ABSTRACT: Exploiting geothermal energy from abandoned wells is a research hotspot at present. However, there is still a lack of research on exploiting geothermal energy using an abandoned well pattern. Aiming at this problem, in this paper, a novel method for exploiting geothermal energy from an abandoned well pattern is proposed. An unsteady heat transfer model is proposed to study the influence of some key parameters on the production law of the novel scheme, and the proposed model is verified with field experimental data. The result indicates that there exists a critical flow rate that can change the form of the characteristic curve of the outlet temperature with production time. The change of flow rate has more influence on the outlet temperature than that of temperature. A higher geothermal gradient is conducive to production. When the total number of wells and the total flow rate of the system are fixed, fewer production wells will be conducive to production. When the number of production wells and injection wells is determined, changing the deployment of production wells and injection wells has little effect on the outlet temperature and thermal power.

1. INTRODUCTION

In the context of the global development of carbon peaking and carbon neutrality goals, the development and exploration of clean energy technology have become a hot topic of international research. Compared with other sustainable energy sources, geothermal energy has the advantages of strong sustainability, wide distribution, and large reserves. However, current research on geothermal energy has been in a relatively stable state. One of the important reasons is that geothermal well drilling is required in developing conventional geothermal energy at present. The process will cost a lot of money.

Some researchers have pointed out that global oil and gas exploitation has produced about 30 million abandoned oil wells, some of which have the potential to exploit geothermal energy. If these abandoned wells can be used in exploiting geothermal energy, on the one hand, the cost of oil well abandonment and geothermal well drilling can be saved, and on the other hand, clean energy can be provided. This is of positive significance for expanding the scale of geothermal energy exploitation and promoting the transformation of the energy structure. Therefore, researchers have put forward the technology of exploiting geothermal energy from abandoned oil and gas wells and carried out numerical simulation research based on them.

The technology of exploiting geothermal energy from abandoned oil and gas wells can be divided into open-loop heat extraction and closed-loop heat extraction.1 Closed-loop heat extraction is the main objective of the numerical simulation at present, which includes heat exchanger heat extraction and “U-shaped well” heat extraction. For exploiting geothermal energy using coaxial heat exchangers, Kohl2 reported a case of using coaxial heat exchangers in abandoned wells to exploit geothermal energy for the first time in 2002. In 2006, Kujawa3 regarded the heat transfer process between the fluid and the formation as the multilayer circular wall cylinder, simulated the heat transfer process using an analytical solution of the Fourier equation, and pointed out that the performance of the insulation of the inner pipe has a great impact on the outlet fluid temperature. In 2012, Bu4 established a transient heat transfer mathematical model for the heat extraction of coaxial heat exchangers and solved the model using the finite volume method. The author calculated the outlet fluid temperature of the model well changing with time and the electric power generated by the flash power generation system and pointed out that the outlet temperature would decrease with production time but eventually become stable. The influence of casing on heat transfer has been neglected in the above research. Cheng5,6 believed that neglecting the influence...
of casing on heat transfer would lead to inaccurate calculation results of the mathematical model. The author considered the influence of casing heat capacity, rewrote the heat transfer function of Ramey’s model, calculated the performance of using a coaxial heat exchanger to exploit geothermal energy from abandoned wells, and analyzed the heat transfer performance of seven kinds of working fluids. In 2016, Alimonti5 supplemented the pressure control equation of fluid in a well based on Kujawa’s research to calculate the pump pressure required for production. After considering the construction of facilities and production costs, the author considered that the benefit of direct utilization of heat energy is higher than that of power generation. In 2021, Pokhrel16 conducted an experiment on a coaxial heat exchanger used in exploiting geothermal energy and modeled the well with ANSYS software. The average error between the calculated results of the outlet fluid temperature and the measured data within a period of time was only 1.8%. To date, the numerical simulation results of coaxial heat exchanger heat extraction have been controlled within a reasonable error range, and the research framework has been relatively complete. More field experiments are needed in the future.

