GRC Transactions, Vol. 42, 2018

# A Design of Downhole Thermoelectric Generation for Horizontal Oil Wells

**Kai Wang, Xingru Wu**

**University of Oklahoma**

**Keywords**

*Oilfield geothermal resource; horizontal wells; thermoelectric technology; geothermal power generation; downhole power generation; heat transfer*

## ABSTRACT

Harnessing geothermal energy for power generation from oil wells features significant advantages over traditional geothermal wells, especially in reducing capital expenditure and operational risks. Downhole geothermal power generation using thermoelectric technology in a vertical well was recently proposed to develop the geothermal energy from oilfields. This paper proposes a new design of downhole power generation to extend the application of thermoelectric generation to horizontal wells which have enlarged contact area with high temperature formation and better heat transfer and conversion efficiency.

In the design, we retrofit the horizontal wellbore to circulate cold water inside the tubing so that the cold temperature interface can be created. The formation fluids (oil and water) flow through the annulus of the tubing and casing so that we can keep hot temperature on the side of tubing. By attaching thermoelectric generators (TEG) on the outer surface of tubing, this retrofit will make it possible to capture subsurface in-situ geothermal energy and directly transfer to electricity in hydraulically fractured unconventional wells. Furthermore, we also built the mathematical model to account for the heat conduction and convention in the horizontal wellbore and formation, which could accurately simulate the temperature distribution and power generation under variable operational conditions. Based on the model, we identified the key parameters with significant impact on power generation and established the well section criteria for best power generation performance. To discover the potential of power generation in horizontal wells, we conducted a case study using the data of YS-1 horizontal well in Daqing Oilfield in northeast China and compared the power generation performance in YS-16 vertical well with same TVD and same power generation device installation.

The results of case study indicated that Daqing Oilfield is of great potential for geothermal power generation using its horizontal wells, and the horizontal well displayed exceeding power generation performance over vertical wells. In practice, this paper enriches geothermal

development methods and provides the foundation for oil and gas producer to identify the opportunity and capitalize on geothermal power generation from horizontal wells.

## 1. Introduction

Geothermal energy is one of the most important modern renewable energies. Geothermal project activities are increasing worldwide to take advantage of such a sustainable resource to produce electricity and to provide space heating with a reduced environmental footprint. However, geothermal energy only accounts for a small part in the overall energy consumption structure and geothermal power generation only comprised an estimated 0.21% of the world's power generating capacity(Li et al., 2015), because of multiple restrictions such as high drilling cost (Barbier, 2002) and low energy conversion efficiency (Zarrouk and Moon, 2014). Using oil wells for geothermal development provides a solution which could significantly reduce the high capital expenditure by taking advantages of existing oilfield assets. Oil wells are considered to be beneficial to develop geothermal energy, because oilfields not only feature massive geothermal storage, but also provide significant advantages for geothermal development and utilizations.

Tester et al.(2006) studied the geothermal power generation potential of produced water from oil wells in California, Oklahoma, and six other states along the Gulf Coast, and they estimated that over 11,000 MW could be generated from coproduced water which 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. Wang et al.(2018) summarized the unique advantages to develop geothermal resource from oilfields and the developing oilfield geothermal resource characterized as cost-effective and less risky compared to traditional geothermal fields development. Moreover, oilfields could offer sufficient wells as geothermal production candidates and provide abundant market to utilize geothermal resource for building heating, geothermal assisted crude oil transportation and geothermal waterflooding.

In current practice, high temperature produced water from oil wells are pumped into binary power plant for power generation. Notable efforts have been made in oilfields in Wyoming (Reinhardt et al., 2011), North Dakota (Gosnold, 2017) in USA and in Huabei Oilfield in China (Xin et al., 2012). However, very limited number of oil wells are qualified for geothermal power generation using current binary power generation technology. First of all, binary power plant has strict requirements on water temperature and inlet rate to efficiently produce electricity (Liu et al., 2015), which excludes many oil wells for geothermal power generation. Meanwhile, the bottom temperature range of a typical oil well falls into low to moderate temperature for power generation, and there exists large amount of heat loss to surrounding formation during the production, especially under declined production rate, which further reduces the number of wells suitable for geothermal power generation. Therefore, although cost is significantly reduced, thermal recovery and conversion efficiency is still low to develop oilfield geothermal energy in a large scale using binary power plant.

To improve thermal recovery efficiency, enrich thermal recovery method and enlarge temperature ranges for geothermal power generation, thermoelectric technology is extensively studied in recent literature. The thermoelectric power generation is based on the Seebeck effect. Under certain temperature difference, thermoelectric modules could directly transform thermal energy into electricity without through mechanical work to turn the turbines. 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. Wang et al.(2017)first put up with the design of downhole power generation from a vertical oil wells, which integrated thermoelectric technology with on-going oil production and directly generate electricity by capturing in-situ geothermal resource using thermoelectric generators (TEGs). By advantages of small size, high reliability, low maintainess requirement, no pollutants and feasibility in a wide temperature range (Liu et al., 2013; Zhang and Zhao, 2015), TEG not only features solid technology foundation, but also provides excellent opportunity to match oil production. To be specific, small size TEG is suitable to be installed on multiple types of subsurface pipes in confined wellbore space. High reliability and low maintainess requirement perfectly match the preferred continuous oil production. Wide temperature range feasibility of TEG could enable downhole power generation applied to enlarged number of wells.

To further enhance the geothermal power generation from oil wells, this paper extends the design of downhole power generation into horizontal wells. Horizontal well brings significant boom for oil and gas productions by enlarging reservoir contact area, and ultimately increase the production of oil and gas. By the same principle, geothermal production could be benefited using horizontal well as an enhanced thermal recovery method. Especially for rapid development of unconventional oil and gas in recent decade, tens of millions of wells are drilled horizontally and hydraulic fractured in multiple stages. Therefore, these unconventional horizontal wells always feature long horizontal sections and fracture networks, which provide largely increased contact area with high temperature formation and large production rate. In this work, we are motivated to take advantages of great geothermal potential in these horizontal wells and design downhole power generation for improved geothermal recovery.

