Downhole Geothermal Power Generation in Oil and Gas Wells

Kai Wang¹, Xingru Wu¹ and Junrong Liu²

1. University of Oklahoma; 2. China University of Petroleum (East China)

Keywords
Geothermal Power Generation; Downhole Power Generation; Thermoelectric Technology; Oilfield Geothermal Energy; Heat Transfer;

ABSTRACT

Increasing attention has been paid to use the massive thermal energy in conjunction with oil and gas production in hydrocarbon reservoirs. In current practice, hot fluids produced from these wells are used for electricity generation through a surface binary cycle power plant. To enrich the thermal recovery methods, we present an innovative design of in-situ geothermal power generation directly from downhole 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 techniques and production operations. In this design, electricity is generated downhole by thermoelectric generators (TEG) installed on the production string under certain temperature gradient between hot fluids and cold fluids. The detailed design and procedures of electricity generation are stated to demonstrate the mechanism of downhole in-situ power generation using co-produced fluid. Heat transfer model is introduced under the designed downhole configuration to determine the temperature field for thermoelectric power generation. Geometric optimization of thermoelectric modules is conducted for this proposed application. A case study is carried out to demonstrate the promising future of downhole power generation using thermoelectric materials, and the results are verified experimentally.

The paper could bridge the gap between thermoelectric technology and geothermal energy utilization in the oil and gas industry through an innovative design and procedure along with case studies. In practice, it could be a great complementary for surface power plants, and gradually reduce the need for power plant as the thermoelectric technology advances. Its application also could reduce the associated cost and environment impacts of power plant. It also could help establish a close-loop production system using downhole electricity to power the artificial lift pumps and water reinjection equipment. The co-production of hydrocarbons and electricity could reduce operating cost and extend the economic lifetime of oil wells, especially for high water-cut wells in mature fields.
1. Introduction

Due to the detrimental effects of fossil fuels on the environment, renewable energy has drawn increasing interest globally, such as geothermal energy. It exists in geothermal reservoirs, which is likely in regions of intense volcanic or hydrothermal activity. In addition, there also exists a huge amount of thermal resource in hydrocarbon reservoirs (Li et al., 2007; Erdlac et al., 2007). It was reported that the future geothermal energy from California, Oklahoma, and six other states along the Gulf Coast is over 11,000 MW, which could be generated from coproduced fluids, and would double the world’s current geothermal capacity. Erdlac et al. (2007) reported that Texas has tens of thousands of oil and gas wells that are sufficiently deep to reach temperatures of over 250°F (121°C) and up to 400°F (204°C), and he also estimated that the possible electricity generation from the hot water was about 47-75 billion MWh, which is equivalent to about 29-46 billion barrels of oil.

Oil and gas wells are not only associated with massive geothermal storage, but also offer tremendous advantages in field utilization: 1) To produce geothermal energy by utilizing oil and gas wells is an economically efficient way. No or very limited drilling activity is needed since the well is already there. Compared to develop geothermal reservoirs, the existing wellbore and downhole well construction will eliminate significant risks in exploration and reduce considerable cost in drilling and completion, and long payback period. Existing surface infrastructures will help sidestep the initial investment, such as installed wellsite facilities, pipes, and service roads to wellsites. 2) A large quantity of data from exploration and production history are available. In most oilfields, geological information, drilling and completion data, reservoir rock and fluid properties, and production activities are usually documented by the oil and gas companies, which provides significant convenience for geothermal energy evaluation. 3) Oilfields have sufficient availability of candidate wells for geothermal energy utilization, especially for mature oilfields. 4) Favorable environment and exceptional opportunity to boost the geothermal utilization are established by the efforts of government and oil companies, who are actively facilitating geothermal energy development forward through incentives.

Efforts have been made to utilize geothermal energy for power generation from oil and gas wells. Typically, thermal energy is harvested and transferred to electricity by an Organic Rankine Cycle (ORC) 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 examples of geothermal power generation from coproduced water. Karl et al. (2009) reported 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 40,00 barrels per day. DOE also supported another project of geothermal power generation in North Dakota. It is recently reported as the first commercial geothermal power production from an oil and gas well in USA. Researchers at the University of North Dakota successfully generated geothermal power from 98°C water from waterflooding Enhanced Oil Recovery (EOR) wells in the Williston Sedimentary Basin (Gosnold 2016).

