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Exploitation and Utilization Technology of Geothermal Resources in Oil Fields

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ABSTRACT

There are plenty of geothermal resources in oil & gas sedimentary basins. Under the condition of short supply of energy and rapid development of new energies, geothermal resources in oil & gas fields raise attention. Based on the analysis of the geothermal resource in an oil & gas field, the possible means of coproduction of geothermal fluids from an oil & gas field was discussed. Considering the existing low- and medium- temperature cogeneration technology, the feasibility of using low- and medium-temperature geothermal resource from an oil & gas field to produce power was analyzed. With the characteristics of geopressured geothermal resource, the potential of using geopressured geothermal water flooding in heavy oil reservoir to improve oil recovery was also investigated. From these studies, it is concluded that sustainable development of oil & gas field and efficient utilization of new energy can be achieved through the "win-win" cooperation between oil & gas production and geothermal exploitation based on the existing infrastructure, technology, experience, and reservoir information in the oil field.

1. INTRODUCTION

With the growing demand for energy and the increasing environmental issues caused by traditional fossil fuels, development and utilization of renewable energy is becoming an important task for the government to facilitate sustainable development. Due to its large reserves and small environmental impact, geothermal energy is considered as one of the important renewable energies to be developed and utilized by each country. Compared with other renewable energies, such as wind and solar, geothermal energy has the characteristics of higher reliability and sustainability, lower carbon footprint and maintenance cost. However, its higher initial investment cost and longer investment payback period restrict its development and utilization.

According to the formation theory of oil and gas, usually there are rich geothermal resources in oil and gas sedimentary basins. With the existing oilfield infrastructures, mature production technologies and rich reservoir data, it provides a promising opportunity to develop and utilize geothermal energy in the oilfield. Also, the development and utilization of geothermal energy has the potential to extend the oilfield's life and increase its ultimate oil recovery. Therefore, the exploitation and utilization of geothermal resource in oilfields shall be a "win-win" project.

2. TYPES AND DEVELOPMENT METHODS OF GEOTHERMAL RESOURCES IN OIL FIELDS

Co-produced geothermal resources and water-soluble-gas geothermal resource are the two main geothermal resources in oil fields (Zhu and Shi, 2011; Chang and Liu, 2003). Co-produced geothermal resource comes from the hot fluid produced from the oil wellbore. During the daily production in an oilfield, a large volume of waste and hot water is produced with oil, especially in high water cut period. This resource has been neglected by oilfield developers in the past, but now it gains awareness. In such oil fields, the existing resources can be used for oil and geothermal production. It is estimated that the recoverable heat energy resources amount to 425×10^{18} J only in Daqing, Liaohe and Huabei oilfields (Wang, et al,2014).

There are several modes to develop and utilize this co-produced geothermal resource: (1) Co-production of "oil-geothermal-electricity" using producing wells. The produced heat can be used to maintain temperature for oil-gas gathering and transportation system or supply heat for local workspace or local residents, and the electricity can be supplied to the field for artificial lift or enter into local grid for sale. This is the best mode to utilize the geothermal resource in oifield, since it only requires the investment to install some power generation and/or heat exchange equipment. The oilfield developed with water-flooding and produced-water reinjection is the best candidate for this mode. (2) Co-production using the wells at their end of life or at low production. For such oil wells, it can maintain economic production at a certain oil production rate, but it will become uneconomic when the produced water increases too much. Under this scenario, transferring it into co-production mode will generate additional gains. Geothermal power generation usually needs plenty of produced water, so such wells should be retrofitted to increase flow rate to meet the requirements. Comparing with the first mode, their cost is higher. (3) Drilling new wells with an oil and gas company. When the drilled well produces too much water and cannot produce oil at economic levels, it can be re-completed into geothermal a well to maximize water production and generation capacity. The cost of this mode is the highest. (4) Transforming abandoned wells into geothermal wells or retrofitting the reservoir into an enhanced geothermal system is another effective way to exploit geothermal resource in oil fields.