## 2. Thermoelectric Technology

Thermoelectric technology is one solid-state energy conversion method, which could directly transform thermal energy into electricity in the presence of temperature difference through the Seebeck effect (Zhang and Zhao, 2015). As shown in Figure 1, TEG contains many thermoelectric couples consisting of N-type and P-type thermoelectric elements wired electrically in series and thermally in parallel (Snyder and Toberer, 2008). As a mature technology, thermoelectric technology has been considered as a global sustainable energy solution to harness industrial and automotive waste heat (Aranguren et al., 2017; Gou et al., 2013; Kumar et al., 2013; Snyder and Toberer, 2008; Twaha et al., 2016). Furthermore, the application of thermoelectric technology for geothermal power generation has been extensively studied and testified in the literature (Ahiska and Mamur, 2014; Ben Cheikh et al., 2014; Eisenhut and Bitschi, 2006; Li et al., 2015; Liu et al., 2014; Suter et al., 2012).

A thermoelectric generator uses heat flow across a temperature gradient to power an electric load through the external circuit. The temperature difference provides the voltage from the Seebeck effect while the heat flow drives the electrical current, which therefore determines the power output. The voltage generated from TEG mainly depends on the temperature difference between hot side ($T_H$) and cold side ($T_C$), and Seebeck coefficient ($\alpha$) as given by

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

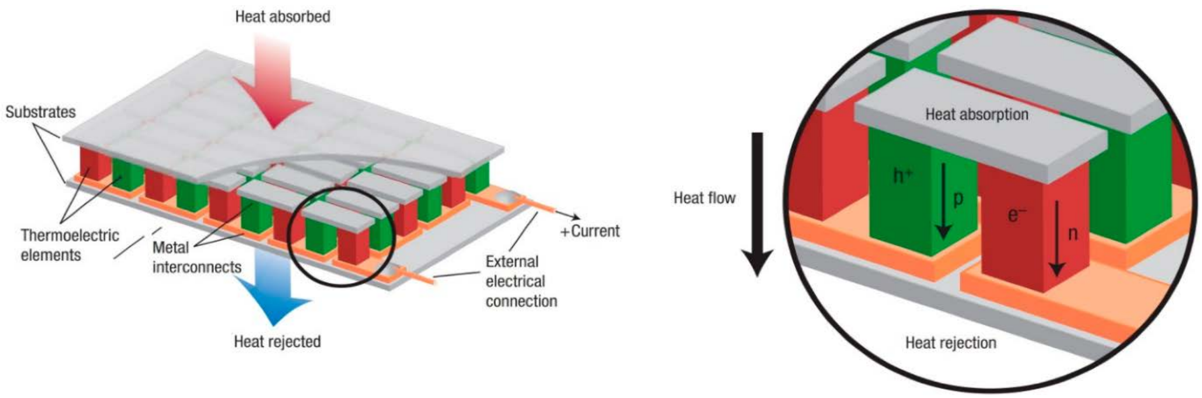


**Figure 1 Schematic of a typical thermoelectric generator (after Snyder and Toberer, 2008)**

In general, to gain the maximum power generation efficiency, the important characteristic for thermoelectric material is the dimensionless figure of merit ZT, which is a nature parameter of a certain material and it is always used to gauge the performance of a thermoelectric material. Figure of merit stands for the ability of a given material to efficiently produce thermoelectric power.

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

where $\alpha, k$ and $\sigma$ stand for the Seebeck coefficient, thermal conductivity and electrical resistivity of the thermoelectric material.

In order to get high thermoelectric efficiency, the figure of merit should be large. For an ideal material, a large absolute value of the Seebeck coefficient, low electrical resistance and low thermal conductivity are preferred. Liu et al.(2018) concluded the temperature of an oil well typically ranges from 80°C to 150°C (176°F to 302°F). Within such temperature range, $Bi_2Te_3$ alloys have been proved to possess the greatest figure of merit for both n- and p-type thermoelectric systems (Figure 2). Therefore, $Bi_2Te_3$-based material would be the best selection for downhole power generation due to its highest ZT value in given temperature range (Cheng et al., 2016; Chet et al., 2015; Snyder and Toberer, 2008) and its viability on current markets (Twaha et al., 2016).

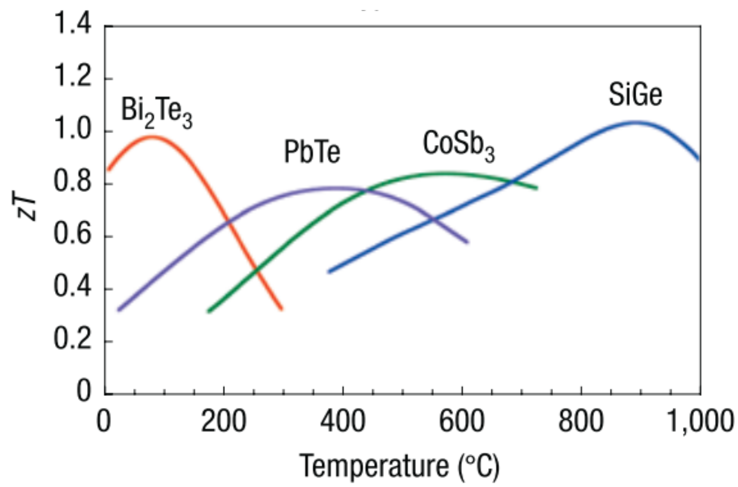


**Figure 2  ZT values of different material in given temperature ranges (Snyder and Toberer, 2008)**

Besides the material selection of TEG, the geometry is also customized for downhole geothermal power generation application. The prevailing TEG products on the market is in small size with flat surface, and disc geometry (Sinha and Joshi, 2011) , annular geometry (Manikandan and Kaushik, 2017), circular geometry (Fabián-Mijangos et al., 2017) and roll cake geometry (Suzuki, 2004) are proposed in the literature. In this study, an annular ring shape TEG to be attached on pipe surface. So far, the expected geometry is as following Figure 3, which shows the front view (i) and top view (ii) of a segment of TEG-mounted tubing.