However, electricity production from oil and gas wells are still in the experimental and testing period. There exist many problems to be solved in order to make it profitable. One important problem is that the geothermal energy from hydrocarbon wells is of low temperature, which is not able to efficiently drive a turbine for power generation. There exist strict requirements on
produced fluid temperature, flow rate, well locations and other parameters to economically
generation electricity, which limits the selections of coproduction wells and hinders the
utilization of oilfield geothermal. To overcome the constraints and make oilfield geothermal
utilization economic competitive, one possible solution is to apply the large-scale thermoelectric
generation technology (Li et al., 2015).

Thermoelectric technology could directly transform thermal energy into electricity by Seebeck
effect (Ahiska and Mamur, 2014). The main advantages are the low maintenance requirement,
the high modularity and the wide temperature range. Hendricks and Choate (2006) carried out
the engineering scoping study of TEG systems for industrial waste heat recovery. Eisehut 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. Chen et al. (2013) 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 from subsurface fluids.

This paper presents a novel design of downhole in-situ geothermal power generation in oil and
gas wells, which can be applied to high water-cut wells. Thermoelectric modules will harvest the
heat and transfer the heat 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 advantages of downhole power generation in oil and gas wells. In practice,
downhole power generation would include more wells for geothermal production, and offset the
operation cost in mature oilfields.

2. Thermoelectric Technology

Current geothermal power generation through surface power plant is converting heat energy into
mechanical energy in the turbine and then driving the generator. Different from that,
thermoelectric technology directly transfers heat to electricity, without involving with
mechanical activities. Thermoelectric modules directly generate electricity through the Seebeck
effect under certain temperature gradient. Seetawan et al. (2014) pointed out that this technology
could offer low cost electricity, and green energy technology without the use of moving parts or
production of environmentally deleterious wastes.

The schematic of thermoelectric material, module and generator is shown in Figure 1. A
thermoelectric module (Figure 1.b) is a circuit containing thermoelectric materials (Figure 1.a)
that output usable electricity. A thermoelectric module requires numbers of thermoelectric
materials to function: p-type and n–type semiconductors electrically connected in series and
thermally connected in parallel. Thermoelectric generator (Figure 1.c) is formed by several
thermoelectric modules.

When the high temperature is applied to one side of the TEG and the other side is kept at the
lower temperature, a temperature difference between surfaces is created, and then, a voltage is
produced and its value depends on the temperature difference and Seebeck constant as given by
\[ V = \alpha (T_H - T_C) \]  

where \( V \) is the voltage of the thermoelement, \( T_H \) is the hot side temperature of the thermoelement, \( T_C \) is the cold side temperature of the thermoelement and the \( \alpha \) 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 semiconductor materials and the values of the external load resistance.

Ahıska and Mamur (2014) mentioned that there are two types of TEGs, which are large-bulk thermoelectric module that are preferred for high power applications and the thin film micron TEGs that are preferred for low power applications. The thin film type draws more attention for power generation in oil and gas application because of relatively low temperature. The layer thickness of micron TEGs is in order of nanometers, and it can also be enlarged for different applications.

3. Downhole Geothermal Power Generation Designs

In mature oilfields, there exist large numbers of high water cut waterflooding wells and they are good candidates to apply downhole power generation to extend the economic life of the well. In this paper, TEGs are installed onto the production tubing, and they have no interference with ongoing production operation. From above discussion, maximizing the temperature difference across the thermoelectric modules is crucially important for power generation design. To create sufficient temperature difference, one side of TEG must be hot and the other side must stay cold. In downhole condition, hot fluid from the well could work as the heat source for hot side and cold fluid is used to keep the other side cold. Under temperature difference, electricity will be
generated as the response to applied temperature gradient, and the electricity could be either transmitted to surface or power downhole tools. Figure 2 demonstrates the schematic of downhole geothermal power generation design in a waterflooding production well.

Figure 2: Schematic of downhole geothermal power generation design in a waterflooding production well.

