °C \cite{7,119,126}. Figure 11 shows the mechanism of this method.

\begin{figure}[h]
\centering
\includegraphics[width=0.6\textwidth]{fig11.png}
\caption{Figure 11 Microwave based EOR Setup (After Rehman, 2012) \cite{119}}
\end{figure}

The advantages of microwave irradiation include short processing time, rapid heating, high energy efficiency, and precise control processes. The microwave heating process can be divided into two stages. The electrical energy is input and converted into microwave energy, then converted into
effective heat. The energy efficiency of this process is the economic performance index. Experimental studies show that the total energy efficiency of microwave heating can be reached by approximately 80% [7], [127].

3.3 SOLAR ENERGY

Recently solar energy has paid attention to reduce the cost of steam generation [10,128-130]. It has the advantages of recovering heavy oil in a friendly environment manner with clean and more efficient way. Currently, solar facilities have been planned in San Joaquin Valley, California and Kuwait [10,131].

3.4 NUCLEAR ENERGY

This method is proposed to replace the natural gas fired facility to generate steam. The first project for the recovery of heavy oil and bitumen was proposed in 1977 in Alberta [10,132]. It helps in reducing pollution by reducing gas emission and reduces the operating cost.

In Venezuela, an advanced nuclear power plant was initiated with three reactors [10,133].

4. THE REFINING OF HEAVY OIL

A refinery designed to handle light petroleum but cannot be totally employed to work with 100% of heavy petroleum, and some changes in the process plants or even installation of new units are mandatory.

Heavy-oil contains high molecular weight hydrocarbons with a high amount of sulfur, nitrogen, oxygen, and metals [2], [134]. The crude oil has more than fifteen carbon atoms in the chain that makes the refining process costly and complex [2], [135].

Petroleum fractions can be described by SARA analysis. The analysis depends on using different solvents and adsorbents to determine the polarity of these fractions [2], [136].

Saturates are defined as the nonpolar hydrocarbons having linear or branched chains like aliphatic cyclic paraffins. Aromatics are the compounds with one or more aromatic rings linked to aliphatic chains. Resins and asphaltenes are the compounds of the high molecular weight in the crude oil [2], [134]. Resins are found to be soluble in pentane and higher hydrocarbons, however, it is insoluble in propane. Asphaltenes are one of the crude oil fractions that are soluble in toluene or benzene but insoluble in n-alkenes of low molecular weight [2], [134], [137]. They are composed of poly condensed aromatic rings and lateral aliphatic chains, presenting a smaller proportion of acidic and basic functional groups.

The quality of crude oil is determined by the hydrogen-to-carbon (H/C) ratio since high-quality oil has a ratio of 1.5 while poor-quality petroleum as low as 0.8. Therefore, increasing the hydrogen or decreasing the carbon contents will improve the heavy oil quality [138].

The idea of upgrading the heavy oil is extracting maximum value from each barrel by converting the heavy crude oil into light crude. The upgrading process uses hydroprocessing to reduce oil viscosity by breaking carbon-carbon bonds and produces smaller paraffin and olefin molecules [2]. The hydrocracking process by heating the heavy oil along with hydrogen under high pressure to break the bonds between the molecules to form smaller chemical structures. Hydrotreating is the process of adding hydrogen to increase and form hydrogenation without breaking structures and to remove impurities [2], [134]. The process is catalyzed by metals such as nickel and platinum [2]. The hydrocracking and hydro refining work on reducing the amount of Asphaltenes and oil Resins by the conversion of Aromatic compounds into naphthenic [2], [134].

Block diagrams of heavy oil and bitumen upgrading processes are given in Figures 12&13.
5. HEAVY OIL TRANSPORTATION

There are numerous challenges for the processing and transportation of heavy oil with flow assurance difficulties. Also a challenge in the production of the high viscous oil using artificial lift. Different parameters affect the transportation of heavy oil like Velocity, Viscosity, Temperature, Density/Gravity and Pour Point [141]. The capacity of a pipeline is dependent on the pressure loss between pump stations. The pressure loss is a direct function of pipe diameter, length, pipe roughness, fluid velocity and friction factor [141].