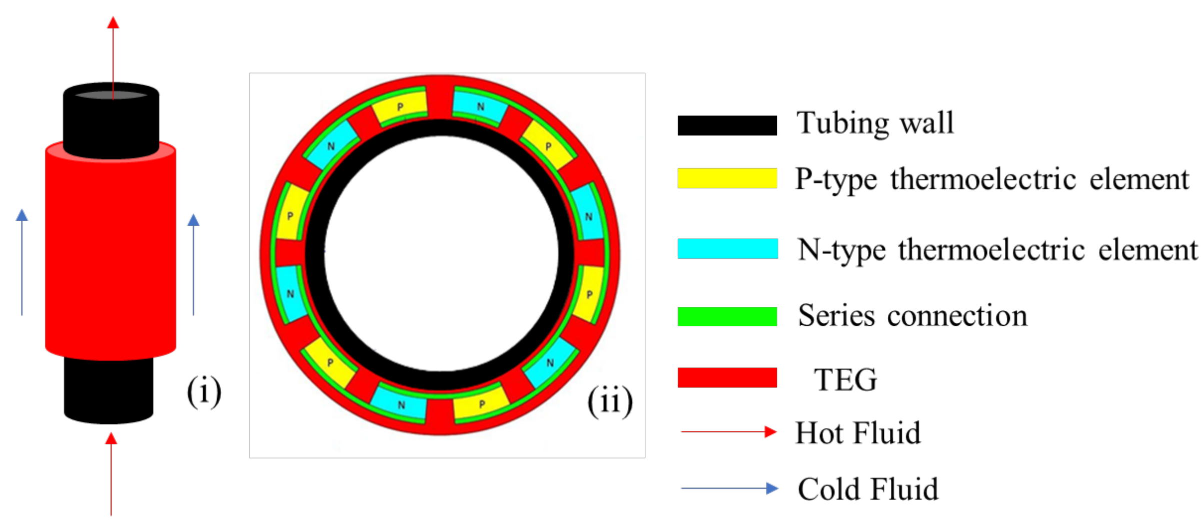


**Figure 3 Schematics of TEG installation on the tubing**

## 3. Downhole Geothermal Power Generation in Horizontal Wells

A design of downhole geothermal power generation in an oil well is recently proposed (Wang et al., 2017) as Figure 4. Such design is aiming to maximize the temperature difference across the TEG. TEGs are installed on the tubing and small size pipes are installed in the annulus between casing and tubing for cold water injection. Temperature difference is created and maximized by hot fluid in the tubing flowing through one side of TEG and cold water flowing through the other side of generator. Temperature at hot side of TEG is maintained by continuous production of hot fluid from the reservoir, and temperature at cold side is kept low by cold water injection and thermal insulation of the injection pipe.

This work is an extension of above vertical well design to horizontal well, motivated by the wide applications of horizontal drilling along with the boom of unconventional oil and gas development. By the principle of enlarged contact area with hydrocarbon reservoir, horizontal well significantly improved the production of unconventional oil and gas, such as shale gas, tight sand gas and shale oil (Cui et al., 2017; Yuan et al., 2017). Similarly, horizontal well is regarded as an improved thermal recovery method in geothermal application with enlarged contact area exposed to the high temperature formation. Furthermore, massive water production has been reported in unconventional resource wells (Kondash et al., 2017), which leads to increasing water disposal cost and decreasing profit. Therefore, to make full use of the existing horizontal well, this work is intended to add geothermal production on the active hydrocarbon production.

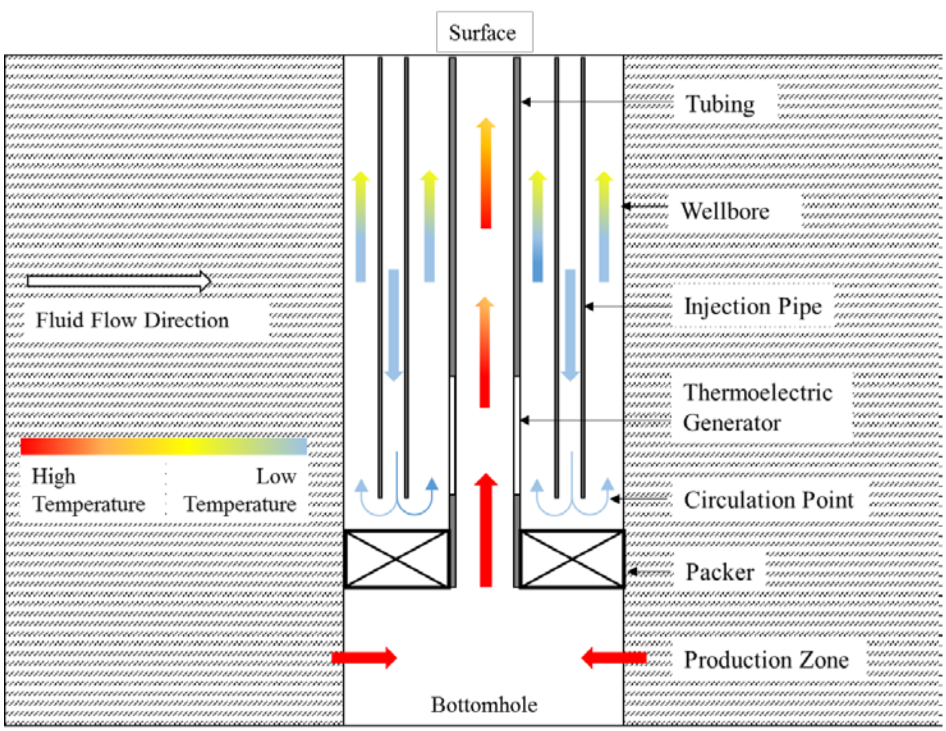


**Figure 4 Schematic of downhole power generation in a waterflooding well (Wang et al., 2017)**

For horizontal wells completed and fractured by plug and perf method, which is the most popular completion method in unconventional plays, we retrofit the wellbore to circulate cold water inside the tubing so that the cold temperature interface can be created. The formation fluids flow through the annulus of the tubing and casing so that we can keep hot temperature on the side of tubing. By attaching TEGs on the outer surface of tubing, this retrofit will make it possible to capture subsurface in-situ geothermal energy and directly transfer to electricity in hydraulically fractured horizontal wells (Figure 5).

