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Solar generated steam injection in heavy oil reservoirs: A case study

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ABSTRACT

Combination of solar generated steam technology and enhanced oil recovery (EOR) techniques have attracted a great deal of attention due to its positive impact on economics and on the environment. Solar steam project has already proven itself as it can reduce both gas consumption and CO_2 emissions by up to 80%. However, operational issues as well as geographical factors (i.e. terrain suitability, drill sites and future field development plans) may affect solar EOR operations. In this study, a heavy oil field in Southeast Turkey was evaluated to find whether solar EOR is technically and economically feasible. Operational data such as injection rate, steam temperature and steam quality were determined by using a numerical model. A solar collector system was designed and combined with the steam injection method. Results indicated that direct normal insolation (DNI) of the oil field location was not high enough to maintain continuous steam injection. In order to sustain continuous steam injection natural gas burner back-up system must be used when DNI is intermittent to maintain required steam especially during winter nights. Economic analysis of combined system showed that fuel saving cannot compensate the initial cost of solar project with current oil price.

1. Introduction

The most promising technique in enhanced oil recovery (EOR) methods is thermal injection which shares 50% of the EOR market. Thermal methods are appropriate for heavy oil reservoirs with API gravities changing from 8° to 22° API and oil viscosities between 100 and 10,000 cP. The basic principle of thermal methods is to heat the reservoir causing an in increase of oil temperature that in turn results in reduced viscosity allowing the oil flow more easily. Steam injection method usually faces several challenges including high installation and maintenance costs. High costs and greenhouse gas restrictions lead the companies to find a way to reduce environmental impact and investment cost. Concentrating Solar Power (CSP) in thermal EOR project (solar EOR) is an excellent idea that was born as a result of these challenges. The main advantage of solar EOR is its ability to produce considerable amount of steam for large scale projects economically and its environmentally friendly nature. Although the concept of solar EOR has been around since late seventies [3] and early eighties [2], the first project that brought the solar thermal power and steam injection together was developed only recently in California, USA and Oman [7].

The major challenge in a solar EOR project is the location of the oil field. As opposed to CSP for conventional electricity where solar arrays can be sited at the cleanest (i.e. low peak and average wind speeds, low dust and particulate levels and no blowing sands) and highest possible radiation areas, in solar EOR location is determined by the location of the oil field where sub-ideal solar radiations and harsh environments may exist. Employed temperatures and steam pressures may vary widely. Typically the operating temperature of solar EOR must be designed to match steam conditions of the oil field steam distribution network. It is generally preferred to employ water sand steam injection rates of from about 1360.777 kg/hr (3000 lbs/hr) to about 18,143.693 kg/hr (40,000 lbs/hr) at temperatures between 280 °C and 330 °C [10]. As a general rule, steam pressure should exceed the formation pressure by from about 3.447 bar (50 psi) to about 68.94 bar (1000 psi), but should not exceed the formation break-down pressure.

Numerical simulations of solar generated steam injection for heavy oil recovery have been studied by Kovscek and Agarwal [17] and Yegane et al. [18]. In both of these studies, it has been assumed that steam was generated by solar generators for a fixed period then gas-generated steam was used for the second period mimicking a daily cyclic fashion without considering seasonal variations. Unfortunately, integration of the solar field with the available direct normal irradiance (DNI) has not been considered. Both studies concluded that solar generated steam injection solar

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generated steam injection.

Turkey is one of the countries that have heavy oil reservoirs and abundant sunshine areas. This study aims to demonstrate whether solar EOR is feasible or not in a heavy oil field located in Southeast Turkey. First, solar field design based on the steam injection criteria will be presented. Then, in order to evaluate the feasibility of solar generated steam injection method, economic analysis will be introduced. The paper will be concluded with discussion of solar EOR case study.

2. Solar generated steam injection model

This section reports the developed process simulation of solar generated steam injection model, the concept of integration of the solar field, the design of the concentrating solar field and a resource assessment of the available direct normal irradiance (DNI) in the oil field.

2.1. The reservoir

The Bati Raman field located in southeast Turkey, which is known as the largest oil field in Turkey, contains very viscous and low gravity heavy oil (9.5°–13.5° API) in the Upper Cretaceous Garzan limestone. The geological structure is an elongated asymmetric anticline of about 17 km long by 4 km wide [1]. The height of the oil column is about 210 m with a 100% Sw OWC at −630 ms. Due to the fact that primary recovery factor is limited to only 1.5% of more than 300 MM m^3 oil in-place, several EOR techniques had been proposed and tested including water flooding, steam flooding and CO_2 injection in pilot level in the 70s and 80s [19]. Based on the success of the lab tests and vast amount of natural CO_2 available in a neighbor field (Dodan) that is located 80 km away from the field, huff-and puff CO_2 injection started in the early 80s. Due to early breakthrough of CO_2 in production wells, the project was converted to field scale random pattern continuous injection. Two pilot scale steam injection projects have been attempted in the field. The most recent field pilot project consisted of two steam injectors with 90 m separation, one observation well and eleven producers (300 m spacing). Once through steam generator with a capacity of 238.48 m^3/day (1500 bbl/day) cold water equivalent – (CWE) at a pressure roughly equal to 172.368 barg (2500 psig), has been used to inject 158.99 m^3/day (1000 bbl/day) CWE at 124.105 barg (1800 psig) [8].