Heavy crude oil can be transported on trunk systems in a variety of modes including segregation, blending, and batching [141].

Segregation requires separate pipelines to handle heavy crude. This requires completely dedicated pipelines, pumps, tanks, meters and manifold. Blending consists of mixing crudes to reduce the overall numbers of batches to be shipped or to reduce viscosity. This in turn reduces the number of individual tanks needed, and simplifies scheduling of shipments and deliveries [141].

Batching refers to the shipping of crude in discrete batches. Different techniques are used to
transport heavy oil safely for a long distance in pipeline. These include Heating, Dilution, lubricated transport and partial upgrading [141].

5.1 HEATING

Heating is used for reducing heavy oil viscosity by increasing temperature is widely used for heavy oil transportation. It is used to mitigate any problems in the transportation of heavy oil. The first application was in India [2], [142]. For stable transportation, maximum viscosity of 500 cp should be reached after heating [2], [143-144]. The heating is not an easy project, many considerations related to the high-temperature values related to the pipeline expansion, the number of pumping stations and its capacity, and the heat loss during the heavy oil flow [2].

This process is considered expensive and a feasibility study should be done before starting the heating project. Figure 14 shows the relation between viscosity and temperature for heavy oil from different oil fields.

An example for pipeline heating is reported from Alyeska in Alaska where the crude oil is transported at at approximately 50°C. A lot of challenges for any heating project should be considered. One of them is the instability of the oil flow due to any change in the rheological properties that may be induced by heating. Also for the long distance pipeline, several heating and pumping stations may be required and this will have an impact on the capital cost. For the warmer climates, an example for shorter production pipeline in Colombia is mentioned where the ambient temperature is high enough that the heavy oil is not exceed the pour point, therefore electrical heating may be used without the need for restart procedures [145].

![Figure 14 Relation between viscosity and temperature for heavy oils from several oil fields. Circles point to reservoir conditions (after Farouq Ali, 2003) [146]](image)

5.2 DILUTION

The method depends on the mixture of two different oils to have a new component with different properties. The addition of less viscous oil and any fractions of distilled petroleum such as naphtha, condensate, kerosene, or gasoline has a great impact on reducing the viscosity of heavy crude oil. This will help in pumping the heavy oil in the pipeline to a long distance [2], [143].

The challenge in using this method is the high amount of the light oil required and their high market value besides their availability close to the regions of heavy oil production or it will require another additional transportation cost of
the light oil to the processing unit of the heavy oil production [2]. Dilution process requires heating, so another cost will be added [147].

5.3 LUBRICATED TRANSPORTATION

The technology-based on transporting heavy oil lubricated by water where the less viscous phase “water” will flow near the pipe wall “high shear region” and lubricates the flow [2].

When pumping pressure equals, the wall shear stress, lubricated transport requires pressure that is comparable to pumping water alone and independent of the oil viscosity [2], [148-149]. The configuration of phases depends on the flow rate of each phase such as core annular flow and crude oil in water emulsion.

5.3.1 CORE ANNULAR FLOW

When the oil flows in the center of the pipe and water in the wall of the pipe, this flow pattern shows great stability in case of the phases are immiscible and don’t form emulsions [2], [150]. A blockage in the pipe section may be happened due to the accumulation of the oil at the pipe wall and oil flow will be prevented [2].

An important example for core annular flow is the project employed in the Shell project in California. 38.6 km pipeline from North Midway Sunset reservoir to the central facilities at Ten Section (California) operates for 12 years [145]. Another example in Venezuela where 55 km lubricated pipelines from San Diego to Budare (Venezuela) used for transporting Zuata heavy crude oil (9.6 API°) and the self-lubricated pipelines of Syncrude’s Canada Ltd. [145,151].

