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Current status and designing of Thermal EOR

SHAHAB UD DIN
Faculty of Earth Resources
China University of Geosciences, Wuhan, Hubei, China

Abstract

According to Energy Information Administration (EIA), world energy consumption and demand are increasing day by day. Still, the major and much-needed source of energy is fossil fuels (oil and natural gas) which contribute 40.7 % of the total world energy. Due to industrialization and development, these sources of energy are draining drastically, which is evident from the past three decades that the supply is shrinking while the demand is sorrowing up. The production of oil from any well goes through three stages such as primary, secondary and tertiary. Upon completion of the first two, only 20-30% of the oil is recovered, while 70 % of the oil still remains. According to an estimate, 2.0×10^{12} barrels of conventional and 5.0×10^{12} barrels of heavy oil remain in the reservoirs worldwide after the conventional recovery methods. At this stage, enhanced oil recovery starts to extract the maximum of the remaining oil. EOR will continue to have a significant place in oil production because of the escalating energy demand and the tight supply. This paper will shed light on the status and methods of EOR and will briefly discuss the thermal recovery method, its types, mechanisms, screening criteria, problems, and limitations.

Keywords: energy, enhanced oil recovery, thermal EOR

1) INTRODUCTION:

With the increase in population and development, the world's need for energy is also increasing. In the last several decades, the world population is increased by several folds. In a similar fashion need for energy is also increased with continuous development and industrialization. The main source of energy is still fossil fuels. But this source of energy is exhausting at an enormous rate while the demand is increasing day by day [1]. According to an estimate, the total proven reserve of oil and gas were shrunk to 232.4 billion tons and 700 trillion m^{3}, respectively [2]. These reserves are enough for the next 50 and 49.8 years of oil and gas at the current consumption rate. The current world oil consumption and production are given in figure (1).

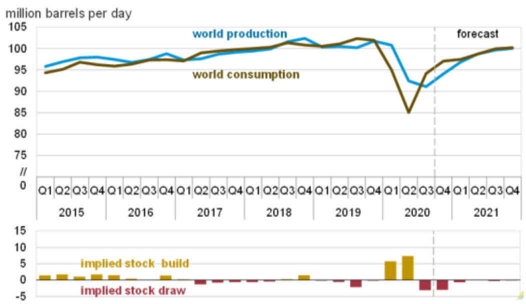

Figure (1): Supply and Demand of Oil and gas [3].

This clearly shows that consumption and production are almost the same. In the coming years, this demand will increase enormously and hence will lead to a crisis. That's why the oil and gas sector is moving to the exploration of unconventional energy resources (Shale gas, gas hydrates CBM, and ultra-deep reservoirs) to satisfy the energy demand and find a sustainable source of energy.

But there is a huge amount of oil still left in the reservoirs. The world average recovery factor from hydrocarbon reservoirs is stuck in the mid-30 percent range. The common recovery methods are primary, secondary, and tertiary. The primary recovery comes from natural forces such as dissolved gasses or solution gas, gas cap, gravity drainage, combination drive, and strong water aquifers. Primary drive mechanisms and their oil recovery ranges are given in Figure (2). The secondary recovery is comprised of water flood, gas injection. Gas injection is further divided into continuous and intermittent gas injection, which depends on the type of formation and reservoir conditions. Overall, the recovery factor for primary and secondary recovery in the conventional fields is 30 to 40%. And for unconventional oil reservoirs, it is only 3 to 7% of the original oil in place. According to an estimate, around 2.0×10^{12} bbl of conventional and 5.0×10^{12} bbl of heavy oil remains in the reservoirs after the depletion of conventional recovery methods.

To increase the recovery factor and to recover the remaining 60 to 70% of the reserve, we need some specialized techniques, which are known as EOR, also called the tertiary recovery, which is the focus of this paper. This paper will discuss the term EOR, the role of EOR, its current status, and different techniques of EOR, its use in different formations, and its economics.

