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**QUESTION**

Discuss the following types of thermal recovery with annotated diagrams

**WHAT IS THERMAL RECOVERY**?

As reported in the literature, thermal EOR methods are very important and are widely applicable worldwide. Different types of aqueous methods, which are related to water and its derivatives, are widely used over the last few decades. Processes such as cyclic steam stimulation (CSS) and hot water injection, ISC, hot water, and steam ﬂooding and steam-assisted gravity drainage (SAGD) are the most prominent thermal EOR techniques. The other thermal EOR techniques are the use of non-aqueous methods, which supply the thermal energy to the reservoir without injecting water or its derivatives. Such methods include electric heating and electromagnetic heating. The non-aqueous methods are rarely applicable due to technical constrains and environmental issues, subsequently, future work is required order to make the non-aqueous methods more competitive. A recent development toward that involves the combination of the non-aqueous methods with water or solvent injection. Details about thermal EOR methods will be presented in this paper later.

1. **STEAM-ASSISTED GRAVITY DRAINAGE**.

 In the case **of SAGD**, steam at high pressure is injected continually in a horizontal well to provide thermal energy in the well that reduces the oil

Viscosity. This method is best suited for heavy oil extraction in carbonate reservoirs as reported by Hosseini et al. These are mostly naturally fractured reservoirs but only few studies had been conducted in this area. It is considered highly promising technique and it needs more work and research in order to fully attain its potentials. The effect of fracture properties like fracture orientation, fracture spacing, and fracture permeability on the SAGD performance in naturally fractured reservoirs was studied by Hosseini et al. through experimentations and modeling using CMG-STARS thermal simulator. Experimentally, the combination of the SAGD and multiple thermal ﬂuids-assisted gravity drainage process was also tested by the authors. They reported that fracture orientation affects the steam expansion and oil production from the horizontal well pairs. It is also reported that horizontal fractures have a negative effect on oil production, while vertical fractures have a higher production rate compared to its horizontal counterpart. Similarly, increase in fracture permeability was shown to positive positively improve oil production. Furthermore, they reported that an increase in fracture spacing enhances oil production, because in wider fractures, the steam accompanied with its thermal energy will take more time to diffuse into matrices and provides thermal energy to the entire reservoir. Literature is available on the use of an optimization simulation method called proportional-integral-derivative coefﬁcient to optimize the steam injection process while achieving higher oil production and lower steam-oil ratio. Process integration tools have been applied in some instances to improve efﬁciencies in the SAGD process. This was conducted by Forshomi et al. in which a distributed efﬂuent treatment system was designed to improve the economics while tackling environmental issues. Different conﬁgurations of water treatment technologies and steam generation options in SAGD were employed to target an optimum process. An energy cost savings of up to 19.5% and 12% in water treatment system of SAGD operations was reported by the authors simply by diverting ﬂows in wastewater streams. Thermal integration of the system was, however, not considered in the study. Artiﬁcial intelligence approaches are used for predicting SAGD recovery performance and in assisting conventional SAGD analysis. In the ﬁeld, SAGD is considered the most popular in the oil sands and extra-heavy crudes of AB. The use of a hybrid version of SAGD (e.g., injection of solvent with steam) is, however at its pilot stage. Some old statistics showed that, in 1993, worldwide production from cyclic steam and steam drive was more than 700,000 bbl/day. This amount had increased to 919,917 bbl/day in USA, Canada, Brazil, and Norway in 2013. However, the Steam-based applications are limited to shallow reservoirs, which are less than 3000 feet deep. Horizontal wells are always used in SAGD and it is proven to be successful in the ﬁeld and many studies are available in the literature in this regard. Recently, vertical well as alternative method for SAGD had been developed. The well consists of two strings, the ﬁrst one is used as a producer on the bottom and the other is used as an injector on the top,with the distance between injector and producer perforations being changed gradually. It is reported by Suranto et al. That increasing the steam injection rate directly increases production rate. Furthermore, their results showed that vertical well SAGD can improve the drainage radius to 85 m using both multilevel injector and multi-level injection rate. However, good performance of the multi-level injector can be achieved if the injector perforation is moved gradually. They recommended using vertical well SAGD in the case of thick reservoir. Vertical wells method has advantages such as;

1. decreasing cumulative steam oil ratio,
2. Increased drainage area
3. Enhanced steam chamber volume; as a result, it can increase the efﬁciency of steam injection.



1. **CYCLIC STEAM STIMULATION**.