In this design, tubing and a packer connected at the end of tubing are run to the top of production zone. There are TEGs mounted on the tubing (One segment of generator is shown in Figure 2 as an example). The annulus is also installed with smaller size pipes for cold fluid injection. After the packer is set, annulus between casing and tubing will be sealed, which will provide long-term isolation between hot fluid and cold fluid. Injected cold fluid will flow downwards and start to reverse back at the circulation point because of the isolation of packer. Temperature difference is created by hot fluid in the tubing flowing through one side of TEG and cold fluid flowing through the other side of generator. Temperature at hot side of TEG is maintained by produced hot fluid from the reservoir, and temperature at cold side is kept as low as possible by continuously injecting cold fluid from surface.

4. Mathematical Models of Temperature Distribution

To evaluate downhole electricity production in the above designs, it is necessary to obtain temperature difference created by hot fluid and cold fluid. Mathematical models are established to study the temperature distribution along the tubing and annulus. Considering wellbore as a
cylindrical geometry, well symmetry simplifies the problem into two dimensions by ignoring $\theta$-direction. According to Wu and Pruess (1990), and Hasan and Kabir (1994), heat conduction is only radial and vertical heat conduction can be neglected, which further reduce the model to one-dimension radical heat transfer problem.

Additional assumptions are made as: 1) Produced fluids and injected fluids are both incompressible; 2) Production rate and injection rate are assumed to be constant; 3) Geothermal gradient is constant; 4) It is steady state heat transfer system in downhole environment; 5) Temperature drop across both the tubing and casing walls are neglected due to high thermal conductivity of metals as well as the small thickness of the walls; 6) Temperature drop across the fluid film is ignored; 7) Cold fluid injection are thermally insulated in order to keep a low temperature at cold side of TEG.

Heat exchange among tubing fluids, annulus fluids and the surrounding formation results in temperature difference. Figure 3 shows a schematic diagram of wellbore construction used for downhole power generation in a waterflooding production well. An element of length, $dz$, is treated as a control volume at distance of $z$ from the surface, where $z$ equals to zero.

Figure 3: Well construction for downhole power generation in a waterflooding production well.
For the flowing fluid in the tubing, fluid enters at the depth of \((z + dz)\) and leaves at \(z\) with heat convection towards the annulus. Thus, the energy balance for a differential fluid element is given by,

\[
H_{t|z} + \frac{gz}{g_cJ} + \frac{(v_{t|z})^2}{2g_cJ} + \frac{Q_t}{w_t} \, dz = H_{t|z+dz} + \frac{g(z + dz)}{g_cJ} + \frac{(v_{t|z+dz})^2}{2g_cJ}
\]  

(2)

\(H\) is the fluid enthalpy in Btu/lbm, \(g_c\) and \(J\) are conversion factors, \(v\) is fluid velocity in ft/sec, \(Q\) is heat transfer rate per unit length in Btu/(hr-ft) and \(w\) is fluid mass flow rate in lbm/hr.

Rearranging the above equation as,

\[
\frac{dH_t}{dz} + \frac{g}{g_cJ} + \frac{v_t}{g_cJ} \frac{dv_t}{dz} = \frac{Q_t}{w_t} \quad (3)
\]

For the up flowing fluid in the annulus, the energy balance involves heat transfer from tubing to the annular and heat transfer from surrounding formation, as given by,

\[
\frac{dH_a}{dz} + \frac{g}{g_cJ} + \frac{v_a}{g_cJ} \frac{dv_a}{dz} = -\frac{Q_t - Q_F}{w_{inj}} \quad (4)
\]

According to Hasan and Kabir (2002), heat conduction from the formation to the wellbore, \(Q_F\), is

\[
Q_F = \frac{2\pi k_e}{T_D} (T_F - T_{wb}) \quad (5)
\]

where \(T_D\) is the dimensionless temperature. \(T_F\) and \(T_{wb}\) are formation temperature and wellbore temperature, respectively. The heat conduction from the formation to wellbore equals to the heat convection from the wellbore to annulus, which gives the following equation,

\[
Q_F = \frac{2\pi r_c U_a k_e}{k_e + r_c U_a T_D} (T_F - T_a) \quad (6)
\]

where \(U_a\) is the overall heat transfer coefficient of heat flow through cement, casing wall and annulus fluid, and it can be calculated by the multiple methods (Hasan and Kabir, 2002; Davis and Michaelides, 2009). \(r_c\) is casing radius. \(k_e\) is the thermal conductivity of formation. Eliminate the term \(T_{wb}\) and obtain the heat transfer rate from formation to annulus as,

\[
Q_F = \frac{2\pi r_c U_a k_e}{k_e + r_c U_a T_D} (T_F - T_a) \quad (7)
\]