For “U-shaped well” heat extraction, Schulz9 put forward the production plan of drilling two abandoned wells into “U-shaped wells” and extracting geothermal energy from them for the first time in 2008. Rayme’s steady-state model was used to solve the fluid temperature field. It was considered that the length of the horizontal section of “U-shaped wells” and the fluid flow rate had a great impact on the heat extraction performance. In 2016, Song10 thought that the accuracy of calculating the heat extraction of abandoned wells using Rayme’s steady-state model should be improved, so he established the transient heat transfer model of the formation, solved the model using the finite difference method, explained the accuracy error between the proposed model and Rayme’s model, and pointed out that the inlet temperature is very important to the actual production. In 2021, Liao11 proposed a production scheme to expand the number of horizontal wells. It was calculated that this production scheme could effectively improve the thermal power and production life compared with the “single U-shaped well” heat extraction.

For the production technologies mentioned above, there are already relatively mature models for reference. However, in the production of oil fields, different well patterns are often deployed to improve the oil and gas recovery efficiency.12 There is still a lack of transforming a five-spot abandoned well pattern into a closed-loop geothermal system in the existing research. Therefore, a novel production scheme based on the five-spot well pattern is proposed. In addition, the influence of some production parameters in this scheme on the heat extraction law is discussed.

The structure of this paper is as follows. First, the principle and production process of this development scheme are introduced. Second, the physical model and the numerical model are established. Then, the mathematical model proposed in the paper is verified. Finally, the calculation results are analyzed. The main innovations of this paper are as follows. First, the method of exploiting geothermal energy from an abandoned well pattern is proposed for the first time. Second, the influence of the injection-production method on the outlet temperature and thermal power is studied.

2. CONSTRUCTION SCHEME AND PRODUCTION PRINCIPLE

Deployment of the well pattern is an important step in oilfield development, which is crucial to improving oil and gas production efficiency.12 Common well pattern deployment schemes include the four-spot, five-spot, and nine-spot methods as shown in Figure 1.13

![Figure 1. Common well pattern deployment methods.](https://doi.org/10.1021/acsomega.2c05925)

This paper proposes a scheme to convert the abandoned five-spot well pattern into a geothermal well pattern. The construction process is as follows.

1. The abandoned five-spot well pattern with geological conditions and well depth meeting the production requirements shall be selected in advance.
2. Connect by drilling at the appropriate depth of five wells, build artificial walls, and install casing.
3. After confirming the production well and injection well, inject water until it fills the whole circulation system and then start heat extraction.

This transformation scheme has the following advantages.

1. Compared with transforming the abandoned well into an enhanced geothermal system (EGS) and “injection-production” heat extraction, it can effectively avoid the risk of corrosion and scaling caused by the formation of chemicals carried by the working fluid.11,14
2. Compared with “U-shaped well” heat extraction and “heat exchanger” heat extraction, this scheme expands the number of wells, which can increase the total heat energy in unit time under the same injection flow of a single well. When the total flow rate of the system is the same, the geothermal exploitation life can be effectively prolonged.10,11

3. MODEL DEVELOPMENT

3.1. Geological Model. Assuming that the formation temperature of an oilfield is high, the well pattern will be used to construct geothermal wells to exploit geothermal energy after finishing the oil and gas production. For the geological model studied in this paper, please refer to Ma’s study,15 which is shown in Figure 2.

![Figure 2. The schematic diagram of the model.](https://doi.org/10.1021/acsomega.2c05925)

The well pattern is deployed by the five-spot method, and every well is a vertical well. The well located in the center is the production well, and the others are injection wells. The distance between the injection well and the production well is 200 m, and the depth of reconstruction bottom for both is 3000 m. They are connected by horizontal wells. The dimension parameters of the model are given in Table 1.6,16

3.2. Numerical Model. 3.2.1. Assumptions. To describe the complex unsteady heat exchange process between the
wellbore and formation and to enhance the feasibility of calculation, the assumptions and considerations of the heat transfer model are as follows.

