Reviewing Crude Oil Extraction Methods and Investigating Innovative Improvements

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Abstract

New discoveries of crude oil are declining rapidly. To keep up with the constantly increasing demand for fossil fuels, the petroleum industry must begin recovering more oil from existing wells. Current recovery methods often leave reservoirs with over half of the original oil still deposited. Carbon dioxide enhanced oil recovery (CO_2 EOR) has begun to pick up steam as a viable method to improve recovery rates. Supporters are particularly interested in carbon dioxide injection, because of the potential to partially negate the large carbon footprint the fossil fuel industry creates. Fossil fuels are largely responsible for the majority of anthropogenic carbon dioxide emissions. Improving CO_2 EOR techniques could help solve both the recovery rate and pollution issues.

1. Introduction

The goal for many oil companies in today's world is to maintain a profitable economic oil rate and maximize their oil recovery factor. Maximizing the recovery factor in a cost-efficient way is becoming more important, as experts now believe that new recoverable oil field discoveries will begin to decline sharply (Miller et al. 2013).

Unexplored oil fields from the past decade tend to be too small to be economically viable or based in locales that are either remote or environmentally sensitive. However, there is an abundance of unconventional hydrocarbons, but technologies for exploiting these resources are either very energy intensive, politically charged, or just not ready to be deployed on a large, industrial scale. Motivation to find a clean method of extracting leftover hydrocarbons is at an all-time high (Muggeridge et al. 2013).

The petroleum industry directly contributes to the increasing emissions of greenhouse gasses into the atmosphere. Burning petroleum and its byproducts account for approximately 87% of anthropogenic carbon dioxide (Quéré et al. 2016). Implementing storage systems in geological formations can drastically reduce carbon dioxide emissions. Carbon dioxide can remain stored in natural traps and faults for decades before seeping to the Earth's surface. The petroleum industry has experimented with injecting carbon dioxide into the earth for the past four decades; both as a lubricant for greater recovery and as purely a disposal method (Aycuger et al. 2001; Dai et al. 2013; Ohara et al. 2007; Alvarado 2010).

However, in recent years, there has been increased interest in developing technology to sequester carbon dioxide in enhanced oil recovery sites because of amendments to the Carbon Capture and Sequestration (CCS) program. This U.S. Department of Energy program is designed to support and encourage the research of new methods to sequester carbon dioxide emissions. Growing awareness of the accumulation of greenhouse gasses in the atmosphere has been a catalyst for increased focus on ways to sequester carbon. In 2012, the CCS program was expanded to the CCUS (Carbon Capture, Utilization, and Sequestration) program (Dai et al. 2013). The new emphasis on utilization will promote the development of many new methods of not only storing carbon dioxide but using it in ways to increase the recovery rate of existing wells.

Carbon dioxide enhanced oil recovery is likely to undergo large-scale expansion in the next decade because of high oil prices and advances in CCS technology (Hamilton 2009). However, because CO_2 EOR is still a relatively new process, several important issues regarding implementation must be resolved before it can be commercialized (Manrique 2010; Pandey 2016). The goal of this paper is to examine the various methods that preceded CO_2 EOR and how these classic techniques can be applied to improve the recovery rate and reduce the footprint of the industry.

2. Background

It is important to understand the chemical and physical properties of crude oil before discussing the ways in which it is extracted. These properties dictate how the crude oil is formed, where it is found, the ease of extraction and the value of the final product.

What is Crude Oil?

Crude oils are complex mixtures comprising varying types of hydrocarbon compounds. These compounds may differ in appearance, consistency, and composition from one field source to another. The differences in the characteristics of the hydrocarbons are correlated to the differing number of carbons and hydrogens in each molecule along with the molecular structure. Molecules with one to four carbons are gaseous, five to 19 carbons are liquids, and molecules with more than 20 carbon atoms are typically solids. This wide range of compositions allows the viscosity of crude oil to vary dramatically. The shapes of the hydrocarbon chain and the bond order are also essential factors in determining the nature of the oil (Glover 2012, Petroleum Refining Process 2015). A wide range of petroleum-based products can be created from the same source of oil because of these variations within crude oil (Kokal 2002).