5.3.2 CRUDE OIL-IN-WATER EMULSIONS

Although the high cost of the heating and diluent processes, they still widely used for their great results in heavy oil transportation. Lubricated pipeline methods are paid attention to be used due to its low cost and its effect on saving energy by decreasing the friction pressure.

The emulsification process works on reducing heavy oil viscosity to values of 50-200 cp [2], [144] to pump the heavy oil easily [2], [147], [152-154]. The transportation of heavy oil using this method by dispersing the heavy crude oil in water and are stabilized by surfactants. The emulsion, in general, is either dispersion of oil in water (O/W) or water in oil (W/O) with droplet sizes in microns (Figure 15). [152]

An example from Egyptian Geisum field for stabilizing O/W emulsion using an anionic surfactant for the crude oil transportation was studied. They found that by increasing the concentration of anionic surfactant, more stabilization and increasing in the surfactant viscosity could be achieved [145,155].

An example for the transportation of the emulsified heavy oil was reported for a joint project between BP Canada and the Alberta Energy Company has developed TRANSOIL® [145,156].

Another example for the emulsion flow for a heavy oil from a field in Shanjiasi (China) where the pressure loss is reduced by 80% by emulsions formulated with water fractions around 0.6–0.8.

Another test was performed in Sicily and the Adriatic Sea (Italy), a trial for forming an emulsion showed a reduction in viscosity 30–50 times lower than that of the diluted oil that will help in the transportation of the heavy oil. The experiment also showed an increase in oil productivity was four times higher than obtained with the conventional diesel dilution production [145,157].

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![Figure 15 Schematic represents emulsion structures a) O/W emulsion & b) W/O emulsion.](image-url)
6. HEAVY OIL RESERVES

The world oil resources have been estimated by around 9 to 13 trillion barrels, 30 % represents the conventional resources while the remaining 70 % represents the unconventional resources. The unconventional resources are classified by 30 % oil sand and bitumen, 15 % heavy oil, and 25 % extra-heavy oil in more than 70 countries [158]. The estimated heavy oil in place and bitumen are 5.9 trillion barrels where 80% are found in Venezuela, Canda, and the USA [158-160]. Table-3 shows that 1 trillion barrel (434.3 Billion barrel heavy oil & 650.7 Billion barrel bitumen) are considered technically recoverable [159].

Table 3 Estimation for the global in place heavy oil and bitumen resources and technically recoverable reserves and the percentage of global reserves occurring in each region (After Meyer and Attanasi, 2003) [159]

<table>
<thead>
<tr>
<th>Region</th>
<th>Heavy &amp; Extra Heavy Oil (BBO) Resources</th>
<th>Heavy &amp; Extra Heavy Oil (BBO) Reserves</th>
<th>%</th>
<th>Bitumen (BBO) Resources</th>
<th>Bitumen (BBO) Reserves</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>North America</td>
<td>185.8</td>
<td>35.3</td>
<td>8.1</td>
<td>1659.1</td>
<td>530.9</td>
<td>81.6</td>
</tr>
<tr>
<td>South America</td>
<td>2043.8</td>
<td>265.7</td>
<td>61.2</td>
<td>1.1</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>Europe</td>
<td>32.7</td>
<td>4.9</td>
<td>1.1</td>
<td>1.4</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>Russia</td>
<td>103.1</td>
<td>13.4</td>
<td>3.1</td>
<td>259.2</td>
<td>33.7</td>
<td>5.2</td>
</tr>
<tr>
<td>Middle East</td>
<td>651.7</td>
<td>78.2</td>
<td>18</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Asia</td>
<td>211.4</td>
<td>29.6</td>
<td>6.8</td>
<td>267.5</td>
<td>42.8</td>
<td>6.6</td>
</tr>
<tr>
<td>Africa</td>
<td>40</td>
<td>7.2</td>
<td>1.7</td>
<td>430</td>
<td>43</td>
<td>6.6</td>
</tr>
<tr>
<td>Western Hemisphere</td>
<td>2315.4</td>
<td>301</td>
<td>69.3</td>
<td>1659.4</td>
<td>531</td>
<td>81.6</td>
</tr>
<tr>
<td>Eastern Hemisphere</td>
<td>1025.4</td>
<td>133.3</td>
<td>30.7</td>
<td>920.8</td>
<td>119.7</td>
<td>18.4</td>
</tr>
<tr>
<td>World Total</td>
<td>3340.8</td>
<td>434.3</td>
<td>100</td>
<td>2580.1</td>
<td>650.7</td>
<td>100</td>
</tr>
</tbody>
</table>