 Cyclic steam stimulation (also known as huff and puff method) involves three stages, which are namely: injecting of steam, soaking period, and production of oil. In this technique, steam is injected into the well for a period of time to raise the oil temperature resulting in reduced oil viscosity, which facilitates its mobility. After ensuring that there is enough amount of steam in the well, it is shut-in for a period of time extended from few days to few weeks to make sure that the thermal energy is spread out well. Subsequently, the well can produce oil due to the pressure generated by the injected steam. The production continues to a point at which its rate decreases signiﬁcantly to warrant cycle restart as the oil cools with time resulting from thermal energy losses. The same previous steps are repeated again and again, but naturally the effectiveness of this process decreases after few cycles. Li et al conducted experimental and numerical analysis for the huff and buff process using CO2 instead of steam; it was found that at the ﬁfth CO2 cycle, the recovered oil reached 31.56%. Every EOR method has its effectiveness, which is measured by the amount of oil recovered percent of the total capacity of the well. The maximum recovery by CSS is relatively low (around 10–40% of the

OOIP compared with SAGD which has higher recovery average). Smart water, which can be designed by optimizing the chemical composition of injected brine, has been carried out by Jalilian to see its effect on pure limestone carbonate rocks. Increasing the sulfate ion concentration and reducing the total salinity, Jalilian found that the oil recovery factor has increased by 14.5%. Low-salinity water ﬂooding has a weak effect on the oil recovery less than 2%.In CSS technique, a single well is used interchangeably as a steam injector well and as an oil producer well. Since the steam used in the process, for practicability, is generated on the surface, to be injected using surface lines and wellbore, thermal energy losses from these surfaces need to be considered. Subsequently, limiting parameters such as reservoir depth, pressure, and lithology have to be taken into account for an efﬁcient oil recovery using steam injection. The steam, after injection, is allowed enough time to soak (soaking time) due to which its high temperature (200–300 °C) helps reduce oil viscosity while the high pressure (about 1 Mpa) fractures the reservoir rock. As the soaking time lapses, with oil ready for production, the production time follows when oil can be produced at high rates. This production continues, until eventually it begins to rapidly decrease meriting another steam injection that will trigger another cycle. The three stages of this cycle can be repeated several times within the limiting case of technical and economic viability. The injection and soaking times normally takes days or weeks while the production time generally takes weeks to months. An optimum injection time and extension of the soaking time depend on mechanical and operational considerations while the oil production rate limits the production time. From the production viewpoint, it is vital to determine the number of cycles that will achieve maximum oil recovery by the process, as it generally becomes less efﬁcient with increasing number of cycles. Cyclic steam stimulation process has been widely employed for EOR since its accidental discovery in 1959 in Eastern Venezuela by Shell Oil Company of Venezuela when testing a steam drive. It has been successfully used in various heavy oil ﬁelds in

Canada, Venezuela, Brazil, and in California, USA, where it is used as a ﬁrst stage before continuous steam injection. The main advantage of cyclic steam stimulation is a rapid pay-out during early production. Its percentage of oil recovery visa-visa OOIP is however comparatively low ranging from 10 to 20%. To improve this low oil recovery in CSS, enhancements such as the use of horizontal rather than vertical well, the use of chemical additives in the steam, and hydraulic fracturing are introduced with the process. Consequently, studies focusing on the optimization of chemical additives in the steam and fracture design are common in recent literatures. Such enhancements were reported to achieve improvements of up to 40% of OOIP, a recovery that is still lower than its other thermal EOR counterparts. Wu et al. studied the effect of gas break through (GBT) with cyclic steam and gas stimulation in an offshore heavy oil reservoir. They introduced a new concept for breakthrough degree and named it gas breakthrough coefﬁcient; this coefﬁcient depends on some parameters such as reservoir thickness, permeability, and the injection strength and injection production pressure. Another consideration in CSS is the steam generation process for the system. Early on, some oil ﬁeld made use of the produced crude oil in steam generators through direct combustion. Environmental as well as economic considerations led to the use of other fuels like natural gas in the steam generation process over time. Those same considerations resulted into targeting other sources like coal, biomass, and solar energy with each having different economic and environmental footprint. Apart from the choice of energy source in steam generation, options of using combined power cycle for more efﬁcient energy utilization were considered in some occasions. The use of natural gas, for instance, in a cogeneration power cycle to produce both electricity and steam for CSS has been actualized in Californian oil ﬁelds with an installed electrical generating capacity of about 2000 MW. Use of solar energy in concentrating solar trough for steam generation to be used in EOR systems is another approach that promises huge environmental beneﬁts. Another approach involves the combination of CSS with air injection in a process called air assisted cyclic steam stimulation. This method is used for heavy or ultra-heavy oil reservoir after CSS became non efﬁcient, where it can compensate for the low reservoir pressure, poor steam sweep efﬁciency, and high water cut. Wang et al conducted a study on ultra-heavy oil reservoir of