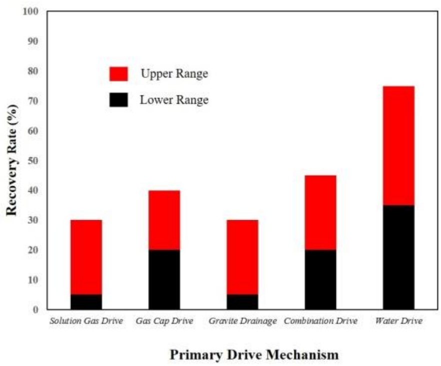

Figure (2): Primary drive mechanism and recovery ranges.

2) Enhanced Oil Recovery (EOR):

Enhanced oil recovery (EOR) is the process of increasing the oil recovery after the primary recovery and the secondary recovery, which is done by natural drive mechanisms and water, gas flooding, respectively [4]. In other words, it is the execution of various techniques for soaring up the quantity of crude oil from an oil field. It is also known as tertiary recovery. And the simplest definition of EOR is the recovery methods other than natural production is termed as EOR. The EOR process can be achieved by various techniques such as chemical injection, gas injection, microbial injection, and thermal recovery [4].

In the life of an oilfield, EOR is used to mobilize the residual oil and sweep the remaining oil as much as possible, and it comes at the end of primary and secondary recovery. Maximum fields around the world are reaching maturity and requiring the usage of secondary and tertiary recovery methods, and oil companies are looking for new practices and technologies to extract more oil from these mature fields [5]. Furthermore, in the next two decades, half of the water flooded fields will need to move to enhanced oil recovery (EOR). The effectiveness of an enhanced recovery method is a measure of its ability to provide greater hydrocarbon recovery than by natural, at an economically attractive production rate. Here we are presenting a comparison for a hypothetical reservoir three forecasts of cumulative hydrocarbon production as a function of time, as shown in figure (3), one curve is for the natural depletion while the other two are for two different proposed enhanced recovery methods. All the forecasts start from the present time “t” up to which production has been obtained by natural depletion. The R1, R2, and R3 are the three recoveries, where R1 represents the natural recovery while R2 and R3 are the proposed recovery methods. And hence the recovery for the proposed EOR techniques are much higher than that of the natural recovery; its effectiveness depends upon the reservoir characteristics, the nature of the displacing and is placed fluids, and last but not the least, the arrangements of production and injection wells.

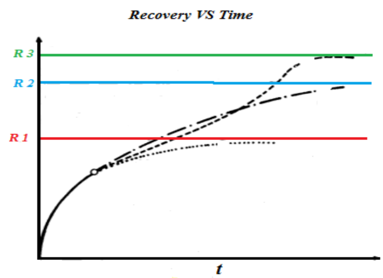

Figure (3): Recovery vs. Time adopted from [6].

Over the past several decades, more and more EOR fields or pilot applications have been reported. The results of it’s success and failure were shared and made public, which made a significant contribution in promoting the oil and gas sector and EOR technologies. Figure (4) shows the number of EOR projects around the world. Similarly, figure (5) shows the production share of different EOR methods around the world. From both figures (4) and (5), it is clear that among other EOR processes, thermal recovery is practiced a lot, and it’s production share is also higher than other EOR processes combine.

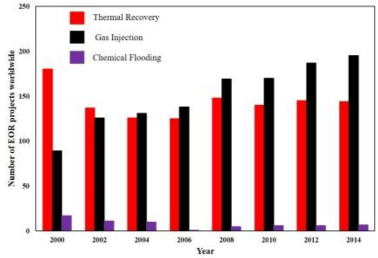

Figure (4): Number of EOR Projects around the world (2000-2014)[7].

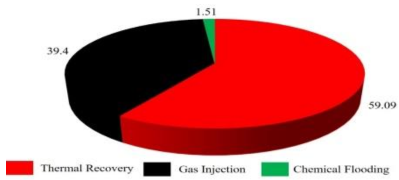

Figure (5): Production proportion between different EOR methods [7].

3) Problem statement:

It is a recognized fact that the term "easy oil" refers to oil that can be extracted easily in occupant areas is now disappearing, and the amount of oil produced by the primary recovery from these areas accounts for only 20 to 30 % of the total amount available which is discussed above [8]. Nowadays, exploration and production companies are looking for oil in very inaccessible areas; like areas where the temperature is below zero, deep waters and unconventional reserves, and to develop fields in areas like these are very costly, instead of investing huge sum of money in the above mention areas it is far better to produce the remaining quantity of oil in the existing fields by applying new technologies to increase the recovery factor by introducing the enhanced oil recovery techniques.