1. The thermophysical properties of the formation, casing, and cement sheath are constant and independent of temperature and pressure.\(^\text{17}\)
2. The materials are isotropic and homogeneous.
3. We assume that the fluid flow in the wellbore is one-dimensional and ignore the radial temperature gradient in the wellbore.\(^\text{18}\)
4. The cement sheath is in perfect contact with the formation, and the casing is in perfect contact with the cement sheath.\(^\text{2}\)
5. The study presented by Bu and Huang\(^\text{4,19}\) demonstrated that the rock temperature is almost constant 20 m away from the shaft axis. Therefore, the temperature is constant in the region 20 m away from the shaft axis.

The physical parameters of the materials are referenced from the values employed by other researchers and are listed in Table 2.\(^\text{5,10}\)

### Table 2. Physical Parameters of the Materials

| physical parameters | density (kg/m\(^3\)) | thermal capacity (J/(kg·°C)) | thermal conductivity (W/m·°C) |
|---------------------|-----------------------|-------------------------------|-------------------------------|
| water               | 1000                  | 4200                          | 0.61                          |
| casing              | 8060                  | 400                           | 43.75                         |
| cement              | 2140                  | 840                           | 1.8                           |
| rock                | 2500                  | 805                           | 2.8                           |

3.2.2. Fluid Flow. Assuming that the fluid flow in the wellbore is one-dimensional and fully developed, the momentum equation of the fluid in the pipeline is as follows\(^\text{20}\)

\[
\rho_l \frac{\partial \mathbf{v}}{\partial t} = -\nabla p - f_D \frac{\rho_l}{2d_h} \mathbf{v} \mathbf{v} + \mathbf{G}
\]

(1)

where \(\rho_l\) is the density of water, kg/m\(^3\); \(\mathbf{v}\) is the flow velocity of water, m/s; \(t\) is the simulation time, s; \(p\) is the pressure in the wellbore, MPa; \(\mathbf{G}\) is the volume force of water, N/m\(^3\); \(d_h\) is the hydraulic diameter, m; and \(f_D\) is the Darcy friction factor. It is defined as

\[
f_D = \frac{64\mu_l}{\rho_l v_d h}
\]

(2)

where \(\mu_l\) is the viscosity coefficient of water, pa·s.

The continuity equation for flow in the pipe is as follows\(^\text{30}\)

\[
\frac{\partial \rho_l}{\partial t} + \nabla (\rho_l \mathbf{v}) = 0
\]

(3)

where \(A\) is the pipe cross-section area, m\(^2\).

3.2.3. Heat Transfer. The fluid in the wellbore will exchange heat with the rock to extract the heat in production. The energy equation for an incompressible fluid flowing in a pipe is as follows\(^\text{21}\)

\[
\rho A c_p \frac{\partial T_f}{\partial t} + \rho_l A c_p f \mathbf{v} \nabla T_f = \mathbf{v} \cdot (A k_f \nabla T_f) + \frac{1}{2} \frac{\rho_l A}{d_h} \mathbf{v} \mathbf{v} + Q
\]

(4)

where \(c_p\) is the specific heat capacity of water, J/(kg·°C); \(T_f\) is the temperature of water, °C; \(k_f\) is the thermal conductivity of water, W/m·°C; and \(Q\) represents the external heat exchange through the pipe wall, W/m\(^2\).

The heat transfer process of a multilayer circular cylinder is shown in Figure 2c. The equation can be used to describe the heat exchange process between the fluid in the wellbore and the rock, which is written as follows\(^\text{7}\)

\[
Q = \frac{T_i - T_0}{\frac{1}{\rho_f c_p} + \frac{1}{\rho_l c_p} \sum_{i=1}^{n} \frac{1}{T_i} \ln \left( \frac{T_i}{T_0} \right)}
\]

(5)

where \(T_i\) is the temperature of the rock, °C; \(T_0\) is the inner radius of the casing, m; \(h\) is the convective heat transfer coefficient, W/m\(^2\)·°C; and \(k\) is the thermal conductivity of materials, W/m·°C.