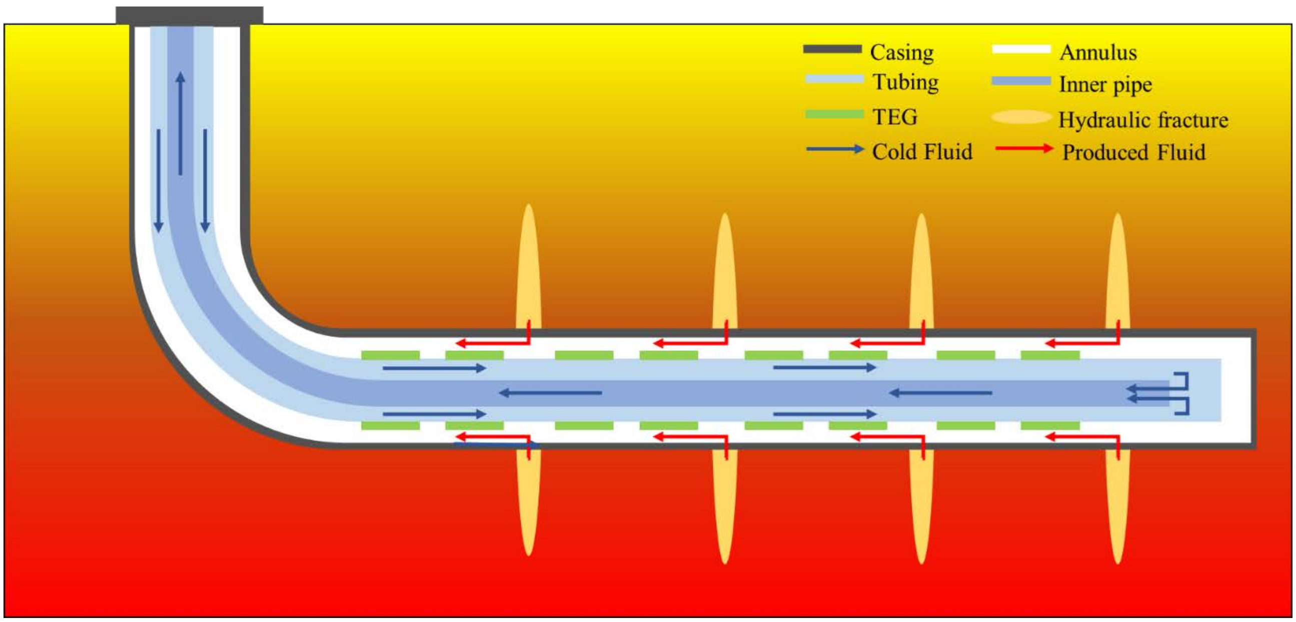


**Figure 5 Schematics of downhole power generation in unconventional horizontal wells**

The long horizontal segment located in the high temperature reservoir can effectively maintain the high temperature on one side of TEG and the circulated cold water in the tubing could keep the other side of TEG at low temperature. By such effort, TEG will be kept at largest temperature difference and the power generation would be maximized consequently. Compared to the design in a vertical well, the new horizontal application could have all TEGs installed in the horizontal segment, where these TEGs could directly exposed to the highest temperature zone to maximize the power generation. While in a vertical well, there are only limited number of TEGs, which located close to the production zone, could enjoy the highest temperature at the hot side.

## 4. Mathematical Model

### *4.1 Assumptions*

To set up the mathematical model accounting for the heat transfer and fluid flow behavior in this geometry, basic assumptions are made as follows. Considering the wellbore as a cylindrical geometry, well symmetry simplifies the problem into two dimensions. Geothermal gradient is considered as constant, and the formation temperature is a linear function of depth. The produced fluid from the stimulated reservoir is assumed with constant temperature, which equals to the reservoir temperature. Both production and injection fluids are assumed to be incompressible Newtonian fluids. The Joule-Thompson effect, viscous dissipation and thermal expansion in wellbore are assumed to be negligible. Thermoelectric material used in this study is assumed to be homogenous and isotropic, and heat transfer in TEG is considered as 1-D from hot side to cold side.

### *4.2 Geometry Schematics*

The entire geometry is divided into different subdomains in radial direction as Figure 6 with fluid flow direction indicators, where red line represents produced fluid and blue lines are injected fluids. Each subdomain is identified as shown in the following Table 1. Each subdomain listed below is under different heat transfer process respectively. Convection appears in the annulus and happens at the contacting inner pipe, tubing and casing wall. On the other hand, the heat transfer inside pipe walls, TEG, cement and formation are governed by heat conduction.

**Table 1 Description of divided subdomains**

| Subdomains | Regions | Physical meaning |
|---|---|---|
| 1 | $0 \le r < r_1$ | Internal of Inner pipe |
| 2 | $r_1 \le r < r_2$ | Inner pipe wall |
| 3 | $r_2 \le r < r_3$ | Annulus between inner pipe and tubing |
| 4 | $r_3 \le r < r_4$ | Tubing wall |
| 5 | $r_4 \le r < r_5$ | Annulus between tubing and casing |
| 6 | $r_5 \le r < r_6$ | Casing wall |
| 7 | $r_6 \le r < r_7$ | Cement sheath |
| 8 | $r_7 \le r < r_8$ | Formation |

### *4.3 Governing Equations*

Based on the assumptions, the mathematical model could be set up as a 2-D cylindrical coordinate system. The fluid flow and heat transfer in this model could be expressed by the equation of change in non-isothermal system. For a small element of volume in this geometry, the equation of energy conservation could be written as

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho v^2+\rho U\right)=-\left(\nabla\cdot\left(\frac{1}{2}\rho v^2+\rho U\right)v\right)-\nabla\cdot q-\nabla\cdot pv-\nabla\cdot\left(\tau\cdot v\right)+\rho\left(v\cdot g\right) \qquad (3)$$

where $\rho$ and $v$ are the density and the velocity of the fluid, respectively. $P$ stands for the pressure, and $U$ represents the internal energy of the fluid per unit mass. $g$ is the acceleration of gravity. Therefore, it is easy to tell that the term on the left side of equation represents the rate of kinetic and internal energy change per volume, and the terms on the right side represents: rate of increase of energy per volume due to convection, rate of energy increase due to molecular transport, rate of work done on the fluid by viscous forces, rate of work done on the fluid by pressure forces, and rate of work done on the fluid by gravitational forces, respectively.