Combine with the linear relationship between formation temperature and depth,

\[
Q_F = \frac{2\pi r_c U_a k_e}{k_e + r_c U_a T_D} (T_{surface} + g_gz - T_a) \quad (8)
\]
For the fluid in tubing, the heat transfer to annulus can be expressed as,

\[ Q_t = 2\pi r_t U_t (T_t - T_a) \]  

(9)

where \( T_t \) and \( T_a \) are fluid temperature in tubing and annulus, respectively. Combine Eqs. 3, 4, 8 and 9, simplify these equations based on the assumptions of incompressible, single-phase fluid, and obtain the following equations

\[ \frac{dT_t}{dz} = \frac{2\pi r_t U_t}{C_{pt} w_t} (T_t - T_a) \]  

(10)

\[ \frac{dT_a}{dz} = -\frac{1}{C_{pa} w_{inj}} \left[ \frac{2\pi r_a U_a k_e}{k_e + r_c U_a T_D} (T_{surface} + g_G z - T_a) + 2\pi r_t U_t (T_t - T_a) \right] \]  

(11)

The boundary conditions could be found that at the bottom hole of the well, fluid temperature is the reservoir temperature, and the annulus fluid temperature at the circulation depth approximately equals to the injected fluid temperature.

at the inlet of tubing: \( z = L \) \( T_t = T_r \)

at the circulation depth: \( z = L_c \) \( T_a = T_{inj} \)

Apply boundary conditions, solve Eqs. 10 and 11 and express the temperature distribution along tubing and annulus as,

\[ T_t(z) = m e^{\lambda_1 z} + n e^{\lambda_2 z} + T_{surface} + g_G (z + \xi) \]  

(12)

\[ T_a(z) = (1 - \lambda_1 B) m e^{\lambda_1 z} + (1 - \lambda_2 B) n e^{\lambda_2 z} + T_{surface} + g_G (z + \xi - B) \]  

(13)

In Eqs. 12 and 13, \( A, B, C, \xi, \lambda_1, \lambda_2, m \) and \( n \) are all constants, presented as follows.

\[ A = \frac{C_{pa} w_{inj}}{2\pi} \left( \frac{k_e + r_c U_a T_D}{r_c U_a k_e} \right) \]

\[ B = \frac{C_{pt} w_t}{2\pi r_t U_t} \]

\[ C = \frac{C_{pa} w_{inj}}{2\pi r_t U_t} \]

\[ \xi = \frac{AB + BC + AC}{C} \]

\[ \lambda_1 = \frac{AB + BC + AC + \sqrt{(AB + BC + AC)^2 - 4ABC^2}}{2ABC} \]

\[ \lambda_2 = \frac{AB + BC + AC - \sqrt{(AB + BC + AC)^2 - 4ABC^2}}{2ABC} \]

\[ m = \frac{(1 - \lambda_2 B) [T_r - T_{surface} - g_G (L + \xi)] - e^{\lambda_2 (L-L_c)} [T_{inj} - T_{surface} - g_G (L_c + \xi - B)]}{(1 - \lambda_2 B) e^{\lambda_1 L} - (1 - \lambda_1 B) e^{\lambda_1 L_c + \xi L_c (L-L_c)}} \]

\[ n = \frac{(1 - \lambda_1 B) [T_r - T_{surface} - g_G (L + \xi)] - e^{\lambda_1 (L-L_c)} [T_{inj} - T_{surface} - g_G (L_c + \xi - B)]}{(1 - \lambda_1 B) e^{\lambda_2 L} - (1 - \lambda_2 B) e^{\lambda_2 L_c + \lambda_1 (L-L_c)}} \]
5. Geometry Optimization of TEG

To apply thermoelectric generation technology, it is necessary to optimize the geometric features of generators for maximal power output, such as optimizations in shapes, sizes and locations. The performance of the TEG is a function of hot side temperature, cold side temperature and material properties, which include Seebeck coefficient, electrical resistivity, and thermal conductivity. In this study, it is assumed that the above parameters are constant over the range of downhole temperature, and this assumption is verified by the experimental result (Cheng et al., 2016). Optimization of a thermoelectric module (Figure 4) is conducted to illustrate the geometrical design of TEG for the purpose of maximal downhole power generation.