By applying the enhanced oil recovery techniques, millions of barrels of oil can be extracted from existing fields; as it increases the recovery of up to 60 % of oil in the reservoir, billions of dollars are invested in enhanced oil recovery researches to get the maximum amount of recovery with the lowest possible cost from the existing fields before moving to the inaccessible areas.

4) Enhanced oil recovery methods:

4.1) Thermal Recovery Methods:

Thermal EOR started in the 1950s, and among the enhanced oil recovery methods, thermal recovery methods are the most advanced and efficient, down to the technology and field experience. Thermal EOR is the technique that is used in almost 50% of the EOR process used worldwide to recover heavy and viscous crude oil [9–11]. In the thermal recovery method, heat is introduced into the reservoir to decrease the viscosity of the reservoir fluid, and vaporize some of the oil, hence increase the mobility of the oil [12–14]. Furthermore, TEOR is the technique used for the oil trap in fractured and dual porosity formations such as dolomite and carbonates [15–20]. Generally, TEOR is divided into two types, one in which the heat is generated within the reservoir, while in the other, heat is injected into the reservoir [21]. Among the thermal EOR techniques, steam injection is the one which is used in most of the EOR process around the world and is considered as the most successful method among thermal recovery techniques and all other EOR methods [22]. TEOR methods have been extremely successful and effective in the USA, Canada, Indonesia, Venezuela, and other countries of the world [14,22].

Thermal EOR is the most popular method in the world among the EOR methods use in the tertiary recovery stage. Whereas the steam injection (steam drive) is the most common method used in the thermal EOR process, produces 50-60% of OOIP. Compare to other EOR processes thermal EOR method does not pose any environmental risks, where other methods like chemical EOR pose serious environmental risks. This makes this method very attractive and can be used in various countries under strict environmental regulations. Figure (6) shows the EOR production from different TEOR around the world.

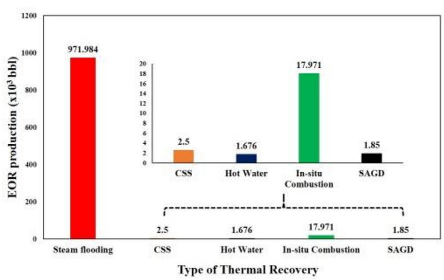

Figure (6): Production by different thermal recovery methods.

TEOR Mechanism:

The foremost mechanism which is used in all the thermal recovery methods is the injection of heat. The increase in temperature causes viscosity reduction, increase in mobility of the oil, wettability modification of the reservoir rock, and also provides the force to increase the flow rates of oil into the production well. Other factors like fluid and rock expansion, compaction, and distillation may also be present. This method is further divided into hot water flooding, steam drive, cyclic steam injection, in-situ combustion, and SAGD, which are discussed in detail below.

4.1.1) Hot Water Flooding:

Hot water flooding is also called hot water injection. This type of thermal recovery method involves the flow of just two phases, water, and oil, in which oil is displaced by water. The driving fluid is heated before sending it into the formation, which carries that heat into the formation. The schematic diagram of the hot water flooding is shown in figure (7) [23]. There are no significant chemical reactions involves in this process [24]. Before using, the water is filtered to remove any contaminations which might cause any problem; certain chemicals were added to control corrosion and scaling, other treatments were also made to minimize the swelling of clays in the reservoir. In the start, the heat front lags behind the leading edge of the fluid displacement front because the reservoir rock has a high heat capacity. So, the reservoir fluid is first subjected to cold water as the injection fluid at the displacement front loses its heat to the reservoir rock. Afterward, as the heat front advances, then the oil is affected by the hot fluid drive. In this process, the recovery is mainly increased by the reduction of viscosity by the hot fluid [4,24]. A rise in the production rate occurs in the final stage when the temperature in the surrounding area of the producing well increases.

Certain selection criteria are used for selecting this method to perform on any field, which is given in table 1. The choice of fluid can be varied according to its availability, like seawater is injected in offshore fields, which is easily available and is cost-effective. Likewise, the mineralogy of the formation should also be tested. The main problem in this method is the quick heat loss around the wellbore area [24].