The convective heat transfer coefficient \(h\) is obtained by the Nusselt number, \(Nu\), definition

\[
h = Nu \frac{k}{d_h}
\]

(6)

and by the form of the Gnielinski equation,\(^\text{22}\) having assumed a turbulent flow inside the casing

\[
Nu = \frac{(f_D/8)(Re - 1000)Pr}{1 + 12.7(f_D/8)^{1/2}(Pr^{2/3} - 1)}
\]

(7)
where $Re = \frac{\rho v d}{\mu}$ and $Pr = \frac{C_p \mu}{k}$.

Therefore, the convective heat transfer coefficient $h$ is as follows

$$h = \frac{(f_d/8)(Re - 1000)Pr^0.5}{1 + 12.7(f_d/8)^{1/3}(Pr^{2/3} - 1)} \frac{k}{d_h} \quad (8)$$

The heat exchange in the rock is controlled by the heat conduction during geothermal exploitation. The heat transfer equation is shown as follows

$$\rho c_p \frac{dT_i}{dt} + V_i \cdot -k \nabla T_i = Q \quad (9)$$

where $\rho$ is the density of the rock, kg/m$^3$; $c_p$ is the specific heat capacity of the rock, J/(kg·°C); and $k$ is the thermal conductivity of the rock, W/m·°C.

3.2.4. Initial Condition. The inlet flow rate $V_{in}$ is a constant; the temperature at the ground surface $T_s = 20$ °C; and the inlet temperature $T_{in}$ is a constant. Injection and extraction wells are full of fluid at the initial time, and the fluid temperature is equal to the initial temperature. The initial temperature of the rocks is given by

$$T(z) = T_s + DT \cdot z \quad (10)$$

where $T_s$ is the temperature at the ground surface, °C; DT is the geothermal gradient, °C/m; and $z$ is the depth of formation, m.

4. MODEL VERIFICATION

Although the model of this paper refers to previous studies and formulas, it is necessary to verify the accuracy of the model to ensure the study’s reliability of the production law of the novel scheme. The novel method for geothermal exploitation has not been applied in the field and laboratory. Thus, it cannot be directly verified through field or experimental data. However, some “U-shaped well” geothermal exploitation experiments have been carried out at present and the heat transfer mechanism in the production is almost the same as that of the novel method. Therefore, the numerical model is used to model a “single U-well” production project in Handan, Hebei Province. The simulation results are compared with the measured data to verify the accuracy of the model.

The parameters used in the model are all referred to Wang’s report. The measured outlet temperature data are recorded from the 16th day. We screened the data recorded every 24 h. Figure 3 shows the comparison of the outlet temperature between the simulation results and the field data.

The calculation result of the numerical model can meet the calculation requirements. The calculated results and the measured data show the same trend of the outlet temperature with time, and the maximum error is not more than 2 °C. It is considered that the accuracy of the numerical model can meet the calculation requirements.

5. RESULTS AND DISCUSSION

To study the law of exploiting geothermal energy from an abandoned well pattern, this paper analyzes the influence of inlet flow, inlet temperature, geothermal gradient, and injection-production scheme on the heat recovery performance of the novel exploitation method.

5.1. Flow Rate. Assuming that the inlet temperature $T_{in}$ is 40 °C, the geothermal gradient $DT = 0.040$ °C/m, and every production well’s flow rate is the same. When the total flow rates of the system separately are 0.008, 0.012, and 0.016, 0.020 m$^3$/s, the variation trend of the outlet temperature with the production time is different. Figure 4 shows the difference.