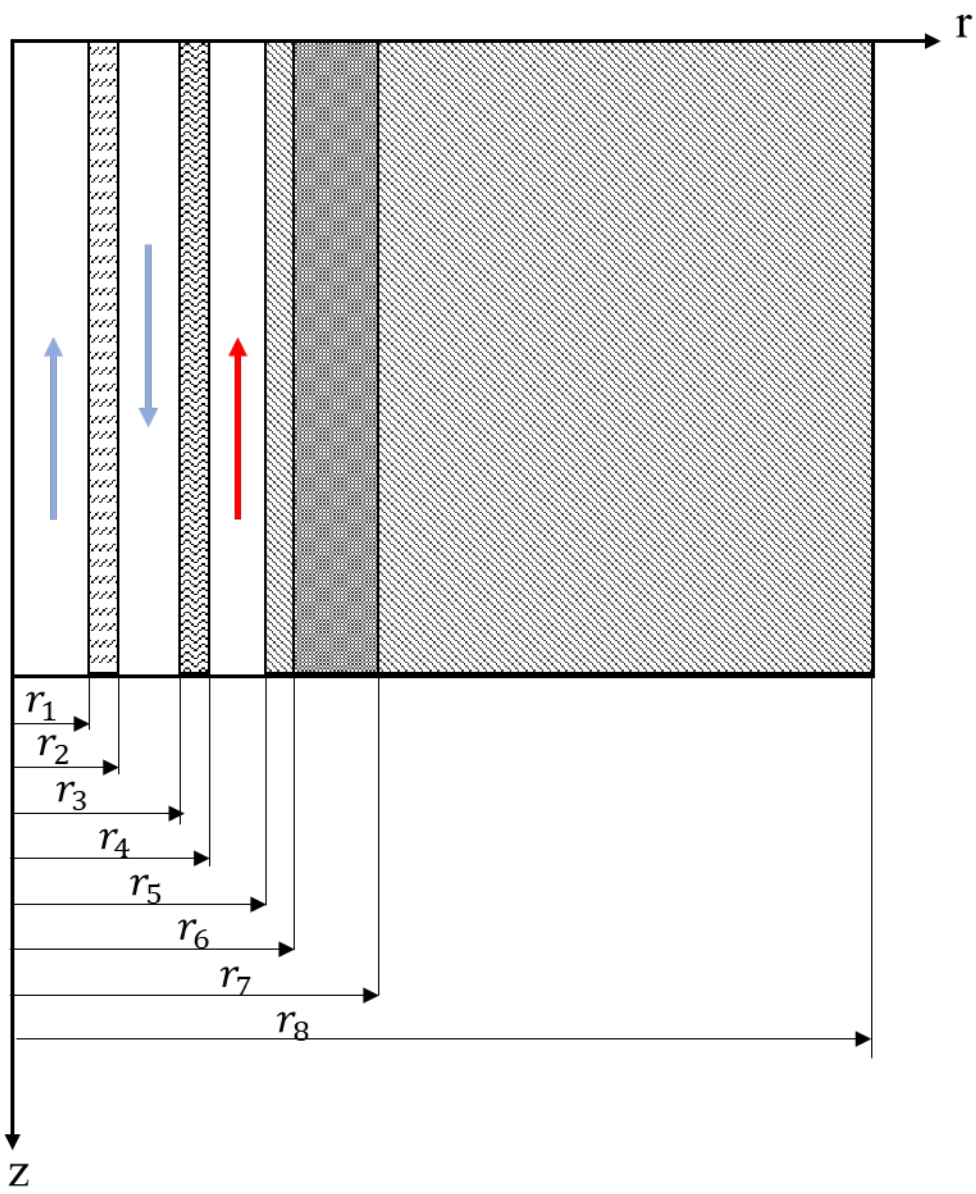


**Figure 6 Schematics of divided geometry**

The equation of mechanical energy change is,

$$\frac{\partial}{\partial t}\left(\frac{1}{2}\rho v^2\right)=-\left(\nabla\cdot\frac{1}{2}\rho v^2 v\right)-\nabla\cdot pv-\nabla\cdot(\tau\cdot v)-(-\tau:\nabla v)+\rho(v\cdot g) \tag{4}$$

Subtract Equation 4 from 3, we could obtain the equation of change for internal energy,

$$\frac{\partial}{\partial t}(\rho U)=-(\nabla\cdot\rho Uv)-\nabla\cdot q-\nabla\cdot pv-(\tau:\nabla v) \tag{5}$$

Heat conduction is modeled by using Fourier's Law, and write into cylindrical coordinate as,

$$\rho C_P\left(\frac{\partial T}{\partial t}+v_r\frac{\partial T}{\partial r}+v_z\frac{\partial T}{\partial z}\right)=\frac{k_r}{r}\frac{\partial T}{\partial r}+k_r\frac{\partial^2 T}{\partial r^2}+k_z\frac{\partial^2 T}{\partial z^2} \tag{6}$$

where $C_p$ is the specific thermal capacity of the fluid, $k_r$ is the thermal conductivity in the radial direction and $k_z$ is the thermal conductivity in vertical direction.

### *4.4 Initial and Boundary Conditions*

After derivation of above equations, initial and boundary conditions are necessary to numerically solve the problem. Assume the well has been produced for a long time and is dominantly producing water over oil, therefore the initial condition is assumed the entire wellbore are mainly filled with water and the temperature is the same as the reservoir temperature. The boundary conditions can be found at the tubing wall and inner pipe wall, where the amount of heat conduction is equals to the amount of heat convection. One more boundary condition is that the outer boundary of the reservoir has constant temperature. These boundary conditions could be mathematically written as,

$$k\frac{\partial T_t}{\partial r}|_{pipe\ wall}=h(T_2-T_1) \tag{7}$$

$$T|_{r=\infty}=T_{constant} \tag{8}$$

### *4.4 Effect of TEG on Temperature Distribution*

The TEGs installed on the outer surface of tubing could largely alter the temperature distribution due to thermal-electricity conversion process as well as generated joule heating during the conversion. To account for the effect of TEG on temperature distribution, a parameter of effective thermal conductivity is introduced into this model to accurately characterize the heat transfer phenomena associated with thermal-electric conversion, which is given by Baranowski et al.(2013) as,

$$k_{eff}=\frac{kT_H\left(1+ZT+\sqrt{1+ZT}\right)}{2(T_H-T_C)}\left(1-\left(\frac{T_H}{T_C}\right)^{\frac{2-2\sqrt{1+ZT}}{ZT}}\right) \tag{14}$$

Applying the concept of effective thermal conductivity greatly simplifies temperature distribution calculation by allowing all of the heat transport to be modeled as heat conduction. Based on the governing equation, initial and boundary conditions, the temperature distribution in multiple pipes in the study unit could be numerically obtained.

## 5. Case Study

### *5.1 Basic Information of Case Study*

A basic case in Xujiaweizi area in Daqing Oilfield in China is study to demonstrate the downhole geothermal power generation potential in a multistage hydraulic fractured horizontal well. Study area in this work is located in northeast China. A large area of thermal anomaly regions can be observed near Harbin city from the geothermal gradient map. Geothermal gradients in this area are generally greater than 4.8/100m, which indicate a great potential for geothermal development (Figure 7).