![Thermoelectric Module and Semiconductors Legs](image)

**Figure 4**: Structures of (a) thermoelectric module (after Ahıska and Mamur, 2014) and (b) semiconductor legs.

First, define parameters to represent the thermoelectric properties in this optimization. As shown above, $A_N$ and $A_P$ stand for the cross-section areas for N-type and P-type semiconductors, and $L$ represents the length of semiconductors (length of N-type and P-type semiconductors are the same in downhole conditions). Define $k$ and $\sigma$ as the thermal conductivity and electrical resistivity of semiconductors, which are both material nature properties. For a thermoelectric module, two semiconductors are connected thermally in parallel and electrically in series. Therefore, the thermal conductance, $K$, and electrical resistance, $R$, could be expressed as,

$$K = K_N + K_P = k_P \frac{A_P}{L} + k_N \frac{A_N}{L} \quad (14)$$

$$R = R_N + R_P = \sigma_P \frac{L}{A_P} + \sigma_N \frac{L}{A_N} \quad (15)$$

Another material nature property is the figure of merit ($Z$), which is a parameter generally used to gauge the performance of a thermoelectric material. It often appears as form of $ZT$, which is a...
dimensionless parameter as the product with an absolute temperature. Figure of merit stands for the ability of a given material to efficiently produce thermoelectric power.

\[ Z = \frac{\alpha^2}{k\sigma} \]  
\[ ZT = \frac{\alpha^2 T}{k\sigma} = \frac{\alpha^2(T_H + T_C)}{2k\sigma} \]  

Secondly, consider the process of thermal energy transmission to electricity. When the thermoelectric module is put under certain temperature gradient, electrical power is generated, and it is defined as,

\[ P = I^2R_L \]  

where \( R_L \) is external load resistance, and \( I \) is current flowing through the circuit. Combine with Eq. 1 and express the current \( I \) as,

\[ I = \frac{V}{R + R_L} = \frac{\alpha\Delta T}{R + R_L} = \frac{\alpha(T_H - T_C)}{R + R_L} \]  

The efficiency of TEG can be defined as,

\[ \eta = \frac{P}{Q_H} \]  

where \( Q_H \) is the heat input from heat source to hot side of thermoelectric module. Angrist (1971) wrote the expressions of \( Q_H \) and \( Q_C \) as,

\[ Q_H = K\Delta T + \alpha T_H I - \frac{1}{2} I^2 R \]  
\[ Q_C = K\Delta T + \alpha T_C I + \frac{1}{2} I^2 R \]  

Combine Eqs.18, 19,20 and 21, and express the efficiency \( \eta \) as,

\[ \eta = \frac{\varepsilon\Delta T}{Z(\varepsilon + 1)^2 + (\varepsilon + 1)T_H - \frac{\Delta T}{Z}} \]  

where \( \varepsilon \) is the ratio of electrical resistance of external load, \( R_L \), to internal electrical resistance of thermoelectric module, \( R \). Eq.23 indicates that for a fixed set of temperatures and selection of materials, the efficiency of thermoelectric generation is a function of \( Z \) and \( \varepsilon \).

Thirdly, based on the analysis above, deal with the optimization of the figure of merit, \( Z \), and electrical resistance ratio, \( \varepsilon \). In order to reach to a high value of efficiency, value of \( Z \) should be higher. According to the expression of \( Z \), it is independent with external load resistance, therefore, maximizing its value is mainly about geometrical optimization regarding the semiconductors.
Combine Eqs. 14, 15 and 16 as,

\[
Z = \frac{\alpha^2}{k\sigma} = \frac{4\alpha^2}{KR} = \frac{4\alpha^2}{k_P\sigma_P + k_P\sigma_N \frac{1}{\mu} + k_N\sigma_P\mu + k_N\sigma_N}
\]  

(24)

where \(\mu\) is the ratio of cross-section of N-type semiconductor over P-type semiconductor. As a geometrical factor, \(\mu\) is the only variable in above equation, thus, obtain its optimal value by calculating the first derivate of \(Z\) to \(\mu\).