As seen in Figure 4, when the flow rate is higher than a certain value, the outlet temperature decreases gradually with time.
the production time; when the flow rate is lower than a certain value, the outlet temperature increases first and then decreases with the production time. Therefore, when using this novel method to exploit geothermal energy, there is a critical flow rate $q_c$ that can change the characteristic curve of the outlet temperature of the system with time. For example, when the production time is 10 years and the flow rate is 0.016 m$^3$/s, the outlet temperature will decrease from the initial 86.17°C to 81.76°C; when the flow rate is 0.012 m$^3$/s, the outlet temperature is initially 84.23°C, rising to the maximum of 85.90°C in the 5.2nd year and then decreasing to 85.48°C in the 10th year. The reason for this difference is as follows.

When the flow rate is low, it will increase the heat exchange time between the fluid and the high-temperature formation so that the fluid has a higher temperature in the deeper layers, and the long heat exchange time will also enhance the effect of heating the shallow low-temperature section by water. The heat loss of the water will decrease with the rise of the rock temperature. Therefore, the outlet temperature at the early stage of production will increase with time. When the temperature of water at the bottom is gradually reduced in the later stage, which is insufficient to maintain the temperature of the shallow section, the outlet temperature will gradually decrease with production time.

When the flow rate is larger than the critical flow, Figure 5 shows the variation process of the outlet temperature and thermal power over time for six different flow rates, and the calculated duration is 30 years. The thermal power can be determined by

$$Q_{\text{out}} = q_{\text{out}} C_p (T_{\text{out}} - T_{\text{in}}) \times 10^{-3} \quad (11)$$

where $q_{\text{out}}$ is the outlet flow rate, m$^3$/s; and $T_{\text{in}}$ and $T_{\text{out}}$ are the inlet temperature and outlet temperature, respectively, °C.

As seen in Figure 5, the outlet temperature and thermal power will decrease continuously with production time. In the early stage of production, the reduction rate is fast. With the production time going on, the outlet temperature gradually tends to be stable. Taking the case of 0.32 m$^3$/s as an example, the outlet temperature declines from 79.4 to 71.3°C and the thermal power declines from 5964 to 4732 kW in the first five years of production. The decrease rates were 10.2, 20.7, 5.6, and 12.6%, respectively.

Figure 6 shows the outlet temperature and thermal power with various flow rates at various times. As the flow rate increases, the outlet temperature decreases, but the thermal power increases. A large flow rate shortens the heat exchange time between the water and the rock, so the outlet temperature declines under higher flow rates. However, increasing the flow rate per unit time will increase the thermal power of the system. Hence, within a certain range of flow rates, a higher flow rate can improve the thermal power.

When the flow rate is smaller than the critical flow, Figure 7 shows the variation process of the outlet temperature and thermal power over time for four different flow rates. As can be seen from the graph, when the system flow is smaller than the critical flow, the larger the flow rate, the higher the temperature in the early stage of production, the earlier the inflection point of the outlet temperature will come, and the faster the decline of the outlet fluid temperature will be after reaching the inflection point; the smaller the flow rate, the later the flow rate, the lower the temperature in the early stage of production, the later the inflection point of the outlet temperature will come, and the slower the decline of the outlet temperature will be after reaching the inflection point. For thermal power, the larger the flow rate, the higher the thermal power. In actual production, flow rates that are too low will reduce the total extracted heat per unit time, so the subsequent sections will only discuss the case where the flow rate is larger than the critical flow rate.

5.2. Inlet Temperature. In this section, the outlet flow rate is set to 0.024 m$^3$/s, and the geothermal gradient $DT = 0.040$ °C/m. Figure 8 displays the outlet temperature and thermal power of the novel production method, with inlet temperatures ranging from 20 to 40 °C at various times.