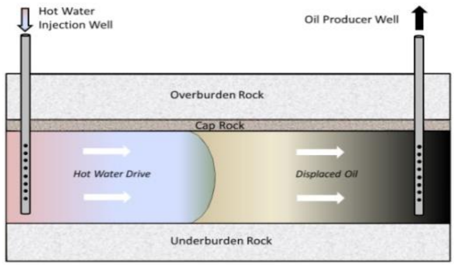

Figure (7): Hot water injection process [23]

4.1.2) Steam drive:

The steam drive is also called stream flooding. It is a pattern drive, similar to water flooding and the performance mostly depends upon the pattern size and geology, as shown in figure (7) [25,26]. In this type of thermal recovery method, high-quality, uninterrupted steam is injected to displace the crude oil towards producing well. The steam zone advances slowly, which causes the oil to move towards the production well due to a reduction in viscosity of the oil [14]. Afterward, the pumping of pressurized steam starts from a few days to several weeks or sometimes to several months. After pumping, the injection is halted usually from few days to several weeks, which permits the heavy oil to separate from the reservoir sand, and then it is artificially lifted. Steam normally travels on the top of the sand, and only gravity helps the oil to re-saturate the steam zone from where it is moving towards the wells. Usually, the recovery factor of the steam flooding method is 50 to 60% of the OOIP, dependent on well patterns and geological conditions [25,27]. Excessive heat loss, steam override, and adverse mobility ratio are the common challenges in steam flooding [25,26]. In addition to this, there is a certain limitation of this process, like it is not applicable in carbonate rocks and usually applicable in sandstones having high permeability. Prevention of sand plugging, steam fingering, and improving steam displacement efficiency are the key impediments to steam flooding success [28–30]. Certain selection criteria are used for selecting this method to perform on any field, which is given in table 1.

4.1.3) Cyclic steam injection:

It is one of the most effective recovery methods and was first applied in the late 1950s, also known as steam soaking [7,31]. In this type of thermal recovery, steam is injected in varying intervals trailed by a period of production, as given in figure (8). Both injection and production occur in the same well [32]. Actually, this method of recovery is divided into three or three steps. In the first step, steam is injected into the well (for almost a month) [32–34]. The well is then shut down for some time (from a week to two); this particular time interval is also called the soaking period. Finally, the well is put on production. This method is also called the huff and puff process because of the periodical injection of steam. In the start, high production rates can be noticed, and it continues for some time and then decline after several months [14,31]. This whole process is continued until the recovery is economical. The quick payout makes this method very attractive. The recovery factors are up to 10-40% OIP [31,35], the recovery factor is lower than other thermal recovery methods due to significant heat loss [36]. Like other recovery methods, one of it's major limitations is that a substantial amount of oil can be left in the reservoir. Furthermore, this method is not effective in thin-layer reservoirs [37]. In a distinction, this process is applied in a fracture pressure [38], but this process becomes very complex and complicated when communication develops among the wells [14]. Screening criteria for selecting cyclic steam injection is given in table 1.

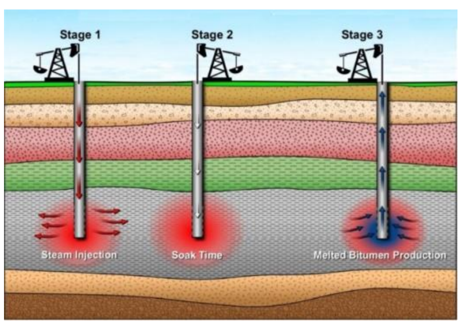

Figure (8): Cyclic steam injection, adopted from [39].

4.1.4) Steam assisted gravity drainage:

