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Downhole geothermal power generation in oil and gas wells

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ABSTRACT

Synergistic development of energy by combining geothermal and hydrocarbon gains an increasing attention. In practice, hydrocarbon reservoir fluids produced from oil and gas wells are used for electricity generation through a binary cycle power plant. To enhance the thermal recovery efficiency, we present an innovative design of in-situ geothermal power generation and illustrate a promising method of geothermal energy utilization in a cost-effective and environmentally friendly manner.

This proposed design is an integration of thermoelectric generation technology, well completion and production operation. In this design, electricity is generated downhole by thermoelectric generators (TEG) installed on the outer side of the production string to convert the thermal energy to electric power. Heat transfer model is set up to determine the temperature field with a case study to demonstrate the downhole power generation efficiency. The results are compared with both simulation and experiment results.

The proposed design capitalizes on existing hydrocarbon production wells and retrofit them for power generation. This practice can be a great complementary for surface power plants, and could reduce operational cost and extend the economic lifetime of oil and gas wells, especially for high water-cut wells in mature fields.

1. Introduction

Due to the detrimental effects of fossil fuels on the environment, geothermal energy has drawn increasing interest globally. For decades. geothermal energy has been primarily developed from geothermal reservoirs. In addition, there also exists a huge amount of thermal resource in hydrocarbon reservoirs (Liu et al., 2018; Wang et al., 2018). Erdlac et al. (2007) reported that Texas, USA has tens of thousands of oil and gas wells with bottomhole temperatures over 121 °C and some up to 204 °C, and the estimated power generation capacity from the produced hot water in these wells was about 47–75 billion MWh, which is equivalent to about 29–46 billion barrels of oil. According to Tester et al.(2006), the future geothermal power generation in California, Oklahoma, and six other states in USA is over 11,000 MW, which would double the world's current geothermal power generation capacity.

The synergistic development of geothermal and hydrocarbon resources from oil wells has multiple advantages (Wang et al., 2018), including: 1) It is an economically efficient choice by significant reduction of drilling cost, which could account for 50% of total cost (Barbier, 2002). The existing wellbore and downhole well construction could eliminate associated risks in exploration and operations. 2) Developing geothermal reservoir needs detailed reservoir characterization using different methods which are usually costly (Wu et al., 2008). A large quantity of data from oil field exploration and production history are available for this purpose. In most oilfields, geological information, drilling and completion data, reservoir rock and fluid properties, and production activities are usually documented, which can be used to identify geothermal production opportunities and evaluate geothermal project. 3) Oilfields have sufficient availability of candidate wells for geothermal development, especially for mature oilfields, where exist large number of high water-cut wells and abandoned wells as the candidates to be transformed for geothermal production. 4) There are favorable environment and incentives for developing renewable energy from the government agencies.

Traditional geothermal power generation is from a binary power station, where a working fluid is expanded rapidly to provide mechanical energy to turn the turbine to generate electrical power (Tester et al., 2006).There are several notable efforts to utilize geothermal energy for power generation from oil and gas wells using produced water. Nordquist and Johnson (2012) reported such a pilot project by US Department of Energy (DOE) beginning in 2006. An ORC power station of 250 KW was built in the Teapot Dome Oilfield in northern Wyoming, and it generated power using 90.6–98.9 °C produced water with a production rate of 4000 barrels per day. DOE also supported

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another project of geothermal power generation in North Dakota. It was recently reported as the first commercial geothermal power production from an oil and gas well in USA. According to Gosnold et al. (2017), electricity was successfully generated from 98 °C water from waterflooding Enhanced Oil Recovery (EOR) wells in the Williston Sedimentary Basin.

However, power generation from oil and gas wells is still in the experimental and testing period, and many problems need to be solved for a large-scale application. One important problem is the temperature range of an oil and gas well is between 65 to 150 °C (Liu et al., 2018), which falls into the category of low to moderate geothermal resource. Moreover, there are massive heat loss from the produced fluid to the surrounding formations when fluids flow upwards. Therefore, the temperature and rate of produced water from hydrocarbon well is relatively low for efficient power generation through a turbine (Liu et al., 2015a), which limits the selections of production wells and hinders the wide development of oilfield geothermal. To overcome the constraints and spread oilfield geothermal utilization, one possible solution is to apply the large-scale thermoelectric generation technology (Li et al., 2015).

Thermoelectric technology directly transforms thermal energy into electricity by Seebeck effect (Ahiska and Mamur, 2014). The main characteristics of thermoelectric technology include the low maintenance requirement, the high modularity and the wide temperature range, and thermoelectric technology has been extensively studied. Eisenhut and Bitschi (2006) studied thermoelectric conversion system for geothermal and solar energy. Suter et al.(2012) modeled and optimized a 1 kW thermoelectric stack for geothermal power generation. Liu et al.(2014) experimentally studied and tested the thermoelectric generation technology in geothermal application. Chet et al.(2015) proposed a method of surface power generation from geothermal energy using thermoelectric modules. Cheng et al.(2016) did an experimental study and economic analysis on geothermal electric power generation system. However, these attempts are all harvesting heat to generate electricity on surface, and very limited attention has been paid to generate electricity by capture in-situ geothermal energy, which features the highest temperature.