The figure indicates that, when the inlet fluid temperature rises, the outlet temperature will increase linearly, but the thermal power of the system will decrease linearly. Taking the production time of 10 years as an example, when the inlet temperature rises from 20 to 40 °C, the outlet temperature rises from 76.857 to 78.473 °C. However, the thermal power of the system decreases from 5670.71 to 3878.08 kW.

5.3. Sensitivity Analysis of Inlet Temperature and Flow Rate to Outlet Temperature and Thermal Power. Both the flow rate and the inlet fluid temperature will affect the outlet temperature. Therefore, it is necessary to analyze the sensitivity of the two parameters to the outlet temperature and thermal power and find the influence law to the outlet temperature and thermal power.

Other parameters of the model are held constant, and the outlet temperatures in the 10th years are calculated separately.
for outlet flow rates from 0.016 to 0.036 m$^3$/s and inlet temperatures from 20 to 40 °C. The result is shown in Figure 9.

It can be seen from Figure 9 that the smaller the flow rate, the lower the sensitivity of the outlet temperature to the inlet temperature change. On the contrary, the larger the flow rate, the higher the sensitivity of the outlet temperature to the inlet temperature change. For example, when the flow rate is set to 0.016 m$^3$/s and the inlet temperature declines from 40 to 20 °C, the outlet temperature declines from 81.84 to 80.41 °C, and the decrease of the outlet temperature is 1.75%; when the flow rate is set to 0.036 m$^3$/s and the inlet temperature declines from 40 to 20 °C, the outlet temperature declines from 67.37 to 61.18 °C, and the decrease of the outlet temperature is 9.19%.

Choosing the right inlet temperature and flow rate is significant to increase the thermal power of the system. Figure 10 is obtained based on eq 11 and Figure 9.

It can be seen from Figure 10 that the smaller the flow rate, the higher the inlet temperature, and the lower the thermal power is. On the contrary, the larger the flow rate, the lower the inlet temperature, and the higher the thermal power. Therefore, choosing a low outlet temperature and high flow rate in an appropriate range is conducive to improving the thermal power of the system.

5.4. Geothermal Gradient. Figure 11 shows the change of the outlet temperature with time in the range of geothermal gradient from 0.030 to 0.050 °C/m when the inlet temperature is 40 °C and the flow rate is 0.024 m$^3$/s.

The outlet temperature will increase with the increase of the geothermal gradient in production formation. It can be seen from Figure 11 that the higher temperature gradient in the production area is conducive to improving the heat recovery effect of the system.
Figure 12 shows the outlet temperature with various geothermal gradients at various times. The figure indicates that, when the geothermal gradient rises, the outlet temperature increases linearly.

5.5. Injection-Production Method. There are five wells in the model proposed in this paper, which have eight injection-production methods available for selection. These methods are shown in Figure 13. The physical model and physical parameters of the materials are consistent with those in Section 3. The production parameters of each method are shown in Table 3.

The calculation results of the outlet temperature for different injection-production methods are shown in Figure 14. The calculation results are taken as the average of the outlet temperature of each production well.

It can be seen from Figure 14 that the fewer the production wells in the system, the higher the average outlet temperature; the more the production wells, the lower the average outlet temperature. When the flow rate of each case is the same, it can be concluded that the more the production wells, the lower the thermal power, and the fewer the production wells, the higher the thermal power.

In addition, the location and number of the abandoned well pattern are fixed. When ignoring the heterogeneity of the formation, and the number of production wells and injection wells is determined, changing the selection scheme of production wells and injection wells has little impact on the outlet temperature and thermal power.

6. CONCLUSIONS

A novel production scheme for exploiting geothermal energy from an abandoned well pattern was proposed in this study. The flow rate, inlet temperature, geothermal gradient, and injection-production method to the heat recovery law under this novel method were studied via a series of numerical simulations. The following conclusions were drawn.