In crude oils, there are three principal hydrocarbon compounds: paraffins (aliphatics), aromatics, and naphthenes. **Figure 1.** shows a chart with some of the general components of crude oil. Based on the proportions of principal hydrocarbon molecules, crude oil can be classified as either paraffinic, naphthenic, aromatic, or mixed. Paraffinic hydrocarbons are saturated compounds and have the general formula C_nH_{2n+2}. Paraffins can be either straight-chained or isomerized. Aromatic hydrocarbons are cyclic compounds containing at least one benzene ring. Aromatics are unsaturated, so the hydrogen deficient carbon atoms are highly reactive. Naphthenes are saturated compounds that have a closed ring structure with a general formula of C_nH_{2n}. Straight-chained paraffins are found in the lighter fraction of crude oil. The branched chain, paraffin isomers are found in the heavier fractions. Naphthenes and aromatics are generally found in the heavier fractions of the crude oil. The location of the different hydrocarbon components is important because, during the refining process heat, chemicals, catalysts, and pressure are applied to separate the crude oil based on molecular size and structure. There are several lesser hydrocarbon compounds in crude oil as well, such as alkenes, alkynes, and dienes (Glover 2012; Kokal 2002; Petroleum Refining Process 2015).

The nonhydrocarbon compounds are the most troublesome components of crude oil. Crude oil contains varying amounts of salts, transition metals, acids, and highly pollutant aerosols, such as sulfur- and nitrogen-based compounds (Petroleum Refining Process 2015). The salts, transition metals, and acids create problems during the refining steps because they can corrode and clog the equipment. The aerosols are dangerous because of the harm they pose to the environment upon combustion. Over 7 million people die per year from lung diseases attributed to atmospheric aerosols (Pandey et al. 2016). The federal government tightly regulates the levels of permissible aerosols in the final product, because of this threat.

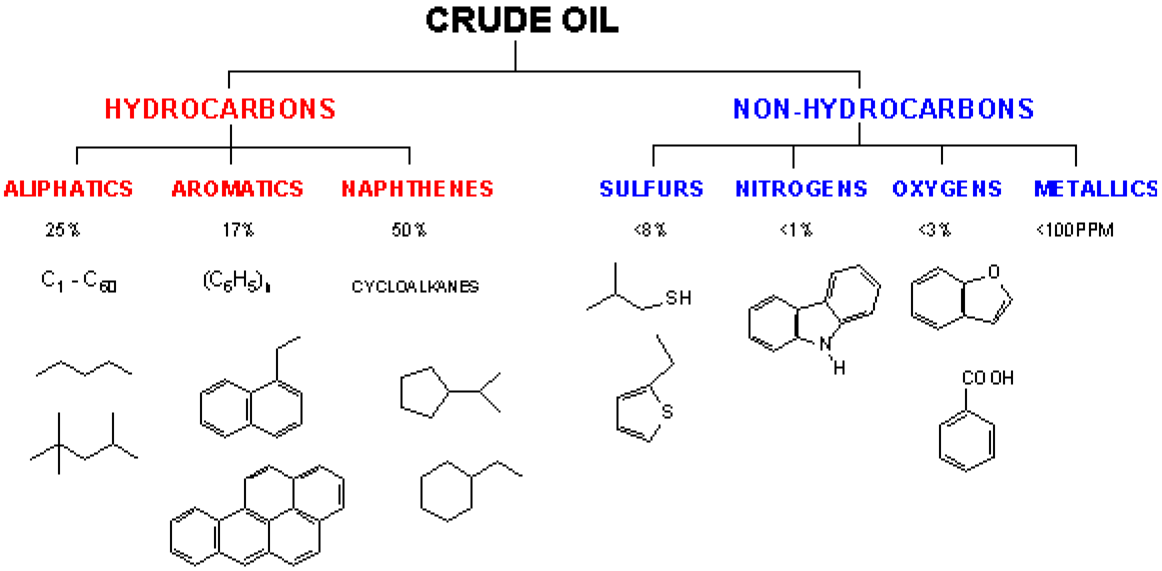

Fig 1. General Components of Crude Oil (Simon et al. 2010)

Where does Crude Oil Come From?