\[
\mu_{opt} = \left(\frac{A_N}{A_P}_{opt}\right) = \sqrt{\frac{k_P\sigma_N}{k_N\sigma_P}}
\]

(25)

which gives the maximal value of \(Z\),

\[
Z_{max} = 4\left(\frac{\alpha}{\sqrt{k_P\sigma_P + k_N\sigma_N}}\right)^2
\]

(26)

To maximize the power output, get the expression of \(P\) with respect to \(\epsilon\).

\[
P = I^2R_L = \left[\frac{\alpha\Delta T}{R(\epsilon + 1)}\right]^2(\epsilon R)
\]

(27)

Do the first derivate of \(P\) to \(\epsilon\) and calculate the optimal load resistance ratio as,

\[
\epsilon_{opt} = 1
\]

(28)

which gives the maximal power output and corresponding efficiency respectively as,

\[
P_{max} = I^2R_L = \frac{(\alpha\Delta T)^2}{4R}
\]

(29)

\[
\eta_{opt} = \frac{\Delta T}{\frac{4}{Z_{max}} + 2T_H - \frac{\Delta T}{2}}
\]

(30)

6. Case Studies

Case studies are conducted in Gudong oilfield, a branch of Shengli Oilfield in northern China. As characterized by Liu et al. (2015), after 20 years of production, Gudong oilfield has entered high water cut phase. The geothermal gradient is about 3.5°C/100 m and the average formation temperature is around 120 °C. In this case study, downhole power generation design will be applied to a waterflooding wells and coupled with on-going power generation operation in power plant.

This well was drilled to the production zone at 2840 m. It was cased with 9-5/8” casing to the bottomhole, followed by cementation and perforation. A packer was set right above the production zone with 3-1/2” tubing connected to surface. During waterflooding, the daily
production rate was 360 m$^3$ per day with 98% water cut. As designed, injection pipe is installed in the annulus down to the depth of 2840 m, with an injection rate of 360 m$^3$ per day. A thermometric generator (20m) is installed on the end of tubing, above the packer. Set the thermoelectric occupancy ratio, which equals to the overall cross section area of thermoelectric module divided by the total surface area, equals to 0.9. Except the TEG section, the rest tubing is insulated with an insulation thermal conductivity 0.068 W/(mK). Data of well construction, reservoir and fluid properties used in this study are summarized in Table 1.

**Table 1:** well construction, reservoir and fluid properties for case study of downhole power generation design.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tubing OD</td>
<td>3.5</td>
<td>in</td>
</tr>
<tr>
<td>Tubing ID</td>
<td>2.992</td>
<td>in</td>
</tr>
<tr>
<td>Casing OD</td>
<td>9.625</td>
<td>in</td>
</tr>
<tr>
<td>Casing ID</td>
<td>8.835</td>
<td>in</td>
</tr>
<tr>
<td>Injection Pipe OD</td>
<td>1.05</td>
<td>in</td>
</tr>
<tr>
<td>Injection Pipe ID</td>
<td>0.824</td>
<td>in</td>
</tr>
<tr>
<td>Bottomhole Depth</td>
<td>2840</td>
<td>m</td>
</tr>
<tr>
<td>Circulation Depth</td>
<td>2830</td>
<td>m</td>
</tr>
<tr>
<td>Geothermal Gradient</td>
<td>0.035</td>
<td>°C/m</td>
</tr>
<tr>
<td>Surface Temperature</td>
<td>21</td>
<td>°C</td>
</tr>
<tr>
<td>Reservoir Temperature</td>
<td>120.4</td>
<td>°C</td>
</tr>
<tr>
<td>Cold Fluid Injection Temperature</td>
<td>20</td>
<td>°C</td>
</tr>
<tr>
<td>Water Production Rate</td>
<td>360</td>
<td>m$^3$/d</td>
</tr>
<tr>
<td>Cold Fluid Injection Rate</td>
<td>360</td>
<td>m$^3$/d</td>
</tr>
<tr>
<td>Water Specific Heat Capacity</td>
<td>4.187</td>
<td>kJ/(kg K)</td>
</tr>
<tr>
<td>Formation Thermal Conductivity</td>
<td>2.42</td>
<td>W/(mK)</td>
</tr>
<tr>
<td>Cement Thermal Conductivity</td>
<td>6.95</td>
<td>W/(mK)</td>
</tr>
<tr>
<td>Production/Injection Time</td>
<td>2880</td>
<td>hour</td>
</tr>
</tbody>
</table>