Figure 16 shows heavy oil reserves for different countries.

Figure 9 Heavy oil reserves values for different countries (After Meyer and Attanasi, 2003) [159]
The largest heavy oil (The Faja Petrolifera del Orinoco) is located in eastern Venezuela. The total recoverable reserves are 310 billion barrels while the oil in place is 1.2 trillion barrels [158].

The second-largest heavy oil is located in California [158]. Table 4 shows the estimates of bitumen in place for 29 major reservoirs in accumulations in Alabama, Alaska, California, Kentucky, New Mexico, Oklahoma, Texas, Utah, and Wyoming.

Table 4 Previous estimates of bitumen & heavy oil resource in place, measured and total, including speculative, in the united states (After Schenk, 2006) [161]

<table>
<thead>
<tr>
<th>State</th>
<th>No. Deposits</th>
<th>API</th>
<th>Measured, MMBO</th>
<th>Total, MMBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utah</td>
<td>10</td>
<td>-2.9 to 10.4</td>
<td>11850</td>
<td>18680</td>
</tr>
<tr>
<td>Alaska</td>
<td>1</td>
<td>7.1 to 11.5</td>
<td>15000</td>
<td>15000</td>
</tr>
<tr>
<td>Alabama</td>
<td>2</td>
<td>N/A</td>
<td>1760</td>
<td>6360</td>
</tr>
<tr>
<td>Texas</td>
<td>3</td>
<td>-2 to 7</td>
<td>3870</td>
<td>4880</td>
</tr>
<tr>
<td>California</td>
<td>6</td>
<td>0 to 17</td>
<td>1910</td>
<td>4470</td>
</tr>
<tr>
<td>Kentucky</td>
<td>4</td>
<td>10</td>
<td>1720</td>
<td>3410</td>
</tr>
<tr>
<td>New Mexico</td>
<td>1</td>
<td>12</td>
<td>130</td>
<td>350</td>
</tr>
<tr>
<td>Wyoming</td>
<td>2</td>
<td>N/A</td>
<td>120</td>
<td>145</td>
</tr>
</tbody>
</table>

The proved reserves for California’s oil fields are 2,854 million barrels while the undeveloped shallow bitumen deposits and seeps are estimated by 4.7 billion bbls [158]. Figure 17 shows a map for California’s heavy oil fields. Table 5 shows the data for the different California’s fields.

![Figure 10 Principal oil fields of California (After Tennyson, 2005) [162]](image-url)
Table 5 Principal California oil fields produced by thermal recovery methods. The fields are arranged by 2017 total oil yield; the volume of associated gas is indicated by the gas oil ratio (GOR), with oil characteristics an in-situ oil temperature of the fields [158].