Along with natural gas, crude oil is found in sedimentary basins in large underground deposits or traps known as reservoirs. **Fig. 2** illustrates a cross section of a common oil trap. These reservoirs originate from organic material slowly transforming underneath the earth's surface. This process can occur along one of three major pathways: 1) deposition and accumulation, 2) burial and transformation, 3) migration and trapping (Dow et al. 1994, Schaefer 2005). These pathways are all similar in the fact they provide organic material with high pressure and temperature conditions in an underground anoxic environment. For extraction to be economically viable, these specific conditions must be achieved during the formation of a reservoir.

These conditions are created during tectonic activity such as mountain building, basin formation, continental rifting, and the growth of continents (Dow et al. 1994).

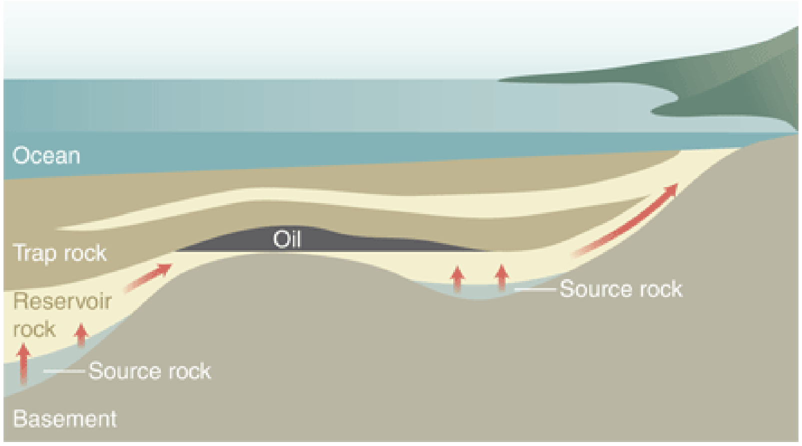

Fig 2. Growth of an Oil Field (Schaefer 2005)

How is Crude Oil Processed?

Once the oil is extracted (the extraction methods of crude oil will be discussed in greater detail throughout the paper) the first process it undergoes is distillation. During distillation, the various types of hydrocarbons are separated into fractions sorted by boiling points. Each fraction is further treated to tune the size of the hydrocarbon molecules in a process unique to their chemical identities, such as decomposition, unification, and alteration. From there, the processed fractions go to more specialized treatment locations to create a final product (Petroleum Refining Process 2015). Primary products from crude oil fractions include asphalt, diesel fuel,

fuel oil, gasoline, kerosene, liquefied petroleum gas, lubricating oil, paraffin wax, bitumen, and miscellaneous petrochemicals (Eser et al. 2013.)

3. Current Recovery Mechanisms

Crude oil is extracted by creating pressure gradients within a reservoir that propel the liquid to the well (Muggeridge 2014). It is currently recovered in three main stages: primary, secondary, and tertiary recovery. Primary recovery utilizes the natural energy of the reservoir to drive the hydrocarbons to the surface. Secondary recovery applies an outside agent to drive the hydrocarbons to the surface. Finally, tertiary recovery (also known as Enhanced Oil Recovery) refers to a variety of techniques that are used to improve production that generally involve changing the properties of a reservoir (Glover 2012).

Primary Recovery

Primary recovery is the initial method of oil recovery that involves utilizing the natural pressure within the well to extract hydrocarbons with a lift such as a pump or jack. Primary recovery is very limited because it can only target the liquid fraction of the oil, which accounts for between five and fifteen percent of the well's supply. Five drive mechanisms dictate the success of primary recovery. These mechanisms are combination drive, gravity drainage, water drive, gas cap drive, and solution gas drive. The drive mechanisms operate based on several different energy sources within the well (Petroleum Refining Process 2015).

Before extraction of the hydrocarbon from the reservoir begins, it is nearly impossible to know which drive mechanism is the main contributor. During the early stages of extraction, the production data is analyzed by examining the reservoir pressure and fluid production ratios to determine the primary mechanism (Petroleum Refining Process 2015; Djuraev 2017). The ratios are revealing because each drive has a unique reservoir pressure.