(1) There exists a critical flow rate that can change the form of the characteristic curve of the outlet temperature with production time. When the production flow rate is larger than the critical flow, the outlet temperature and thermal power will decrease continuously with the production time. When the production flow rate is smaller than the critical flow, the outlet temperature and thermal power
(1) When the production time increases, the outlet temperature will increase first and then decrease with the production time.

(2) When the inlet temperature rises, the outlet temperature will increase linearly, but the thermal power of the system will decrease linearly. The smaller the flow rate, the lower the sensitivity of the outlet temperature to the inlet temperature change. On the contrary, the larger the flow rate, the higher the sensitivity of the outlet temperature to the inlet temperature change. For thermal power, choosing a lower outlet temperature and higher flow rate in an appropriate range is conducive to improving the total thermal power of the system.

(3) For exploiting geothermal energy from an abandoned well pattern, when the total number of wells and the total flow rate are fixed, the fewer the production wells in the system, the higher the average outlet temperature; the more the production wells, the lower the average outlet temperature. The thermal power of the system is also applicable to that law. In addition, the location and number of the abandoned well pattern are fixed. When ignoring the heterogeneity of the formation, and the number of production wells and injection wells is determined, changing the selection scheme of production wells and injection wells has little impact on the outlet temperature and thermal power.

(4) The numerical simulation offers an effective reference to study the heat recovery law of exploiting geothermal energy from the abandoned five-spot well pattern. However, the model assumes that the rock is isotropic and homogeneous and that no fluid flow occurs in the formation. Therefore, in our future work, the effects of other key factors, such as working fluid types, fluid flow in the formation, and anisotropy of the rock, on the performance of this novel production scheme should be further investigated. In addition, the cost and technical difficulty of converting the well pattern into an open-loop heat extraction system are lower. The utilization of geothermal heat energy is also a research hot spot at present. Therefore, studies of an open-loop heat extraction system, power generation by geothermal heat, economic analysis of the proposed scheme, and change mechanism of the critical flow rate will be considered and focused in our subsequent work.

Table 3. Production Parameters of Each Method

| case | 1  | 2  | 3  | 4  | 5  | 6  | 7  | 8  |
|------|----|----|----|----|----|----|----|----|
| inject well | 1  | 1  | 2  | 2  | 3  | 3  | 4  | 4  |
| production well | 4  | 4  | 3  | 3  | 2  | 2  | 1  | 1  |
| inject flow rate (m$^3$/s) | 0.060 | 0.06 | 0.08 | 0.08 | 0.012 | 0.012 | 0.24 | 0.24 |
| production flow rate (m$^3$/s) | 0.024 | 0.024 | 0.012 | 0.012 | 0.080 | 0.080 | 0.060 | 0.060 |
| inlet temperature (°C) | 40 | 40 | 40 | 40 | 40 | 40 | 40 | 40 |

Figure 14. Outlet temperature vs time of different injection-production methods when the flow rate is set to 0.024 m$^3$/s.

Authors

Zouwei Liu — Key Laboratory of Petroleum Drilling and Production Engineering in Hubei Province, Wuhan 430000, China; Yangtze University, Wuhan 430000, China; orcid.org/0000-0002-9041-2150
Kai Xu — Key Laboratory of Petroleum Drilling and Production Engineering in Hubei Province, Wuhan 430000, China; Yangtze University, Wuhan 430000, China
Qianqing Zhang — College of Mechanical and Electrical Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China; Jiangsu Key Laboratory of Precision and Micro-Manufacturing Technology, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c05925

Notes

The authors declare no competing financial interest.

Acknowledgments

The work was supported by SINOPEC’s key scientific and technological project “Key Technologies and Tools for Ultra deep Oil and Gas Drilling Engineering—Study on Circulating Cooling Capacity of Horizontal Wells in Shunbei Block I” (P17049-3).