<table>
<thead>
<tr>
<th>Field</th>
<th>2017 Oil MMBO</th>
<th>2017 GOR “SCF/bbl”</th>
<th>API</th>
<th>Oil Viscosity cp</th>
<th>Oil Temperature °F</th>
</tr>
</thead>
<tbody>
<tr>
<td>Midway-Sunset</td>
<td>22.09</td>
<td>204</td>
<td>11 to 14</td>
<td>1000 - 10000</td>
<td>85 – 130</td>
</tr>
<tr>
<td>Kern River</td>
<td>21.935</td>
<td>468</td>
<td>13</td>
<td>4000</td>
<td>90</td>
</tr>
<tr>
<td>South Belridge</td>
<td>21.166</td>
<td>383</td>
<td>13 to 14</td>
<td>1500 – 4000</td>
<td>95</td>
</tr>
<tr>
<td>Cymric</td>
<td>16.16</td>
<td>171</td>
<td>11 to 14</td>
<td>1000 – 2000</td>
<td>95 – 105</td>
</tr>
<tr>
<td>Lost Hills</td>
<td>9.504</td>
<td>469</td>
<td>12.7 to 13.9</td>
<td>1500 -4000</td>
<td>75 – 82</td>
</tr>
<tr>
<td>San Ardo</td>
<td>7.234</td>
<td>140</td>
<td>11 to 12</td>
<td>1000 – 3000</td>
<td>125 – 130</td>
</tr>
<tr>
<td>Coalinga</td>
<td>6.575</td>
<td>39</td>
<td>9 to 13</td>
<td>2000 – 28000</td>
<td>84 – 105</td>
</tr>
<tr>
<td>Poso Creek</td>
<td>4.419</td>
<td>172</td>
<td>13 to 14.8</td>
<td>1500</td>
<td>80 – 95</td>
</tr>
<tr>
<td>Kern Front</td>
<td>3.684</td>
<td>15</td>
<td>13</td>
<td>2800</td>
<td>110</td>
</tr>
<tr>
<td>Mckittrick</td>
<td>3.004</td>
<td>49</td>
<td>10 to 12</td>
<td>13000 – 51000</td>
<td>83</td>
</tr>
<tr>
<td>Placeita</td>
<td>0.575</td>
<td>0</td>
<td>13</td>
<td>10000</td>
<td>90</td>
</tr>
<tr>
<td>Edison</td>
<td>0.559</td>
<td>215</td>
<td>14</td>
<td>2000</td>
<td>90</td>
</tr>
<tr>
<td>North Antelope Hills</td>
<td>0.259</td>
<td>0</td>
<td>14</td>
<td>1400</td>
<td>80</td>
</tr>
</tbody>
</table>

In Canada, most of heavy oil resources are located in Alberta as shown in figure 18(a) while in Venezuela these heavy oil resources lie parallel to the northern bank of the Orinoco River and extend from east to west along the Orinoco petroleum belt, as shown in figure 18(b) [10,36,169].

![Oil sands reserves in Alberta.](image1)

![Orinoco petroleum belt.](image2)

Figure 11 Heavy oil resources distribution in Canada and Venezuela [10,36,169]

Figure 19 shows the location of the different heavy oil resources in China including Liaohé oilfield, Shengli oilfield, Xinjiang oilfield and Henan oilfield [10,37].
In Russia, the Heavy oil reserves are around 22.6 billion barrels which represents 18% of the total oil reserves [158]. Table 6 shows the four principal petroleum provinces with annual production 451.5 MMBO in 2016 [158], [163].

Table 6 Russian heavy oil and bitumen resources regional distribution (After Bazhenova T.K., 2015) [164]

<table>
<thead>
<tr>
<th>Basin</th>
<th>Region</th>
<th>Resource, BBO</th>
<th>The share of total heavy oil, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>West-Siberian basin</td>
<td>Khanty-Mansiysky Region</td>
<td>10.64</td>
<td>25.7</td>
</tr>
<tr>
<td></td>
<td>Yamalo-Nenets Region</td>
<td>6.51</td>
<td>15.7</td>
</tr>
<tr>
<td>Volga-Ural basin</td>
<td>Republic of Tatarstan</td>
<td>5.35</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>Republic of Bashkortostan</td>
<td>2.29</td>
<td>5.5</td>
</tr>
<tr>
<td></td>
<td>Udmurt Republic</td>
<td>2.01</td>
<td>4.8</td>
</tr>
<tr>
<td>Timan-Pechora basin</td>
<td>Komi Republic</td>
<td>2.56</td>
<td>6.2</td>
</tr>
<tr>
<td>(North-West)</td>
<td>Nenets Region</td>
<td>2.26</td>
<td>5.4</td>
</tr>
<tr>
<td>East-Siberian basin</td>
<td>Krasnoyarsk Region</td>
<td>2.15</td>
<td>5.2</td>
</tr>
<tr>
<td></td>
<td>Offshore</td>
<td>1.34</td>
<td>3.2</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>35.11</td>
<td>84.6</td>
</tr>
</tbody>
</table>