In some scenarios, the reservoir water was trapped between impermeable shale formations and isolated by subsidence and rapid burial. It forms a geopressured resource. The geopressured resource have high temperature, high pressure gradient, and often contains dissolved natural gas (methane). Sometimes it is also called water-soluble-gas geothermal resource. The reserves of dissolved natural gas in such reservoir are big. In the Gulf of Mexico, the total amount of dissolved natural gas in geopressued geothermal reservoir is estimated to be between 3000 to 46000 TCF (Griggs, 2005; Ganjdanesh et al., 2012). In Tanggu geopressured geothermal field of Tianjin, the water layer in Shahejie group sha-3 formation is rich in methane gas and the well T13 showed that the methane component is about 92.33%; the gas dissolved in hot water in Dongying formation is estimated to be between 0.5 to 1 m^3/m^3 (Yang et al., 2010). It shows that the water-soluble-gas geothermal resource can often be found in oil and gas basins. The three energies, namely thermal, hydraulic and chemical energy (methane gas), can be harvested from this resource. During the development of an oilfield, to improve oil recovery, the water layers are prevented from being perforated, and the developers are not aware of the energy hidden in these water layers. This leads to this potential geothermal resource being "left" in the formation. Considering the rich reserves of unconventional gas and the huge volume of high-temperature aquifer, indeed, there is a promising potential to develop and utilize the geopressured geothermal resource in oilfields.

Many oil reservoir aquifers are usually of high temperature. Cubric (1977) had showed that it is possible to exploit geothermal energy from such aquifers with no loss for oil recovery in water flooding reservoir. So it will benefit both sides if their advantages can be combined together. Additionally, exploitation and utilization of oilfield geothermal resource will decrease CO2 footprint, enhance energy saving and reduce emissions. It is estimated that a geothermal power plant with generation capacity of 1 MW can reduce CO2 emissions by 6,000 metric tons per year (Sanyal and Butler, 2010). The low-temperature geothermal resource in some small and medium sized oilfield has the generation capacity of thousands MW (Li, 2011). Thus, the exploitation of geothermal resources in oilfield also has a huge potential to reduce greenhouse gas (GHG) emissions.

3. UTILIZATION OF GEOTHERNAL IN OILFIELD

3.1 House heating and oil gathering heat tracing

House heating and oil gathering heat tracing are the main utilization of geothermal in oilfield at present in China. In Shengli oilfield, the first geothermal well was drilled at Gudao area in 1973 and the successful utilization of geothermal resources was in 2002. There were 55 geothermal wells up to 2013. The total water production was 703×10^4 m^3 in 2012. Among this, about 68.6% was used for house heating, 16.9% for medical treatment and recreation, and 14.5% for greenhouse cultivation. Furong residential area is a typical project of successful utilization of geothermal energy in Shengli Oilfield(Wang, 2004). The Furong geothermal well was taken into production in 2002. Table 1 show the system parameters used in this house heating station. Since operating, total saved energy is up to 103×10^8 GJ. It is equivalent to 3×10^4 tons of coal and 2×10^4 tons of oil. About 9.8×10^4 tons of carbon dioxide and 500 tons of sulfur dioxide had been reduced.

Table 1 System parameters of Furong house heating station

House heating area	7×10^4 m^2	Heating load	4.9 MW
Flow rate	70 m^3/h	Wellhead temperature	82 ℃
Inlet water temperature at end user	65 ℃	Return water temperature	50 ~ 55 ℃
Heat pump output power	344 kW/pump×6 pump	Annual cost saving	156×10^4 RMB

Oil gathering heat tracing systems usually heat the warm water by burning oil. Much oil and gas were consumed during this process. When the oil field enters into high water cut stage, plenty of geothermal water is produced along with oil. This geothermal water can be used to heat warm water for oil gathering heat tracing system. This technology had been adopted by many oilfields in China, such as Huabei and Henan oilfields. Liubei reservoir, located in Huabei oilfield, was taken into production in 1978. The water cut was up to 97.6% in 2006. A series of pilot tests of geothermal utilization began since 2007, including enhancing flow rate, geothermal power generation, oil gathering heat tracing. Four oil gathering and processing stations (Liuyi, Lu-3, Lu-27 and Lu-25) adopted geothermal water to keep system's temperature. The annual saving of oil was 304 tons, 713 tons, 1963 tons and 1629 tons respectively from 2009 to 2012 (Zhang, et al, 2013).