Liaohe oil ﬁeld (China) using a numerical technique validated with experimental work and their study revealed that adding air to

CSS can improve oil recovery with 11% increment in oil production. Another numerical study in air assisted cyclic steam stimulation had been done by the same authors .It was reported that the rate of oil recovery is better than CSS besides improvement in energy efﬁciency and decrease in CO2 emissions. Leaute et al patented a new idea of LASER-CSS, which is summarized as mixing liquid hydrocarbon with the injected steam instead of injecting it alone in front of the steam stimulation cycle and that will improve the recovery efﬁciency. Lu et al studied the in situ formed oil water emulsion droplets transport and plug in porous media. One of their conclusions was that higher pressures can displace larger size of oil water emulsion droplets out of the pore throat and reduce their retention volumes.



1. **HOT WATER FLOODING.**

Hot water and steam ﬂooding is a thermal EOR technique, which requires a huge amount of water to be injected onto high viscous oil in the well to raise its temperature .3D sand packed displacement model and experimental work have been developed to simulate the water ﬂooding and immiscible CO2 ﬂooding processes .In addition, enhanced heavy oil recovery by immiscible CO2 injection is found to be limited by early gas breakthrough due to, mainly, the unfavorable mobility ratio between CO2 and heavy oil. As reported in literature, hot water

ﬂooding is less efﬁcient than steam injection due to the lower thermal energy content of water. On the other hand, the driving power of the water is higher than that of the steam. The steam injection process involves continuous steam injection into an oil bearing porous medium. This results in the information of an almost constant temperature, slow advancing steam zone around which the viscosity of the oil is drastically reduced thereby increasing oil mobility. This highly mobilized oil within the steam zone is subjected to a vaporizing gas drive as a result of which the initial oil saturation is reduced to as low as 10%. Mohebbifar et al used Nano and biomaterials simultaneously; they used three types of biomaterials including bio surfactant, bio emulsiﬁer, and bio polymer besides two types of nanoparticles including SiO2 and TiO2 at different concentrations as injection ﬂuids. The highest efﬁciency of 78% was observed while injecting one pore volume of biopolymer and SiO2 nanoparticles. Steam ﬂooding has a typical recovery factor ranging from 50% to 60% of OOIP. However, being a pattern-driven process, its performance will ultimately depend on the pattern size and geology. Experimental study has been carried out using steam ﬂooding for reservoir with ultra-heavy oil as in AL-1 Block, Shengli Oilﬁeld, China .A numerical study conducted on steam injection in heavy oil revealed that it improves oil recovery up to 60% during a ﬁxed period of time, and that only 30% of OOIP can be recovered by hot water injection method. Hossain developed dimensionless scaling parameters for thermal ﬂooding in porous media. He proposed numbers that measure the thermal diffusivity and hydraulic diffusivity of a ﬂuid in a porous media. Another study focusing on heterogeneous heavy oil ﬁeld located in southern Oman had been conducted to establish the optimum thermal energy transfer conditions via steam injection in the reservoir .A CMG-STARS model was developed in the study to simulate steam injection process with the valve control of steam trap subcooled. They concluded that the valve control gives a faster distribution of thermal energy after steam injection. In addition to that, it gives higher production with low amount of steam required. The use of Nitrogen thermal foam ﬂooding to overcome steam override and steam channeling problems was also reported in the literature .It was observed that using nitrogen required.

The use of Nitrogen thermal foam ﬂooding to overcome steam override and steam channeling problems was also reported in the literature. It was observed that using nitrogen foaming can increase the displacement efﬁciency of steam ﬂooding from 43.30% to 81.24% in single sand-pack experiment. The economic as well as technical success of steam ﬂooding process highly depends on the steam generation unit.

Consequently, efﬁcient operation and maintenance of the steam generators that takes into account the fuel used in the generators, its availability and cost, as well as feed water treatment and cost are highly important. From operation viewpoint, the two most important challenges in steam ﬂooding are the concerns with steam override and that of excessive thermal energy losses. The thermal energy loss can be attributed to the losses in surface lines that transfer the steam from its generating unit to the injection wells. Other losses occur during steam passage into the wells since the steam temperature is much higher than geothermal temperatures. Another source of losses occurs inside the reservoir from the heated portion of the formation to the adjacent lower temperature regions.



Figure **Error! No text of specified style in document.**:1diagram showing the thermal hot water



Figure **Error! No text of specified style in document.**:diagram showing thermal hot water injection