Steam-assisted gravity drainage (SAGD) was first developed by Butler for the in-situ combustion of Alberta bitumen [40]. It is the best example of steam injection, and the schematic diagram is shown in figure (9a). SAGD is specialized for specific heavy oil reservoirs using horizontal wells. This process mostly depends on the gravity segregation of steam while using a pair of horizontal wells, as shown in the picture (from Thomas paper) [14]. The distance between the two horizontal wells is from 5 to 7 meters and vertically separated from each other at a distance of 15 to 20 feet. In this pair of parallel horizontal wells, the upper one is used for injection, while the lower one is used for production. Actually, the steam rises to the top of the formation and forms a heat chamber, which results in a high reduction in the viscosity, which in turn mobilizes the in place bitumen and drain downward by the gravity and is captured by the producer well placed in the bottom of the reservoir [14,41,42]. If the viscosity of the crude oil is too high, then steam is circulated through both wells. After this, only steam is injecting in the upper well a while the lower one is just used for production. Special consideration is needed for the spacing. It must be 5 to 6 meters [40]. The thickness of the reservoir formation also affects the efficiency of SAGD, its efficiency increase with the thickness of the oil layer [43], while it is considered uneconomical when the thickness is less than15 m [44]. Shale thermal fracturing and gravity segregation make SAGD most effective and efficient, resulting in 60 to 70% of OOIP recovery [31]. The reservoir characteristics and other factors of considerations are listed below in table 1.

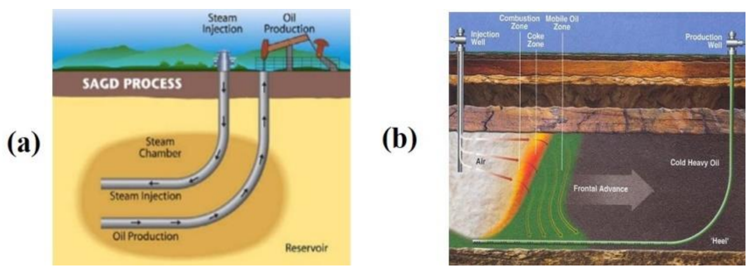

Figure (9): (a) Steam assisted gravity drainage process [45], (b) Schematic diagram of in-situ combustion [46].

4.1.5) In-situ combustion:

This method of recovery is also known as fire flooding. In this method, air or oxygen is injected into the well to burn a percentage (10%) of the in-place oil to generate heat [47–50]. The schematic diagram of in-situ combustion is given in figure (9b). High temperatures in the range of 450 to 600 ^{o}C are generated in a narrow zone, which results in a high reduction in oil viscosity that can be noticed in the vicinity of the combustion zone. The thermal efficiency of this process is very high because of the relatively small heat loss. Common problems of this method are toxic gas production, severe corrosion, complex process, demanding capital investment, gravity override, and very hard to control the combustion front [13,14]. In situ combustion is tested in many parts of the world, a few of them were economical, but none of them was advanced to a commercial scale [14]. The selection criteria of this method are given in table 1. There are two variations in this technique, the first one combustion of forwarding combustion and water flooding (COFCAW), while the second one is reverse combustion, in which the well is fire, which will be ultimately become a producing well. Meanwhile, the injection of air is a shift to the nearby well. However, no successful reverse combustion trial in any field is recorded yet [51,52].

Type	gravity API	v Cp	Φ %	So %	k mD	Net Thickness m	Depth ft	Temp T	Formation Type
Hot Water Flooding	12-25 Avg 18.6	8000 -170 Avg 2002	25-37 Avg 31.2	15-85 Avg 58.5	900-6000 Avg 3346	>20	500-2950 Avg 1942	75-135 Avg 98.5	Sandstone
Steam Drive	8-30 Avg 14.5	5E6-3 Avg 32971.3	12-65 Avg 2	35-90 Avg 66	1-15000 Avg 2605.7	>20	200-9000 Avg 1643.6	10-350 Avg105.8	High porosity sand /Sandstone
In-Situ Combustion	10-38 Avg 23.6	2770-1.44 Avg 504.8	14-35 Avg 23.3	50-94 Avg 67	10-15000 Avg 1981.5	>10	400-11300 Avg 5569.6	64.4-230 Avg 175.5	Carbonate /Sandstone
SAGD	9-13.5	4,700-200000		40-66	>250	>10	1000-4500		High porosity sand /Sandstone

Table (1): Reservoir properties needed for the successful operation of thermal EOR.

5) Designing EOR Project:

Designing any EOR project includes screening criteria, laboratory tests, volumetric calculation, technical studies, and Field trials. Details of all the steps required for a successful EOR are given in figure (10) and chart (1). Some of the steps can be omitted because of the available data by using reservoir analogy when the neighboring reservoir has undergone EOR and having the same properties as the given reservoir.