3.2 Geothermal water flooding

The global reserves of heavy oil are 3,396 billion barrels of original oil in place and it almost accounts for 50 percent of known oil resources (Meyer et al., 2007). The main challenge to produce heavy oil is the flow problem in reservoir and wellbore. Some thermal recovery methods, such as steam flooding, steam huff and puff, in-situ combustion, hot water flooding and electromagnetic heating, are implemented to improve its flow capacity in the reservoir. Burning oil or natural gas to produce steam/hot water, heating by electricity will lead to a higher operation cost. Additionally, the lower utilization efficiency of heat is another disadvantage. Considering the "hidden" geothermal resource besides oil reservoir, utilizing such hot water in deep formations for flooding may provide a new way for heavy oil production.

It has been proved that hot water flooding can decrease oil viscosity and mobility ration, and then improve ultimate oil recovery (Prats, 1982; Goodyear et al., 1996). Due to the lower heat content carried by hot water and the higher heat loss along the wellbore, the application of this technology is limited because of insufficient heat being carried into farther reservoir. Comparing to the conventional hot water flooding, geothermal water flooding can carry the heat of high temperature fluid from deeper aquifer into shallower oil formations effectively with the method of "deep production and shallow injection" in the same well. This method has several distinct advantages, such as reducing heat loss at surface and in wellbore, avoiding cold damage to the formation caused by low-temperature injection water from surface and decreasing energy consumption and environmental pollution.

Some laboratory experiments and numerical simulations showed that geothermal water flooding is superior to conventional water flooding, and can improve oil recovery by 4%~10% (Pederson and Sitorus, 2001;Wang and Wang, 2008, 2009;Chen et al.,2010;). In early 1990, a feasibility study on recovering heavy oil using geopressured geothermal resource in the oilfield of south Texas was conducted. The study showed that the breakeven price for oil is less than 14 dollars per barrel and for gas less than 2 dollars per thousand cubic feet and the payback are less than 2 years at that time. It indicated that application of geopressured geothermal resource to enhance heavy oil recovery is profitable (Wys, et al., 1991).

Geopressured geothermal reservoir has the characteristics of high temperature, high pressure and dissolved natural gas. When used to enhance oil recovery, it has several advantages. (1) Its larger aquifer body can provide enough high temperature water without fresh water make-up, then avoiding the shortage of surface water. (2) Its higher pressure will contribute to inject its hot water into lower pressure formations, then reducing surface injection cost. (3) The produced natural gas with downhole separation technology can be used to drive power generators or take it into gas pipeline, or the dissolved natural gas can be injected into objective formations with hot water to supply additional driving force. The feasibility to conduct such project will depend on several factors, such as whether a suitable geopressured geothermal resource under an oil reservoir and a corresponding injection formation could be found or not, whether the chemical and thermodynamic problems between geopressured geothermal liquid and injected formation could be solved or not, whether the changes of temperature, pressure and salinity of geopressued geothermal aquifers during production will affect formation's injectivity and productivity or not.

3.3 Geothermal power generation

Geothermal power generation is one of the most important ways of geothermal utilization. Dry steam, flash steam and binary cycle are the three common types of geothermal power generation technology. Among them, the binary cycle technology is especially suitable for low-temperature geothermal resource. In this system, the low-temperature geothermal fluid will not reach the turbine/generator units. It exchanges heat energy with secondary cycling fluid (binary) which has a lower boiling point through a heat exchanger. The exchanged heat causes the secondary cycling fluid to flash to vapor, and then drives the turbines and the generators subsequently.

United States is a one of the leading countries on research and utilization of low-temperature geothermal power generation. The Organic Rankine Cycle (ORC) power plant in Chena Hot Spring, Alaska, is a representative low-temperature geothermal power plant in the world. The plant utilizes the hot water with temperature as low as 74℃ to produce 225 kW of electricity and can produce with 50 cents per kWh (Lund, et al., 2010; Chena Power, 2007). In order to transfer the low grade heat into electricity economically and effectively, a newly low-temperature generation device with 40kW~60kW capacity, namely GEN4 system, was developed by Ener-G-Rotors. It uses hot water or low-heat steam at 65.5℃~148.9℃ (150℉~300℉) to produce electricity. The thermoelectric conversion efficiency is about 10%~15%. The GEN4 system is a complete, modular and drop in ORC system with the payback of less than three years (Ener-g-rotors, 2009).