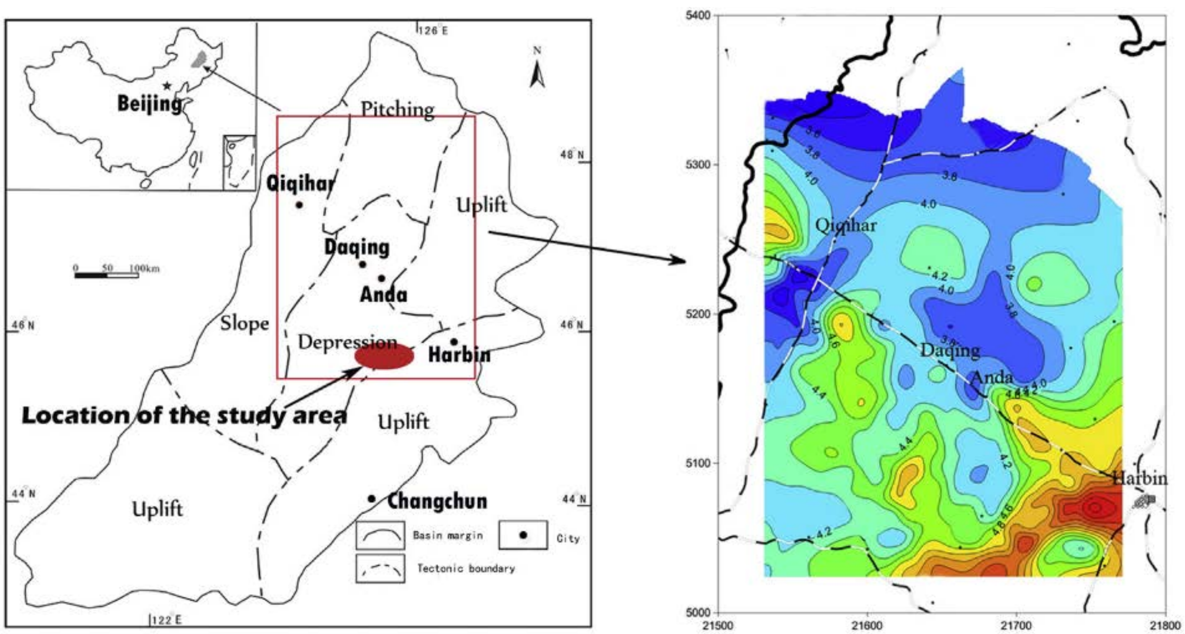


**Figure 7 Location and geothermal gradient map of study area (Zhang et al., 2014)**

The well was drilled to total depth of 5000m with 1500m horizontal section and 3250m TVD. The surface temperature is 20°C and the geothermal gradient is 4.8°C/100m, which leads to the reservoir temperature to 176°C. It was cased with 7’’ API casing to the bottomhole, followed by cementation and perforation. The well was divided into 13 stages and successfully hydraulic fractured in each stage. As designed, 3-1/2’’ tubing is installed to the depth of 4950 m, with an 2-1/16’’ inner pipe inside to the depth of 4940m. A series of TEGs are mounted on the outer surface of tubing. 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 2.

**Table 2 Parameters of horizontal well and target formation in this case study**

| Parameters | Value | Unit |
|---|---|---|
| Tubing OD | 3.5 | in |
| Tubing ID | 2.992 | in |
| Casing OD | 7 | in |
| Casing ID | 6.456 | in |
| Injection Pipe OD | 2.063 | in |
| Injection Pipe ID | 1.751 | in |
| Bottomhole Depth | 5000 | m |
| Circulation Depth | 4940 | m |
| Geothermal Gradient | 0.048 | °C/m |
| Surface Temperature | 20 | °C |
| Reservoir Temperature | 176 | °C |
| Cold Fluid Injection Temperature | 20 | °C |
| Water Production Rate | 360 | $m^3/d$ |
| Cold Fluid Injection Rate | 120 | $m^3/d$ |
| Water Specific Heat Capacity | 4.187 | kJ/ (kg K) |
| Formation Thermal Conductivity | 2.42 | W/(mK) |
| Cement Thermal Conductivity | 6.95 | W/(mK) |
| Production/Injection Time | 2880 | hour |

As previously discussed, Bi2Te3-based material is selected as the semiconductor of TEG and the thermal and electrical properties of n-type and p-type pairs are listed as below Table 3 referenced from the experimental investigation of Cheng et al.(2016).

### *5.2 Result and Discussion*

Temperature distributions in tubing, annulus and formations are plotted in the following Figure 8. The four lines are representing the injected fluid temperature, return fluid temperature, reservoir temperature and produced fluid temperature, respectively in red, purple, green and blue. Heat to electricity conversion happened at those locations, and led to temperature drops in produced fluid due to heat consumption and temperature increase in injected fluid due to heat conduction and joule heating. The temperature of produced fluid was quickly returned to normal due to continuous thermal supply from the production and temperature drop and resume was repeated in each stage

**Table 3 Thermoelectric properties of TEG material in this case study**

| Parameters | | Value | Unit |
|---|---|---|---|
| P-type: $Bi_{2-x}Sb_xTe_3$ | Seebeck coefficient | 222.48 | μV*K$^{-1}$ |
| | Electrical Resistivity | 12.5 | μΩ*m |
| | Thermal Conductivity | 1.36 | W/(mK) |
| | Length | 0.5 | inch |
| | Cross-section Area | 0.5 | cm$^2$ |
| N-type: $Bi_2Se_{3-y}Te_y$ | Seebeck coefficient | -223.06 | μV*K$^{-1}$ |
| | Electrical Resistivity | 12.9 | μΩ*m |
| | Thermal Conductivity | 1.41 | W/(mK) |
| | Length | 0.5 | inch |
| | Cross-section Area | 0.48 | cm$^2$ |