2.2. Numerical model

A numerical sector model was used to optimize steam injection parameters using CMG STARS (2013), which is a thermal, compositional, chemical reaction and geomechanics finite difference reservoir simulator ideally suited for advanced modeling of oil recovery processes involving the injection of steam, solvents, air and chemicals. The model consisted of $23 \times 22 \times 5$ Cartesian grids with a changing porosity and permeability (Table 1). The steam injection pressure changed between 124.105 barg (1800 psig) and 137.895 barg (2000 psig). A sensitivity analysis was conducted to optimize steam quality (0.50–0.95), steam temperature (279.4 °C – 335 °C) – (535 °F – 635 °F) and steam injection rate 39.75–317.97 m^3/d (250–2000 bpd). In order to consider pressure drop and heat losses in the wellbore with vacuum insulated tubing, a semi analytical model proposed by Fontanilla and Aziz [20] was used. The model considers the variation of steam temperature and pressure due to friction, as well as heat losses by pressure due to friction, radiation, conduction, and convection. Tables 1 and 2 show parameters that were used to describe the steam injection sector model.

The injection pressure was selected as the initial reservoir pressure of 124.105 bar (1800 psi). The steam injection temperature was taken as 327.78 °C (622 °F). Input wellhead steam quality changed between 0.5 and 0.95 using the aforementioned thermal properties. It has been observed that if the injected steam quality is higher than 80% it does not have a significant effect on the oil recovery. More than 11% steam quality reduction is observed in all cases (Fig. 1). Although a higher injected steam quality apparently means more heat for reducing the oil viscosity and more energy for displacing the high density oil from the upper reservoir layers towards the production wells, the extra contribution of a higher injected steam quality is not readily predictable. The major reason is the wellbore heat losses given in Fig. 1. Using a constant input steam quality of 80% steam injection rate sensitivity is studied. It has been observed that when the input flow rate is above 158.99 m^3/d (1000 bbl/day) (cold water equivalent) the steam quality at the well bottom is not affected (Fig. 2).

2.3. Resource assessment of available DNI

Direct normal insolation (DNI) is defined as the radiant flux density in the solar spectrum (0.3–3 μm) incident at the earth's surface perpendicular to the direction to the sun integrated over a small cone tracing the sun [11]. Commercial CSP projects tend to be built in areas with an average annual DNI value in excess of 2000 kWh/m^2/year. In order to evaluate the oil field's DNI choosing representative meteorological data is the first hurdle to be taken in the planning and engineering phase. Typical meteorological year (TMY) procedure is an empirical approach that picks out the most appropriate properties of the months from different years period. For example, all September data in a database that consist of 30 years record are analyzed and the most representative and the most adjacent one is chosen to be built in TMY. The other months are selected using same methodology to obtain the whole year. Five main elements global horizontal radiation, direct normal radiation, dry bulb temperature, dew point temperature, and wind speed obtained from each station are taken into consideration to select 12 months. Other elements may or may not be typical but they are less significant to determine the desired months. On the other hand, in Sandia Laboratories method, the selection is based on nine daily elements: the maximum, minimum, and mean dry bulb and dew point temperatures; the maximum and mean wind velocity; and the total global horizontal solar radiation. Finally, determination of a month is conducted by the examination of the monthly mean and median and the persistence of weather patterns.

Using TMY approach the weather data of the Batman region (i.e. oil field location) was obtained from Meteonorm in TMY2 format. Since there is no weather station in Batman, the interpolation method was used. The radiation interpolation locations are: Diyarbakır (82 km), Elazig Airport (180 km), Van (203 km) and Malatya (273 km). The interpolation is carried out with a 3-D inverse distance model (Shepard's gravity interpolation) [16] (IEA Task 9), with additional North–South distance penalty [15]. Obtained results are summarized in Table 3.

2.4. Parabolic trough concentrating solar collector

A concentrated solar collector consists of a concentrating parabolic mirror to focus the sunlight onto a tube that sits trough the center of it. The tube is a pipe in pipe assembly and the area between the outer glass tube and inner fluid filled absorber tube is usually evacuated but sometimes may be filled with air or hydrogen. The heat transfer fluid (HTF) is pumped through each collector and energy is transferred from the sun to the HTF. The HTF used in this study is Therminol-VP1 that is a mixture of biphenyl