In early 1970's, some low-temperature geothermal power generation plants, which used flash steam or binary cycle technology, had been built up and produced electricity successfully in China, such as Dengwu (92℃, 300kW), Huitang (98℃, 300kW), Houhaoyao (87℃,200kW), Tangdongquan (98℃, 300kW), Xiongyue (90℃, 200kW), Reshuicun(79℃, 200kW) and Wentang(67℃, 100kW) (Zheng and Pan, 2009). Due to the lack of market requirements at that time, the development of such technology was halted seriously. In recent years, with the emergence of screw expander technology, it again promotes the development of low-temperature power generation. The medium, suitable working types for screw expander include overheated steam, saturated steam, two phase (steam-water) and/or sewage hot fluid/water. The screw expander can be directly used to produce electricity when the temperature is higher than 150℃. If the temperature is between 70℃ and 150℃, the screw expander with binary cycle should be used (Hu and Hu, 2007).

It can be seen that the technology and equipment of low-temperature power generation has made progress gradually. The key points are to find a suitable hot water resource (temperature higher than 70℃) and supply enough flow rates. In China, the water-cut in some oilfields has reached up to or exceeded 90%, a large amount of "waste hot water" was produced every day. These "waste hot water" can not only be used to heat oil gathering-transporting system, but also to produce electricity if the temperature is high enough. There are several representative cases. One is operated by Rocky Mountain Oilfield Testing Center (RMOTC) at NPR-3 (Teapot Dome Oilfield) near Casper Wyoming. This Organic Rankine Cycle (ORC) power plant used the oilfield waste stream at about 77℃ to generate electricity with a nominal rating of 250 kW. It produced over 586 MWh of power with 3 million barrels of hot water from September 2008 to February 2009, and over 322 MWh of power with 1.7 million barrels of hot water from September 2009 to January 2010 (Johnson and Simon, 2009; Johnson and Walker, 2010). Another is a 400 kW binary screw expander geothermal power plant operated by Huabei Oilfield Company in China. It uses the hot water produced from 8 oil wells in LB reservoir with the water cut up to 97%. The inlet water temperature is about 110℃ and the flow rate is about 2880 m^3/d. Under full load operation, the power plant is estimated to produce electricity of 270×10^4 kWh, increase 12,000 tons of oil, and save 4,100 tons per year of fuel. During the pilot test from April 2011 to December 2011, it totally produced about 31×10^4 kWh of electricity (Xin et al., 2012).

These successful projects had indicated that it is feasible to accomplish "oil—heat--electricity" coproduction from oil production waste stream with the existing low-temperature power generation technology. Its economy depends on the flow rate and temperature of the produced stream, scale of power generation, ambient temperature, and so on. As to the installed low-temperature power plants at present, their scale and capacity are smaller. However, these small-scale plants usually have a flexible capacity for expansion and can be upgraded easily according to the oilfield production. If an oilfield is transformed into a geothermal coproduction field thoroughly and integrated with a geopressued geothermal resource which has less attention at present, the oilfield will have the capacity of large-scale power generation afterwards.

4. CLOSE-LOOP PRODUCTION SYSTEM USING GEOTHERMAL RESOURCE IN GUDONG OILFIELD

There are rich oilfield geothermal resources in China. Based on current estimation, 2 percent of these resources exploited will produce 100 times the energy consumption in 2010 in China (Xiangshan Science Conference, 2013).

Shengli Oilfield, located at Bohai Bay Basin, is the second largest oilfield in China. The normal geothermal gradient in the oilfield is around 3.4～3.8℃/100 m. The main geothermal reservoirs are located at Guantao Formation, Dongying Formation and Cambrian – Ordovician Formation. The distribution and characteristics of these geothermal reservoirs are showed in Table 2 and Table 3. Figure 1 shows the regional tectonics of the main geothermal reservoir in Shengli Oilfield (Wu, 2003).