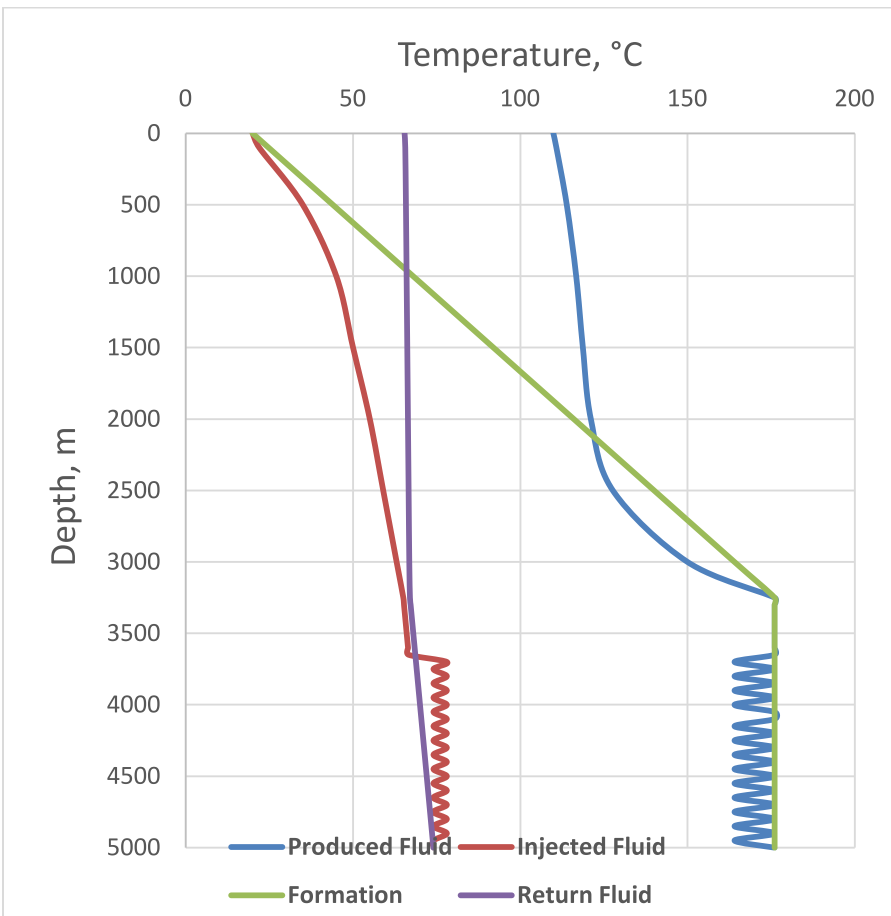


**Figure 8 Downhole temperature distributions in this case study**

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 128,024W. Thermoelectric performance is quantified in Table 4.

**Table 4 Thermoelectric Performances in this case study.**

| Thermoelectric Parameters | Value | Unit |
|---|---|---|
| Figure of Merit (Z) | 0.0028 | $K^{-1}$ |
| Dimensionless Figure of Merit (ZT) | 0.97 | / |
| Optimal Efficiency | 4.7% | / |
| Maximum Power Output | 128,024 | W |

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 5, including dimensionless figure of merit, and power generation efficiency, which shows very competitive TEG performance compared to the literature.

**Table 5 Thermoelectric Performances Comparison with other results from literatures**

| Reference | Temperature Range, °C | Result Type | ZT |
|---|---|---|---|
| This study | 20-120 | Simulation | 0.97 |
| Cheng et al., 2016 | 26-176 | Experiment | 0.96 |
| Liu et al., 2014 | 30-180 | Experiment | 1 |
| Suter et al., 2012 | 20-140 | Simulation | 1 |

## 6. Conclusions

A design of downhole geothermal power generation in hydraulic fractured unconventional horizontal wells is proposed in this study. Mathematical model was established to characterize the temperature field associated with such design. A case study in Daqing Oilfield demonstrated the technical feasibility and geothermal potential. The following conclusions have been drawn:

1) Downhole geothermal power generation from a horizontal well can significantly enhance the heat exchange and improve thermal recovery efficiency, compared to a vertical well.

2) A numerical simulation model of heat conduction and convection is established based on the horizontal wellbore construction design, and could be used to calculate the temperature distribution along the wellbore.
3) Key parameters which have great impact on temperature distribution and power generation are identified. The increase of the horizontal segment length and the fluid injection rate can significantly increase power generation efficiency, and a good thermal insulation tubing is preferred to reduce heat loss and increase the temperature difference across the TEGs. Fluid injection rate and horizontal segment length can be optimized based on specific well and reservoirs parameters to maximize the conversion efficiency.
4) This design could add extra geothermal production on routine oil production, which not only offset the operation cost and extend economic life of a well, but also have considerable social and environmental benefit by providing a new method to produce clean energy.
5) This method is expected to be promising due to large numbers of horizontal well entering declined production period and the global trend of renewable and clean energy. In practice, this study could help oil and gas producers to evaluate their assets, identify opportunities for geothermal power generation project and capitalize on such project.
6)

## REFERENCES


Ahiska, R., Mamur, H., 2014. A review: Thermoelectric generators in renewable energy. Int. J. Renew. Energy Res. 4, 128–136.

Aranguren, P., Araiz, M., Astrain, D., Martínez, A., 2017. Thermoelectric generators for waste heat harvesting: A computational and experimental approach. Energy Convers. Manag. 148, 680–691. https://doi.org/10.1016/j.enconman.2017.06.040

Baranowski, L.L., Snyder, G.J., Toberer, E.S., 2013. Effective thermal conductivity in thermoelectric materials. J. Appl. Phys. 204904, 1–11. https://doi.org/10.1063/1.4807314

Barbier, E., 2002. Geothermal energy technology and current status: An overview. Renew. Sustain. Energy Rev. 6, 3–65. https://doi.org/10.1016/S1364-0321(02)00002-3

Ben Cheikh, R., El Badsi, B., Masmoudi, A., 2014. Geothermal sources-based thermoelectric power generation: An attempt to enhance the rural electrification in southern Tunisia. 2014 9th Int. Conf. Ecol. Veh. Renew. Energies, EVER 2014. https://doi.org/10.1109/EVER.2014.6844080

Cheng, F., Hong, Y., Zhang, B., Tang, W., 2016. Experimental optimization of the area-specific power for thermoelectric modules. Spacerfaft Envoriment Engeering 33. https://doi.org/10.3969/j.issn.1673-1379.2016.04.015

Chet, D.L., Singh, B., Remeli, M.F., Date, A., Singh, R., Akbarzadeh, A., 2015. Prospects of Power Generation from Geothermal Energy Using Thermoelectric Modules. World Geotherm. Congr. 2015 8.

Cui, G., Ren, S., Zhang, L., Ezekiel, J., Enechukwu, C., Wang, Y., Zhang, R., 2017. Geothermal exploitation from hot dry rocks via recycling heat transmission fluid in a horizontal well. Energy 128, 366–377. https://doi.org/10.1016/j.energy.2017.04.027

Eisenhut, C., Bitschi, A., 2006. TE conversion system based on Geothermal and Solar Heat. 2006 Int. Conf. Thermoelectr.

