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EXCEPTIONAL ENHANCED GEOTHERMAL SYSTEMS FROM OIL AND GAS RESERVOIRS

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ABSTRACT

A lot of oil and gas reservoirs have been or will be abandoned in petroleum industry. In this study, we pointed out that these oil and gas reservoirs might be transferred into exceptional enhanced geothermal reservoirs with very high temperatures by oxidizing the residual oil with injected air. A concept to generate power from these exceptional enhanced geothermal reservoirs by using geothermal power generation technology was proposed. Using Du84 reservoir in Shuguang oil field, Liaohe, PetroChina as an example, we estimated the possible power and the income that might be generated from such an exceptional enhanced geothermal system.

INTRODUCTION

Recently geothermal HVAC (Heating, Ventilation and Air Conditioning), direct use, and power generation by using hot fluids co-produced from oil and gas reservoirs have been hot topics in cases in which oil and gas are being produced by water injection (Erdlac, *et al*., 2006, 2007; Li, *et al*., 2007; McKenna, *et al*., 2005; Milliken, 2007). The point of this study is different: we focus on abandoned oil and gas reservoirs or those reservoirs in which in-situ combustion technology is being used for enhanced oil recovery by air injection. The residual oil saturation is usually over 30% in many abandoned oil reservoirs. Air may be injected in these abandoned oil reservoirs and in-situ combustion will occur through oxidization. Based on the existing research, the temperature in oil reservoirs under air injection with in-situ combustion could reach over 400^{o}C for light oil reservoirs and over 600^{o}C for heavy oil reservoirs (Moore, *et al*., 2002; Gillham, *et al*., 2003). The oil reservoirs under such temperature conditions may be transformed as exceptional enhanced geothermal reservoirs (EEGS), compared to the normal EGS systems in Hot Dry Rock (HDR) formations. High temperature and high pressure steam can be obtained for power generation using water injection followed by air injection. The efficiency of power generation using the fluids from in-situ combustion reservoirs will be much higher than that by using hot fluids co-produced from oil and gas reservoirs because of the high temperature. In the current study, a heavy oil reservoir, Du84 reservoir, in Shuguang oil field, Liaohe, PetroChina was evaluated to form an exceptional EGS by using in-situ combustion technique for power generation.

MECHANISMS OF IN-SITU COMBUSTION BY AIR INJECTION

Investigation on in-situ combustion began long time ago (1900's). The technique has been applied in the field since the 1950's, particularly for heavy-oil reservoirs (Buxton and Pollcok, 1974; Germain and Geyelin, 1997). Research on reaction kinetics has been carried out since the 1960's (Gates and Ramey, 1958; Bousaid and Ramey, 1968; He, 2004).

Many researchers studied the oxidation of crude oil with air injected in porous media. Their kinetics results confirmed the occurrence of three major types of reactions: (1) low temperature oxidation (LTO), (2) fuel deposition or medium temperature oxidation (MTO), and (3) high temperature oxidation (HTO), i.e., fuel combustion, (Gates and Ramey, 1958; Bousaid and Ramey, 1968; Dabbous and Fulton, 1974). The mechanisms of different types of combustions are discussed briefly in the following.

Low Temperature Oxidation (LTO)

LTO is usually taken place in the beginning of air injection into porous media. This process happens during the stage of combustion when oxygen consumption is incomplete and air channels propagate ahead of the combustion front. The fuel deposited in the combustion front is not sufficient to complete oxidation. LTO results in the production of partially oxygenated compounds. These include carboxylic acids, aldehydes, ketones, alcohols, and hydroperoxides as well as water. Even though significant amount of oxygen is consumed in the process of LTO, little amount of carbon oxides are created. So the stage of LTO is characteristic of either no carbon oxides or low concentration of carbon oxides in the effluent gas. Large amount of oxygen is involved in the partial oxidization reactions. The partial oxidation changes the crude oil properties that are critical to the displacement process. For example, the viscosity and the boiling range are increased. Furthermore, several researchers have shown that LTO reactions could enhance the fuel deposition and change the properties of the fuel and the coked sand (Dabbous, Fulton 1974).