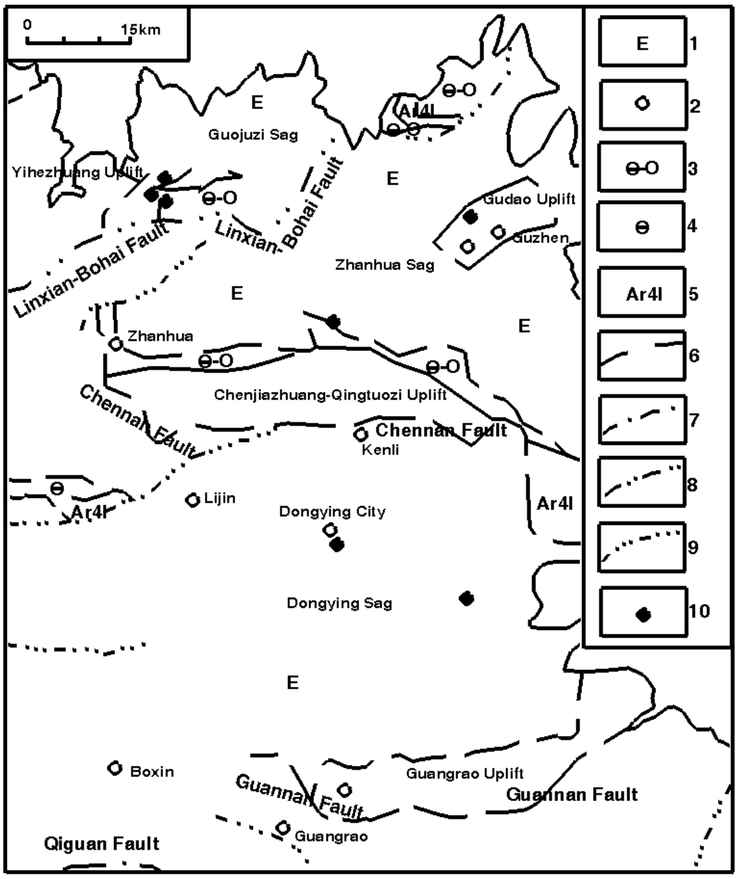

Figure 1: The regional tectonics of main geothermal reservoir in Shengli Oilfield. 1- paleogene, 2- Ordovician, 3- Cambrian-Ordovician, 4- Cambrian, 5- Taishan Group, 6-Fault, 7- Boundary of second-order structural element, 8- Boundary of third-order structural element, 9- Boundary of fourth-order structural element, 10-geothermal well location

Table 2 Distribution of main geothermal reservoir in Shengli Oilfield

Formation	Reservoir temperature	Depth	Resources enrichment area
Guantao	54 ~ 77 ℃	1000 ~ 1450 m	near Dongying city – Niuzhuang – Liuhu, Gudao
Dongying	64 ~ 100 ℃	1 400 ~ 1900 m	near Dongying city – Niuzhuang – Liuhu, Hekou and Gudao
Cambrian - Ordovician	70 ~ 90 ℃	1450 ~ 1800 m	Gudao

Table 3 Characteristics of main geothermal reservoir in Shengli Oilfield

Area	Geothermal gradient	Average temperature	Average reservoir thickness	Reservoir area	Type of geothermal reservoir
Yihezhuang Uplift	4 ~ 5 ℃/100 m	51.0 ℃	650 m	158 km^2	Cambrian – Ordovician formation, fissure type
Zhanhua Sag	3 ~ 4 ℃/100 m	73.0 ℃	170 m	456 km^2	Guantao and Dongying formation, porous type
Gudao Uplift	4 ~ 5 ℃/100 m	75.0 ℃	220 m	108 km^2	Guantao formation, porous type Cambrian – Ordovician formation, fissure type
Chenjiazhuang-QingtuoziUplift	4 ~ 5 ℃/100 m	75.0 ℃	500 m	414 km^2	Cambrian – Ordovician formation, fissure type
Dongying Sag	3.1 ~ 4 ℃/100 m	71.0 ℃	180 m	258 km^2	Guantao and Dongying formation, porous type
Guangrao Uplift	4 ~ 5 ℃/100 m	72.0 ℃	800 m	288 km^2	Cambrian – Ordovician formation, fissure type

The total hot water reserves in these three formations are estimated to be about 460 billion cubic meters, equivalent to 12.5 billion tons of coal. The recoverable reserves are about 75 billion cubic meters, equivalent to 2.7 billion tons of coal (Liu, 2001; Zhang and Zhang, 2009). The depths of most oil wells in Shengli Oilfield are 1000~3000 meter, the temperature of produced fluid at wellhead is around 60~100℃. Some wells are even higher.