Erdlac, R.J., Armour, L., Lee, R., Snyder, S., Sorensen, M., Matteucci, M., Horton, J., 2007. Ongoing Resource Assessment of Geothermal Energy From Sedimentary Basins in Texas, in: Proceedings of 32 Workshop on Geothermal Reservoir Engineering.

Fabián-Mijangos, A., Min, G., Alvarez-Quintana, J., 2017. Enhanced performance thermoelectric module having asymmetrical legs. Energy Convers. Manag. 148, 1372–1381. https://doi.org/10.1016/j.enconman.2017.06.087

Gosnold, W., 2017. Electric Power Generation from Low to Intermediate Temperature Resources Executive.

Gou, X., Yang, S., Xiao, H., Ou, Q., 2013. A dynamic model for thermoelectric generator applied in waste heat recovery. Energy 52, 201–209. https://doi.org/10.1016/j.energy.2013.01.040

Kondash, A.J., Albright, E., Vengosh, A., 2017. Quantity of flowback and produced waters from unconventional oil and gas exploration. Sci. Total Environ. 574, 314–321. https://doi.org/10.1016/j.scitotenv.2016.09.069

Kumar, S., Heister, S.D., Xu, X., Salvador, J.R., Meisner, G.P., 2013. Thermoelectric generators for automotive waste heat recovery systems part I: Numerical modeling and baseline model analysis. J. Electron. Mater. 42, 665–674. https://doi.org/10.1007/s11664-013-2471-9

Li, K., Bian, H., Liu, C., Zhang, D., Yang, Y., 2015. Comparison of geothermal with solar and wind power generation systems. Renew. Sustain. Energy Rev. 42, 1464–1474. https://doi.org/10.1016/j.rser.2014.10.049

Liu, C., Chen, P., Li, K., 2014. A 500 W low-temperature thermoelectric generator: Design and experimental study. Int. J. Hydrogen Energy 39, 15497–15505. https://doi.org/10.1016/j.ijhydene.2014.07.163

Liu, C., Chen, P., Li, K., 2013. Geothermal Power Generation Using Thermoelectric Effect Power Tests of Different TEG Modules. GRC Trans. 37.

Liu, X., Falcone, G., Alimonti, C., 2018. A systematic study of harnessing low-temperature geothermal energy from oil and gas reservoirs. Energy 142, 346–355. https://doi.org/10.1016/j.energy.2017.10.058

Liu, X., Gluesenkamp, K., Momen, A., 2015. Overview of Available Low-Temperature / Coproduced Geothermal Resources in the United States and the State of the Art in Utilizing Geothermal Resources for Space Conditioning in Commercial Buildings.

Manikandan, S., Kaushik, S.C., 2017. Transient Thermal Behavior of Annular Thermoelectric Cooling System. J. Electron. Mater. 46, 2560–2569. https://doi.org/10.1007/s11664-016-5055-7

Reinhardt, T., Johnson, L.A., Popovich, N., Poplar, N., 2011. Systems for Electrical Power From Coproduced and Low Temperature Geothermal Resources, in: Proceedings of 36th Workshop on Geothermal Reservoir Engineering.

Sinha, A., Joshi, Y.K., 2011. Downhole Electronics Cooling Using a Thermoelectric Device and Heat Exchanger Arrangement. J. Electron. Packag. 133, 041005. https://doi.org/10.1115/1.4005290

Snyder, G.J., Toberer, E.S., 2008. Complex thermoelectric materials. Nat. Mater. 7, 105–114. https://doi.org/10.1038/nmat2090

Suter, C., Jovanovic, Z.R., Steinfeld, A., 2012. A 1kWe thermoelectric stack for geothermal power generation - Modeling and geometrical optimization. Appl. Energy 99, 379–385. https://doi.org/10.1016/j.apenergy.2012.05.033

Suzuki, R.O., 2004. Mathematic simulation on power generation by roll cake type of thermoelectric double cylinders. J. Power Sources 133, 277–285. https://doi.org/10.1016/J.JPOWSOUR.2004.02.014

Tester, J.W., Anderson, B.J., Batchelor, A.S., Blackwell, D.D., DiPippo, R., 2006. The Future of Geothermal Energy - Impact of Enhanced Geothermal Systems (EGS) on the United States in the 21st Century. MIT - Massachusetts Inst. Technol. 358.

Twaha, S., Zhu, J., Yan, Y., Li, B., 2016. A comprehensive review of thermoelectric technology: Materials, applications, modelling and performance improvement. Renew. Sustain. Energy Rev. 65, 698–726. https://doi.org/10.1016/j.rser.2016.07.034

Wang, K., Wu, X., Liu, J., 2017. Downhole Geothermal Power Generation in Oil and Gas Wells. GRC Trans. 41.

Wang, K., Yuan, B., Ji, G., Wu, X., 2018. A comprehensive review of geothermal energy extraction and utilization in oilfields. J. Pet. Sci. Eng. 168, 465–477. https://doi.org/10.1016/J.PETROL.2018.05.012

Xin, S., Liang, H., Hu, B., Li, K., 2012. A 400 kW Geothermal Power Generator Using Co-Produced Fluids From Huabei Oilfield. GRC Trans. 36.

Yuan, B., Zheng, D., Moghanloo, R.G., Wang, K., 2017. A novel integrated workflow for evaluation, optimization, and production predication in shale plays. Int. J. Coal Geol. 180, 18–28. https://doi.org/10.1016/J.COAL.2017.04.014

Zarrouk, S.J., Moon, H., 2014. Efficiency of geothermal power plants: A worldwide review. Geothermics 51, 142–153. https://doi.org/10.1016/j.geothermics.2013.11.001

Zhang, X., Zhao, L.-D., 2015. Thermoelectric materials: Energy conversion between heat and electricity. J. Mater. 1, 92–105. https://doi.org/10.1016/j.jmat.2015.01.001

Zhang, Y.J., Li, Z.W., Guo, L.L., Gao, P., Jin, X.P., Xu, T.F., 2014. Electricity generation from enhanced geothermal systems by oilfield produced water circulating through reservoir stimulated by staged fracturing technology for horizontal wells: A case study in Xujiaweizi area in Daqing Oilfield, China. Energy 78, 788–805. https://doi.org/10.1016/j.energy.2014.10.073