For downhole thermoelectric modules, Bi$_2$Te$_3$-based material are selected as the semiconductor due to its commercially availability, high performance and proven engineering applications under moderate to low temperature (Chet et al., 2015; Cheng et al., 2016). Cross-section areas of semiconductors are determined by the optimal geometrical factor $\mu$ discussed in last section. TEG parameters are shown as following Table 2.
Table 2: Thermoelectric properties and design parameters in this case study.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>P-type: Bi$_{2-x}$Sb$_x$Te$_3$</td>
<td>Seebeck coefficient</td>
<td>222.48</td>
</tr>
<tr>
<td></td>
<td>Electrical Resistivity</td>
<td>12.5</td>
</tr>
<tr>
<td></td>
<td>Thermal Conductivity</td>
<td>1.36</td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Cross-section Area</td>
<td>0.5</td>
</tr>
<tr>
<td>N-type: Bi$<em>2$Se$</em>{3-y}$Te$_y$</td>
<td>Seebeck coefficient</td>
<td>-223.06</td>
</tr>
<tr>
<td></td>
<td>Electrical Resistivity</td>
<td>12.9</td>
</tr>
<tr>
<td></td>
<td>Thermal Conductivity</td>
<td>1.41</td>
</tr>
<tr>
<td></td>
<td>Length</td>
<td>0.5</td>
</tr>
<tr>
<td></td>
<td>Cross-section Area</td>
<td>0.48</td>
</tr>
</tbody>
</table>

Simulations of downhole power generation are conducted using the above data. Temperature distribution in both tubing and annulus are calculated and parameters related to power generation are also obtained. Results analysis and discussion are as follows.

7. Results and Discussion

7.1 Results of Temperature Distribution

Temperature distributions in tubing, annulus and formations are plotted in the following Figure 5, and dotted lines are drawn to highlight the impact of TEG on temperature distribution. The produced water entered the tubing at reservoir temperature and flowed out with a temperature drop of 16.8°C due to major thermal energy conversion to electricity at TEG section, and minor heat loss during production. The surface temperature of coproduced water is still high up to 103°C, which could be sent to the binary power plant for power generation, and it indicates the downhole power generation will not interfere routine power generation. As the fluids flow upwards, annulus is heated up by 33°C mainly because of the heat conducted from surrounding formation and heat transfer from tubing. TEG is installed at the circulation depth, where features the highest temperature inside the tubing, lowest temperature in the annulus as well as the largest temperature difference across the two sides of TEG. In addition, the presence of injection pipe could keep continuous cold fluid injected down to the circulation depth to cool the TEG, and flowing upward to extract heat conducted out of TEG and the heat from surrounding formation, which not only help maintain a low temperature for the cold side of thermoelectric module, but also provide heated fluid for surface direct use.

7.2 Results of Thermoelectric Performance

In this study, we obtained that the dimensionless figure of merit is 0.97, which is a normal value in the range of thermoelectric industry and very close to unit. Maximum efficiency of thermal to electricity is calculated as 4.7%, leading to the maximum power is 9848W. Thermoelectric performance is quantified in Table 3.
Figure 5: Downhole temperature distributions in this case study

Table 3: Thermoelectric Performances in this case study.

<table>
<thead>
<tr>
<th>Thermoelectric Parameters</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure of Merit (Z)</td>
<td>0.0028</td>
<td>K⁻¹</td>
</tr>
<tr>
<td>Dimensionless Figure of Merit (ZT)</td>
<td>0.97</td>
<td>/</td>
</tr>
<tr>
<td>Optimal Efficiency</td>
<td>4.7%</td>
<td>/</td>
</tr>
<tr>
<td>Maximum Power Output</td>
<td>9,848</td>
<td>W</td>
</tr>
</tbody>
</table>

To evaluate the TEG performance, the result is compared with both experimental and simulation results using same thermoelectric material in the literature. Listed are the parameters of interests
in comparison in Table 4, including dimensionless figure of merit, power generation efficiency, and power generation per unit area.