Figure 20 shows the percentage of the different heavy oil basin in Russia.
Table 7 shows the estimation of the reserves for the different fields in the West Siberian Basin, which consider the largest sand accumulation for heavy oil in Russia.

<table>
<thead>
<tr>
<th>Field</th>
<th>Depth, m</th>
<th>API</th>
<th>Reserves, MMBO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Russkoye</td>
<td>664</td>
<td>19.7</td>
<td>2649</td>
</tr>
<tr>
<td>S.-Komsomolstoye</td>
<td>1056</td>
<td>19</td>
<td>1256</td>
</tr>
<tr>
<td>Van-Eganskoye</td>
<td>893</td>
<td>16.8</td>
<td>1069</td>
</tr>
<tr>
<td>Tazovskoye</td>
<td>1162</td>
<td>19.4</td>
<td>454</td>
</tr>
<tr>
<td>V.-Messoyakhskoye</td>
<td>834</td>
<td>17</td>
<td>2144</td>
</tr>
<tr>
<td>Z.-Messoyakhskoye</td>
<td>834</td>
<td>17</td>
<td>812</td>
</tr>
</tbody>
</table>

Also, there are four regions of Colombia where heavy oil production is now occurring on a commercial scale. These are the anticlinal Castilla, Chichimene, Apiay, Suria, and Libertad fields [158].

7. NANO FLUIDS

Recently several studies have been performed to study the effect of Nano particles in the improving of the recovery of heavy oil. Montes et al. [166] studied the effect of using NiO nanoparticles and an ultrasound cavitation treatment to decrease heavy oil viscosity by decreasing its asphaltene content and convert the heavy oil into lighter compounds using a catalytic decomposition reaction.

Askarian et al. [166,167] have evaluated nanoparticle usage in a cavitational cracking process. They worked on iron oxide nanoparticles and used gasoline to donate hydrogen. They found that the viscosity could be reduced by 20% and this lead to an improvement in the cracking reactions.
Cheraghian [168] studied the effect of silica nanoparticles on polymer viscosity to increase heavy oil recovery. They conducted an experiment of polymer flooding with adding the nano silica and they found that the presence of nano silica helps in improving recovery compared to the polymer flooding only.

8. FUTURE STUDIES

1. The usage of Nanoparticles to enhance oil recovery is a good area for study now by studying the effects of the usage of Nanocatalysts on the upgrading of the heavy oil.
2. Electrically enhanced oil recovery which can be an alternative method for the conventional EOR.

CONCLUSIONS

1. Heavy oil is considered now one of the main resources for energy in the future.
2. Heavy oil and bitumen have been found in many countries with large in-place volumes.
3. The recovery of heavy oil can be increased economically by good optimal selection for the suitable production method either one of the thermal methods or Electrical heating methods.
4. More experimental work is still required in the field of Nanocatalysts for increasing recovery.
5. A pilot field project for the different electrical heating methods that widely used in experiments is required in the future.
6. The upgrading process for heavy oil processing is widely used but finding the optimal quantities of light oil with its high cost is still challenging.
7. The heating and dilution methods act well in the transportation of heavy oil but more studies are still in progress to evaluate the lubricated transportation method.

ABBREVIATION

AC : Alternating Current
API : American Petroleum Institute (Density Indicator)
BO : Barrel Oil
BP : British Petroleum
BSOC : Bayou State Oil Corporation
CAGD : Combustion Assisted Gravity Drainage
COSH : Combustion Override Split Horizontal Well

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