In this paper, we present a novel design of subsurface geothermal power generation in oil and gas wells, which could be applied to harness in-situ geothermal energy for power generation in high water-cut wells. Downhole thermoelectric modules convert the thermal energy into electricity. Mathematical models are established to study the temperature distributions related to the TEGs. In this paper, we also optimized the downhole thermoelectric modules based on thermoelectric material properties. Case studies are presented to demonstrate the potential of downhole power generation in oil and gas wells.

1.1. Thermoelectric technology

Different from current geothermal power generation in power plants, which convert heat energy into mechanical energy in the turbine and then driving the generator, thermoelectric technology directly transfers heat to electricity through the Seebeck effect under certain temperature gradient, without involving with mechanical activities. TEG has no greenhouse gas emission, no moving parts, is silent in operation and very reliable (Twaha et al., 2016). Thermoelectric technology is used multiple industries as a green and flexible source of electricity able to meet a wide range of power requirements.

The schematic of thermoelectric material, module and generator is shown in Fig. 1. A thermoelectric module (Fig. 1b) is a circuit containing thermoelectric materials (Fig. 1a) that output electricity. A thermoelectric module requires numbers of thermoelectric materials to function. P-type and N–type semiconductors are electrically connected in series and thermally connected in parallel. Several thermoelectric modules could form a thermoelectric generator (Fig. 1c).

When a high temperature is applied to one side of the TEG and the other side is kept at a lower temperature, then a voltage is produced and can be modeled by Eqn. (1):

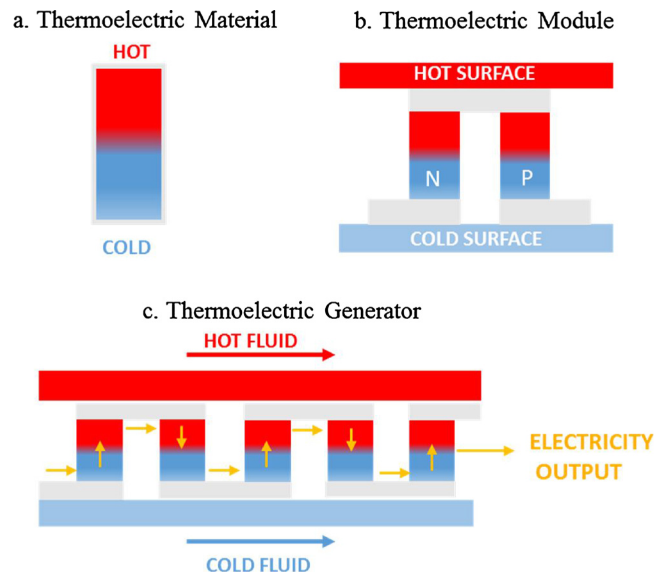

Fig. 1. Schematic of (a) thermoelectric material, (b) thermoelectric module and (c) TEG.

$$V = \alpha (T_H - T_C) \tag{1}$$

where V is the voltage of the thermoelement, T_H is the hot side temperature of thermoelement, T_C is the cold side temperature of the thermoelement and the α is the Seebeck coefficient of the thermoelectric module. When the generator is connected to an external load, a current will flow through the load. The electrical power and the current will depend on the temperature difference, the properties of the thermoelectric materials and the values of the external load resistance.

The performance of a thermoelectric material is also gauged by the figure of merit (Z), which is the material nature property, and often appears as a dimensionless form of ZT. Figure of merit stands for the ability of a given material to efficiently produce thermoelectric power as:

$$ZT = \frac{\alpha^2 T}{k\sigma} = \frac{\alpha^2 (T_H + T_C)}{2k\sigma} \tag{2}$$

where $\boldsymbol{k}$ and $\boldsymbol{\sigma}$ are the thermal conductivity and electrical resistivity of thermoelectric material.

In general, the efficiency of a TEG is defined as the net power output over heat input, and the maximum efficiency using thermoelectric material is shown in Eqn. (3),

$$\eta = \frac{T_H - T_C}{T_H} \frac{\sqrt{1 + ZT} - 1}{\sqrt{1 + ZT} + \frac{T_C}{T_H}} \tag{3}$$

1.2. Downhole geothermal power generation design

In mature oilfields, there exist large numbers of high water cut wells as the consequences of waterflooding, and they are good candidates to employ downhole power generation to extend the economic life. In this paper, TEGs are designed to be installed onto the production tubing, without interference to the on-going production operation. From above discussion, maximizing the temperature difference across the thermoelectric modules is crucially important for power generation. To create sufficient temperature difference, one side of TEG must be hot and the other side must stay cold. In downhole condition, hot fluid produced from the reservoir could work as the heat source for hot side and cold fluid could be injected to keep the other side cold. Electricity will be