Fuel Deposition

Gates and Ramey (1958) reported another type of oxidation reaction, in which fuel deposition took place between LTO and HTO. This stage of combustion can also be characterized as medium temperature oxidation (MTO). Fuel deposition includes the process of distillation, molecule breaking, and coke formation as oil flows. The mechanism of fuel deposition may be carbon deposition from the fuel (Burger, 1971). Carbon is produced by the following pyrolysis reaction:

$$C_X H_Y = xC \downarrow + \frac{y}{2} H_2 \quad (1)$$

Where the symbol $\downarrow$ indicates carbon deposition. Others assume that oil deposited onto the solid matrix as coke, a heavy residue generated from breaking down of oil:

$$C_X H_Y = C_n H_m \downarrow + C_{x-n} H_{y-m} \quad (2)$$

Experimentally, it was observed that hydrocarbons deposit on the solid matrix. The deposited "coke" is almost insoluble in organic solvents.

Fuel Combustion

One of the important combustion reactions is high temperature oxidation (HTO) or referred as fuel combustion. It involves oxidation of the cracked hydrocarbon residue formed in the deposition process. HTO can be described by the following equations:

$$CH_x + \frac{y}{2} O_2 \rightarrow CH_x O_y \quad (3)$$

$$CH_x O_y + [\frac{2+\beta}{2(1+\beta)} + \frac{x}{4} - \frac{y}{2}] O_2 \rightarrow \frac{1}{1+\beta} CO_2 + \frac{\beta}{1+\beta} CO + \frac{x}{2} H_2 O \quad (4)$$

In the process of HTO, the main products from oxidation are fully oxidized CO_2 and CO. While most researchers divided the combustion process into three stages: low temperature oxidation (LTO), medium-temperature oxidation (MTO), and high temperature oxidation (MTO), the model developed by Mamora (1993) included only LTO and HTO reactions.

The factors controlling the combustion performance have always been of the highest interest. Among the possible approaches to improving the combustion performance are chemical additives such as metallic salts. Burger and Sahuquet (1972) studied the reactions involved in the combustion process via kinetic study of oil oxidation with metallic additives. They observed that the oxidation reactions were at lower temperature and the area under the high temperature peak increased. Fassihi (1981) measured a greater Arrhenius constant in low temperature reactions. Racz (1985) proposed the application of iron pentacarbonyl to catalyze in-situ combustions of oil from Demjen-Kelet field in Hungary for the first time. Racz (1985) also found the oxidation rate increased significantly in the temperature range of 140-200^oC in the presence of iron pentacarbonyl. Shallcross (1991) conducted experiments to modify the performance of in-situ combustion by using water-soluble additives.

Reaction Rate

Bousaid and Ramey (1968) correlated the combustion reaction rate with the fuel content and system pressure and deduced the Arrhenius constant of the reaction. In their experiments, the temperature of the sand matrix was increased at a constant rate, or kept constant. The gases produced from combustion were analyzed to determine the percent of carbon dioxide, carbon monoxide, oxygen, and nitrogen. The rate of oxidation of crude oil in porous medium, *R*, is

$$R = -\frac{dC_f}{dt} = k P_{O_2}^a C_f^b \quad (5)$$

where C_f is the fuel concentration, k is the reaction rate constant, P_{O2} the partial pressure of oxygen and a, b the reaction orders. The reaction constant, k, is a function of temperature and is dictated by the Arrhenius Law:

$$k = A_r \exp(-\frac{E}{RT}) \quad (6)$$

where A_r is the Arrhenius constant, E is activation energy, and R is the gas constant. Substituting Eq. (6) into Eq. (5):

$$R = A_r P_{O_2}^a C_f^b \exp(-\frac{E}{RT}) \quad (7)$$

It has been reported that A_r is a function of the rock surface area (Burger and Sahuquetm, 1972; Dabbous and Fulton, 1974).

THE BACKGROUND OF SHUGUANG OIL FIELD

In this research, we selected Du84 reservoir in Shuguang oil field of Liaohe, PetroChina as an example. Du84 reservoir is located in the slope band in the western of west hollow which is close to the western uplift. It is a part of Shuguang oil field. There are two super heavy oil reservoirs which are the main oil-bearing layers, identified as the *N* Tertiary Guantao formation and the *E* Tertiary Xinglongtai formations. The Guantao formation, which forms a single structure for the North-West lift monoclinic structure, has a stratigraphy angle of 2°-3°. Guantao formation sandstone, developed by alluvial plains aggradation, has poor diagenesis and loose lithology (gravel and conglomerate). Cement has pore contact.

Xinglongtai Formation, which forms a single structure for approximate elliptic monoclinic structure, has a formation tendency as Northwest-Southeast and a stratigraphy angle of 2°-4°. Xinglongtai formation is characteristics of rapid deposition and loose cement; it has stable oil development; the overall connectivity level is more than 85%.