Table 4: Thermoelectric Performances Comparison with other results from literatures

<table>
<thead>
<tr>
<th>Reference</th>
<th>Temperature Range, °C</th>
<th>Result Type</th>
<th>ZT</th>
<th>Efficiency</th>
<th>Power Generation per Area, W/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>This study</td>
<td>20-120</td>
<td>Simulation</td>
<td>0.97</td>
<td>4.7%</td>
<td>0.246</td>
</tr>
<tr>
<td>Cheng et al., 2016</td>
<td>26-176</td>
<td>Experiment</td>
<td>0.96</td>
<td>5%</td>
<td>0.282</td>
</tr>
<tr>
<td>Liu et al., 2014</td>
<td>30-180</td>
<td>Experiment</td>
<td>1</td>
<td>4%</td>
<td>0.287</td>
</tr>
<tr>
<td>Suter et al., 2012</td>
<td>20-140</td>
<td>Simulation</td>
<td>1</td>
<td>4.2%</td>
<td>/</td>
</tr>
</tbody>
</table>

7.3 Results of overall power generation

Coproduced water can be collected at surface and transported to binary power plant for power generation. Using the existing coproduction practice (power plant outlet temperature 85°C) reported by Xin et al. (2012), the well in this case study could provide power generation up to 34kW alone and 276 kW following 8 well waterflooding practice. If calculating the power generation potential using model of Tester et al. (2006), which allows a lower outlet temperature (35°C), the power generation is estimated as 79kW. Combining both downhole and surface power generation, the total power generation in one well could reach up to 43.8kW and 88.8kW, based on aforementioned two models, respectively. The overall power generation in this study is very competitive with the results of power generation using coproduction fluid reported by Xin et al. (2012) and Liu et al. (2015) in per well basis.

Along with the development in thermoelectric technology, advanced material with higher figure of merit will enhance the power generation performance and further accelerate the application of TEG in oilfield geothermal utilization. If more wells are refitted to use downhole TEG and TEG section length is increased, considerable power could be generated in downhole condition. The generated electricity could be used to power on-site equipment, such as injection pump, and offset the related operation cost. Besides on-site application, downhole power generation could assist the surface power plant and provide additional electricity to the grid, reducing the electricity cost. The application of downhole power generation could include more wells feasible for geothermal power generation, especially for wells that cannot be considered for coproduction due to geographically located in low popular density area, or located far from power plant, where is not economic to build a power plant.

8. Conclusions

This paper proposed an innovative design for downhole power generation after reviewing the features of geothermal resource in oil and gas wells and the thermoelectric technology. A detailed downhole construction design is demonstrated, followed by the calculation of temperature distribution and TEG optimization. The design is applied into a case study in
Gudong oilfield in China, and the advantage of downhole power output is emphasized by comparison with both theoretical studies and real practices.

Based on above review and analysis, we draw conclusions as follows.

1. It is very beneficial to utilize geothermal energy in oil and gas wells due to the abundant storage and existing advantage. Thermoelectric technology is considered to be one possible solution to spread oilfield geothermal utilization.
2. An innovative downhole power generation design is presented and power generation performance is illustrated by case study. The electricity conversion efficiency of downhole TEG system reached 4.7% at temperature of about 120°C on the hot side and a temperature of 20°C on the cold side, and the power generation per unit is about 0.246W/cm². Competitive power generation is achieved in this study.
3. To apply thermoelectric technology in oilfield geothermal utilization, it is crucial to generate sufficient temperature difference for better thermoelectric performance.
4. Downhole power generation using thermoelectric technology could work together with binary power plant as a complementary without interfere with on-going operation. It also could work solely in wells that far from a power plant.
5. Downhole power generation from high water cut oil wells could provide great advantages to benefit the oilfield in terms of offsetting operation cost, extending economic life of mature oilfield and reducing greenhouse gas emissions.
6. Proposed downhole power generation design is also applicable for abandoned wells, geothermal wells, and EGS wells.

REFERENCES


Karl, B., Hebert, I., &Jesse, W., 2009. Electric power generation using geothermal fluid coproduced from oil and/or gas wells. *GRC Transaction*, 33, 671–672


Angrist, S. Direct Energy Conversion. *Allyn and Bacon Inc.*, 1971