Solution Gas Drive. A solution gas drive mechanism occurs when a reservoir does not initially contain free gas, but upon depletion of pressure within a reservoir, gas is developed. This drive mechanism requires the reservoir rock to be completely encased in impermeable cap rocks. During extraction, the pressure within the reservoir is lowered. Lowering the pressure causes the source rock, water, and dissolved gasses in the reservoir solution to expand. Energy from the expanding components propels the oil up the collection pipe.

A solution gas reservoir can be considered saturated or unsaturated depending on the existence of free gas within the reservoir. If no free gas exists, then the system is undersaturated and derives energy solely off the expansion of the rock and water. If the system is saturated, then a dissolved gas existing within the reservoir fluid assists in the propulsion of the crude oil. Some form of a solution gas drive can be observed in nearly every other form of primary recovery (Glover 2012).

Gas Cap Drive. Some reservoirs contain a natural gaseous divide between the oil column and the cap rock. This phenomenon is referred to as a gas cap. Reservoirs with a gas cap exhibit a gas cap drive mechanism. In his mechanism, the gas pushes down on the oil. The compressed oil is then propelled into the extraction pipes (Glover 2012).

Water Drive. In a reservoir fueled by a water drive, an aquifer interacts with the oil and provides the drive energy. The aquifer pushes the oil up the pipe, and as oil is removed, the aquifer continues to rise towards the surface. The success of a water drive reservoir depends on the production rate of the reservoir and the size and permeability of the aquifer. It is more beneficial to have a large, highly permeable aquifer, than a high production rate. This is true because if the oil is slowly extracted the aquifer can rise to replace all space and maintain the pressure. If the aquifer is not permeable enough or too small, it cannot keep up with the rate of flow and the reservoir will lose pressure (Glover 2012).

Gravity Drainage. Gravity drainage is a mechanism that works based on density differences between oil, gas, and water. The differing densities promote a natural separation within a reservoir. As the elements flow to their respective zones, a minimal driving force is created. Gravity drainage is largely ineffective on its own but works well when combined with other drive mechanisms (Glover 2012).

Combination Drive. It is very uncommon for a reservoir to utilize only one drive mechanism. A typical reservoir will have at least two of the main drive mechanisms, but often more. A combination drive refers to the collect reservoir as a whole and all the coexisting mechanisms that drive its production (Glover 2012).

Secondary Recovery

Secondary recovery begins when the natural driving mechanisms have been depleted, therefore requiring human intervention to recover the crude product efficiently. The most common means of improving reservoir efficiency are waterflooding and gas injection. These methods involve injecting either water or gas into the base of a reservoir to maintain pressure and to force the oil towards the surface (Glover 2012). Secondary recovery produces approximately 20-30% of the oil in a well (Blunt et al. 1993; Parker 2009).

Enhanced Oil Recovery

Current primary and secondary recovery methods are very inefficient. On average, they are only able to recover 33% of the oil in a reservoir. Due to the economics related to the cost of production, most reservoirs are abandoned with around 70% of the product still in the ground (Lake et al. 1992). Enhanced oil recovery surpasses secondary recovery because it injects a specialized solution into the reservoir to maintain pressure as opposed to just water or gas. Even though enhanced oil recovery is better than primary and secondary recovery, it still leaves behind nearly 25% of the oil in a reservoir. Engineers have been experimenting with supercritical carbon dioxide to improve the recovery rate. Under supercritical conditions, carbon dioxide becomes a powerful solvent that readily dissolves in the oil to reduce viscosity. This is notable because the last remaining fractions of oil in a reservoir tend to be thick sludge. By reducing the viscosity, this sludge is able to flow more easily through production pipes (Parker 2009; Jaramillo et al. 2009; Aycaguer et al. 2001).

4. Conclusion

Carbon dioxide enhanced oil recovery is a promising method of carbon dioxide sequestration because it creates a market for carbon dioxide to become a valuable good. Aycaguer et al. reported in 2001 that 80% of the world's commercial carbon dioxide was used for enhanced recovery purposes. By expanding the need for carbon dioxide, corporations that are responsible for large quantities of pollution will be encouraged to devise ways to capture their emissions so that they may profit from them. Improving enhanced oil recovery can exponentially prolong the global oil reserves.

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