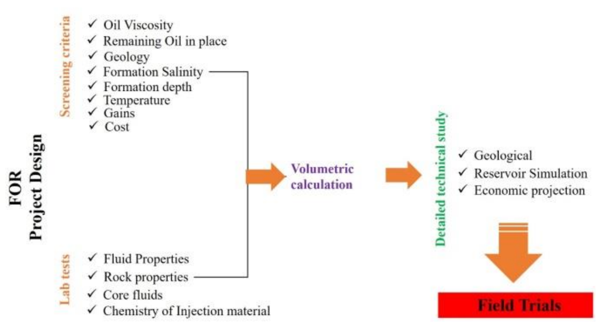

Figure (10): basics steps for designing an EOR project.

Time	Steps for Successful EOR.		
	Reservoir Modeling	Engineering Data	Economics
↓	Analogy Data	Field Selection EOR Process	Screening
	Analytical Tools	Geological Studies	
	Course Simulation	Design Parameters Lab Data, Field data	Detailed Economics Model
	Fine simulation	Pilots Field Testing Project Implementation	

Table (2): Steps for successful EOR.

6) Economic Evaluation:

Before implementing any EOR method, it is necessary to study its economic benefits. Mostly, in all forms of thermal recovery methods, we need to inject heated fluid. So the injection cost of fluid should be calculated separately, and this cost can be expressed as a unit such as the capital plus the operating cost of cold water, hot water, steam, compressed air, etc. When having some doubts or not clarity so just put contractor delivering cost it at the wellhead. Intellectual states that the operations such as producing and handling oil in thermal drive as the same as we do in the primary phase of production. Furthermore, there might be some increments in overall cost per well, but the wells being more productive, and thus the production costs per barrel should be roughly the same. The injection process adds reserve to the total reserve in place. It is, therefore, appropriate to calculate or to report the injection cost in the capital cost per unit of extra producing oil. So the unit price of the reserve can be usefully compared with the market price of primary or initial reserves. Injection per unit of extra oil is a key factor in deciding any type of EOR project and evaluating the cost estimates.

7) Conclusion:

The most efficient technology for the production of heavy oil recovery is TEOR. By successfully designing the EOR techniques, the recovery can be increased up to 75%, depending on the type of EOR technique. With each passing year and induction of new technologies global EOR market is growing, and it exceeds 16 billion barrels. Similarly, the revenue generated from these resources is in excess of 80 billion US dollars. This paper focuses on TEOR, which is the dominant EOR technique. It shares is around 60 % of the total EOR production. The oil production using TEOR reached to 995.9 x10^3 barrels /d in the year 2016. Among the TEOR stream drive is the most successful method, which is successful employed in various fields around the world and showed good results compare to other TEOR techniques. Currently, steam flooding and in-situ combustion are developed for full-field applications. Meanwhile, the SAGD techniques have also successfully completed the pilot tests and can be utilized at a large scale.

Overall, this paper presented the advantage and disadvantages of all TEOR techniques. It is needed to decrease the heating cost, enhance the efficiency of TEOR techniques also, and the researchers need to work on how to operate TEOR in a controlled manner. The forecast of EOR methods is given below in figure (11), which shows that other EOR techniques are also getting pace, but TEOR is still a principal method.

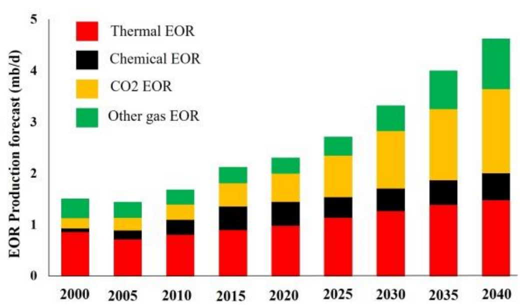

Figure (11): EOR techniques production forecast [53].

Nomenclature:

EOR: Enhanced Oil Recovery
OOIP: Orignal Oil In Place
EIA: US, Energy Information Administration
TEOR: Thermal Enhanced Oil Recovery
SAGD: SteamAssissted Gravity Drainage
COFCAW: *Combustion of Forwarding Combustion and Water Flooding*
bbl: barrel
K: Permeability
Φ: Porosity

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