The non-homogeneous coefficients between and inside the oil layers of Du84 reservoir are 2.27-4.67 and 1.41-3.15 respectively. The content of clay in the reservoir is about 7.0% on average. The composition of clay mineral is mainly montmorillonite, followed by illite and kaolinite. Most of montmorillonite is honeycomb / debris-shaped inclusions on the particle surface; illite is patchy / silk shaped weaving-bypass-show in pore spaces, and kaolinite is sustained worm-like fillings in the pores.

Guantao Group's proven oil-bearing area is about 1.4 km^2, proven geological reserves is around 1970 × 10^4t. Guantao is shallow buried with a depth of 530-640 m, the average reservoir thickness is about 106 m and the original reservoir temperature is very low, in the range of 28-32℃.

Xinglongtai Group’s proven oil reservoir area is 376 km^2 and the proven geological reserves is 3,661 × 10^4t, the average effective thickness is about 82.0 m. This formation is also shallow buried, with a depth of 660-810 m. The original reservoir temperature is about 38 ℃.

The overall rock property of Du 84 reservoir is good, with a porosity of 21.6-31% and a permeability of 1.06-1.55 Darcy. The total volume of the reservoir is about 4.5672 × $10^8 m^3$.

Du84 reservoir has been developed for many years using cyclic steam stimulation and has almost entered into the period close to be abandoned. This was why we chose this reservoir as an example. In this study, it was assumed that Du84 reservoir has been abandoned at a residual oil saturation of S_{or}.

THEORETICAL BACKGROUND OF POWER GENERATION

The volume of residual oil left in abandoned oil reservoirs can be calculated as follows：

$$V_o = A \cdot H \cdot \phi \cdot S_{or} \qquad (8)$$

Where V_o is the volume of residual oil left in the reservoir after being abandoned, *A* the area of the reservoir, *H* the average thickness of the reservoir, the average porosity, and S_{or} the residual oil saturation.

The heat energy generated by combustion can be expressed as follows:

$$E_C = m \cdot q \qquad (9)$$

Where E_c is the heat energy generated by combustion, *m* the mass of oil, *q* the calorific value of oil.

The mass is equal to $V_o * \rho_o$ (density of oil), according to Eqs.8 and 9, the heat of combustion can be represented as follows：

$$E_C = \rho_o \cdot A \cdot H \cdot \phi \cdot S_{or} \cdot q \qquad (10)$$

The heat can be recovered from oil reservoirs after the oil is burned through the air injection. However, it is almost impossible to recover all the heat energy in oil reservoirs by using either binary power generation technology or other methods. Assuming the value of the heat recovery factor is η, the power that may be generated at the surface is calculated as follows：

$$W = E_C \cdot \eta \qquad (11)$$

Where *W* is the power that may be generated at the surface.

RESULTS AND DISCUSSIONS

Using Du84 reservoir in Shuguang oil field as an example, we calculated the power and the possible income that might be generated by in-situ combustion in oil reservoirs through air injection. Figure 1 shows the results of the power.

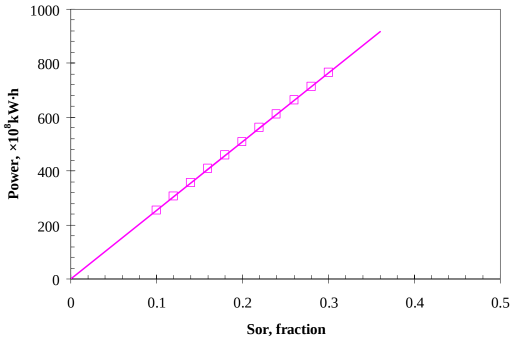

Figure 1. Power generated by in-situ combustion in oil reservoirs through air injection (assuming energy recovery factor η=20%).

The density of the heavy oil from Du84 reservoir was about 900-1000 kg/m^3, we used the average value of 950 kg/m^3 to calculate the power in Figure 1. The calorific value was 39.36-41.03 MJ / kg, and we used the average of 40.195 MJ / kg. It was assumed that energy recovery factor is equal to20% in Figure 1.

One can see from Figure 1 that the power might be generated by in-situ combustion in oil reservoirs through air injection is very attractive. It is reasonable that the greater power could be generated in oil reservoirs with higher values of residual oil saturation.