Gudong oilfield, with an area of 68 km^2, is located in Gudao Uplift. After 20 years of production, it entered into high water cut phase. Gudong oilfield includes Shahejie Formation, Dongying Formation and Guantao Formation from lower to upper. The lower formation temperature (Shahejie Formation and Dongying Formation) is usually 40 ℃ to 70 ℃ higher than the upper (Guantao Formation). The wells in Gudong oilfield had usually drilled through several strata with larger temperature intervals. Such as well Gushen-2, the oil pay zone is between 1000 m to 3800 m, its formation temperature varies from 48 ℃ to 169 ℃. The lower formation is a good heat source for the upper formation. The formation temperatures of well GD-281-5, well GD-301-1, and block GD-18 are 141.3 ℃, 121.7 ℃ and 114.3 ℃ respectively. The geothermal resources are very rich in this oilfield. Gudong oilfield also has rich heavy oil resources. There are four important heavy oil blocks, i.e., Gudong-9 block, Kendong-521 block, Kendong-53 block and Ken-92 block. The typical surface oil viscosities are around 3000 mPa.s ~7000 mPa.s. The steam huff and puff method was used in these blocks. According to the results of well Gushen-2, the oil viscosity will decrease from 3949 mPa.s to 1671 mPa.s when oil temperature is higher than 55 ℃. Wang (2008) had discussed the feasibility of recovering heavy oil using its geothermal energy in this region.

Based on the proposal of Wang (2008) and considering the higher water cut (above 80%) at present in Gudong oil ield, if formation and wellbore are further retrofitted, such as closely spaced perforating, fracturing or acidizing to increase flow rate, renewing conventional tubing with insulated tubing to avoid extra heat loss, the surface temperature of produced fluids could meet the requirements of low-temperature geothermal power generation. Combining low-temperature geothermal power generation with geothermal oil production, a close-loop production system using geothermal resource for this oilfield was proposed (Figure 2).

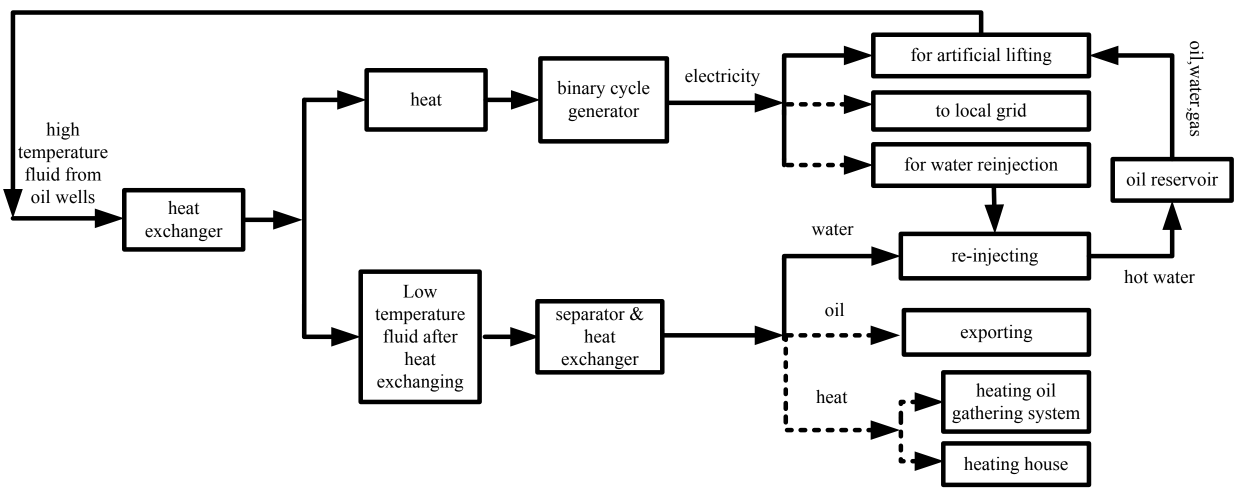

Figure 2: Close-loop production system using geothermal resource in oilfield

The high temperature fluids (including oil, gas and water) produced from oil wells will pass through first-stage heat exchanger at first. The exchanged heat will be used to generate electricity and the low temperature fluids after heat exchanger will enter into a three-phase separator and second-stage heat exchanger for further processing. Some of the electricity produced by binary cycle generator will supply for artificial lifting equipment, such as electrical submersible pump (ESP), beam pumping unit, some for water reinjection equipment, and the surplus can be incorporated into local power grid. The hot water after the three-phase separator and second-stage heat exchanger will be re-injected into heavy oil reservoir. If the temperature of the re-injected water is not high enough, the solar energy can be used to assist heating to raise its temperature. The heat exchanged at second-stage heat exchanger can be used for oil gathering-transporting system heating and/or field workplace heating.