Figure 2 depicts the results of the equivalent standard coal of the power generated by in-situ combustion in oil reservoirs (see Figure 1).

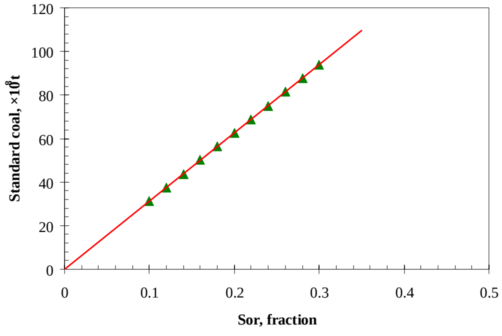

Figure 2. Equivalent standard coal of the power generated by in-situ combustion in oil reservoirs through air injection (assuming energy recovery factor η=20%).

The power price in China was about 0.5 Yuan /kW.h, the exchange rate between Yuan (RMB) and American dollar was about 7.3 (1 dollar=7.3 Yuan). With these data, the income was calculated according to the power shown in Figure 1 and the results are plotted in Figure 3.

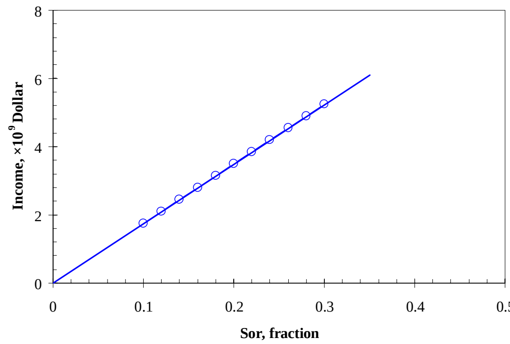

Figure 3. Income by power generation using the heat obtained from in-situ combustion in oil reservoirs through air injection (assuming energy recovery factor η=20%).

Billions of dollars could be made from oil reservoirs which might be abandoned according to the present technology and production criteria.

The approach proposed in this study to estimating the power that might be generated from the exceptional enhanced geothermal systems made from oil reservoirs is very simple and may not be accurate enough to conduct actual engineering design. However this method may be used to initially screen candidate oil reservoirs for exceptional enhanced geothermal systems.

Note that there are also some disadvantages in the cases of in-situ combustion. For example, the content of CO_2 is very high in steam.

One question arises to generate power from EEGS: are the current geothermal power generation technologies suitable? The main methods to generate geothermal energy to electricity are: 1) flash; 2) binary cycle; 3) screw expander; 4) integrated system. Because the fluids produced from EEGS are very complicated, including a large amount of CO_2, and other non-condensate gases, only the binary cycle method may be used to generate electricity in EEGS. By choosing binary cycle method, it is not necessary to separate non-condensate gases from steam before electricity generation. Note that binary cycle is usually used in cases in geothermal resources with low temperatures. This should not be a problem if water is used to substitute the frequently-used second working fluid with low boiling point. Figure 4 shows a proposed schematic of power generation from exceptional enhanced geothermal systems.

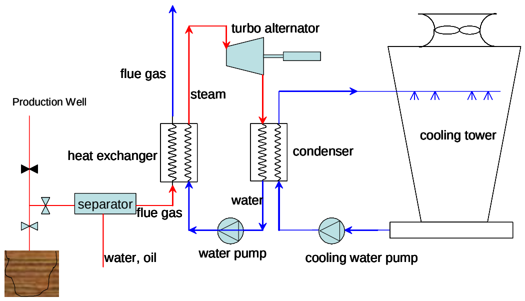

Figure 4. Schematic of power generation from exceptional enhanced geothermal systems.

Note that the only difference from a traditional binary cycle technology in Figure 4 is that the second working fluid is water instead of liquids with low boiling points.

CONCLUSIONS

A concept to generate power from abandoned oil and gas reservoirs by using geothermal power generation technology was proposed. The main idea was to inject air into oil or gas reservoirs which might be abandoned based on the present rules of development. The oil reservoirs could be transferred into enhanced geothermal systems because the reservoir temperature could be raised up to about 600^{o}C by the in-situ combustion. Then the heat energy could be recovered using the state of the art geothermal power generation technology.

Using Du84 reservoir in Shuguang oil field as an example, the power and the possible income that might be generated from such an exceptional enhanced geothermal system were calculated.

Geothermal industry is embracing the present boom in power generation. At the same time, longevity or sustainability of this boom is worried about. We speculate that the geothermal industry will boom much longer based on this study.

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