Binary cycle generating systems are in consideration. The method of Rashid et al (2012) is utilized. Their formulas are:

$$P_{thmax} = c_w \times m_w \times (T_{in} - T_{out})^2/(2T_{out}) \quad (1)$$

$$\eta_{cycle} = (T_{in} - T_{out})/(2T_{out}) \quad (2)$$

$$\eta_{util} = \frac{(T_{in} - T_{out})\eta_{cycle}}{(T_{in} - T_o) - T_o ln(T_{in}/T_o)} \quad (3)$$

$$P_{electr} = P_{thmax} \times \eta_{util} \quad (4)$$

where P_{thmax}, P_{electr}, c_w, m_w, T_{in}, T_{out}, T_o, η_{cycle}, η_{util} are the potential maximum useful work (kWe), net power output (kWe), specific heat of the thermal water (kJ/kg K), mass flow rate of the thermal water (kg/s), thermal water inlet temperature (K), thermal water outlet temperature (K), ambient temperature (K), thermodynamic cycle efficiency of the heat exchanger (%), utilization efficiency of Rankine organic cycle (%).

The well GD-301-1 is an ideal geothermal well (Wang, 2008). Assuming other 9 geothermal wells will be drilled around this well and the total flow rate is 60 kg/s, ESP are used to produce the wells with a power consumption is 0.8 kWh per ton produced liquid (Xu and Zhang, 2012), inlet temperature at first-stage heat exchanger is 110 ℃ and outlet temperature is 55 ℃, and the annual average ambient temperature in Gudong oilfield of 18 ℃, using the above formulas, the calculated maximum potential useful work, thermodynamic cycle efficiency, utilization efficiency and net power output are 1133.86 kWe, 8.38%, 38.24% and 433.57 kWe, respectively. The daily generating capacity will be 10 405.70 kWe. The daily power consumption by ESP to lift liquid is 5 529.60 kWh. The daily power consumption by beam pumping units and power consumption by water injection system in Gudong oilfield are about 236.00 kWh (Zhu, 2011) and 5.22 kWh/ m^3 (Zong, 2010), respectively. The daily surplus (about 4 876.10 kWh) can supply the power for 21 oil wells or for injecting 934.12 m^3 water. If capacity factor is assumed as 8000 hours annually and the power price is 0.65 RMB/kWh, the annually income by selling the surplus to local grid will be up to 2.25 million RMB.

Comparing the geothermal power generation and oil productivity enhancement by improving flow rate at high water-cut period (Xin,2012) and the simple oil production using geothermal resource (Wang, 2008), the proposed close-loop system integrates both advantages. It improves oil recovery by hot water flooding as well as achieves the cascade utilization of oilfield geothermal resources.

5. CONCLUSIONS

Oil & gas basins usually have rich geothermal resources. Co-produced geothermal resource and water-soluble-gas geothermal resource (geopressured geothermal resource) are the two main resources in oilfield and are causing more and more attentions by oil companies. In the high water-cut period of oilfield, a plenty of produced water, which was treated as a troublesome waste in the past, provides a huge potential to exploit and utilize such “forgotten” energy. Water-soluble-gas geothermal resource has the characteristics of high temperature, high pressure and dissolved natural gas; it is very suitable for hot water flooding in heavy oil reservoir. Basedon the analysis of oilfield geothermal resource and infrastructure in Gudao oilfield, a close-loop production system, which integrates both advantages of geothermal utilization and hot water flooding, is proposed in this paper. It is a more economic and effective way to tackle geothermal and oil. With the existing infrastructure, reservoir data and production history, oilfield geothermal resource exploitation will be a “win-win” choice for maintaining the sustainable development of oilfield and promoting the exploitation of new energy.

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