Nomenclature

Variables

- \( A \): pipe cross-section area, m$^2$
- \( \epsilon_{fw} \): specific heat capacity of water, j/(kg·°C)
- \( \epsilon_{fr} \): specific heat capacity of rock, j/(kg·°C)
- \( dh \): hydraulic diameter, m
- \( DT \): geothermal gradient, °C/m
- \( f_D \): Darcy friction factor
- \( G \): volume force, N/m$^2$
- \( h \): convective heat transfer coefficient, W/m$^2$·°C
Greek letters

- $k$: thermal conductivity of materials, W/m·°C
- $k_w$: thermal conductivity of water, W/m·°C
- $k_r$: thermal conductivity of rock, W/m·°C
- $p$: pressure in the wellbore, MPa
- $Q$: external heat exchange through the pipe wall, W/m²
- $r_0$: inner radius of the casing, m
- $t$: simulation time, s
- $T_w$: temperature of water, °C
- $T_r$: temperature of rock, °C
- $T_s$: temperature at the ground surface, °C
- $v$: flow velocity of water, m/s
- $z$: depth of formation, m

**REFERENCES**

(1) Harris, B. E.; Lightstone, M. F.; Reitsma, S. A numerical investigation into the use of directionally drilled wells for the extraction of geothermal energy from abandoned oil and gas wells. *Geothermics* 2021, 90, No. 101994.

(2) Kohl, T.; Brenni, R.; Eugster, W. System performance of a deep borehole heat exchanger. *Geothermics* 2002, 31, 678–707.

(3) Nowak, W.; Stachel, A. A.; Kujawa, T. In Utilization of Existing Deep Geological Wells for Acquisitions of Geothermal Energy, Proceeding of Thermal Sciences 2004. Proceedings of the ASME - ZSIS International Thermal Science Seminar II, 2004; ppS57–S64.

(4) Bu, X.; Ma, W.; Li, H. Geothermal energy production utilizing abandoned oil and gas wells. *Renewable Energy* 2012, 41, 80–85.

(5) Cheng, W.-L.; Li, T.-T.; Nian, Y.-L.; Xie, K. An Analysis of Insulation of Abandoned Oil Wells Reused for Geothermal Power Generation. *Energy Procedia* 2014, 61, 607–610.

(6) Cheng, W.-L.; Li, T.-T.; Nian, Y.-L.; Xie, K. Evaluation of working fluids for geothermal power generation from abandoned oil wells. *Appl. Energy* 2014, 118, 238–245.

(7) Alimonti, C.; Soldo, E. Study of geothermal power generation from a very deep oil well with a wellbore heat exchanger. *Renewable Energy* 2016, 86, 292–301.

(8) Pokhrel, S.; Sasmito, A. P.; Sainoki, A.; Tosha, T.; Tanaka, T.; Nagai, C.; Ghoreshi-Madiseh, S. A. Field-scale experimental and numerical analysis of a downhole coaxial heat exchanger for geothermal energy production. *Renewable Energy* 2022, 182, 521–535.

(9) Schulz, S.-U. Investigations on the improvement of the energy output of a Closed Loop Geothermal System (CLGS), 2008.

(10) Song, X.; Shi, Y.; Li, G.; Shen, Z.; Hu, X.; Lyu, Z.; Zheng, R.; Wang, G. Numerical analysis of the heat production performance of a closed loop geothermal system. *Renewable Energy* 2018, 120, 365–378.

(11) Liao, Y.; Sun, X.; Sun, B.; Wang, Z.; Wang, J.; Wang, X. Geothermal exploitation and electricity generation from multibranch U-shaped well–enhanced geothermal system. *Renewable Energy* 2021, 163, 2178–2189.

(12) He, H.; Liu, W.; Chen, Y.; Liu, H.; Liu, H.; Luo, G. Synergistic mechanism of well pattern adjustment and heterogeneous phase combined flooding on enhancing oil recovery in mature fault-block reservoirs. *J. Pet. Explor. Prod. Technol.* 2022, 12, 3387–3398.

(13) Litvak, M. L.; Angert, P. F. In Field Development Optimization Applied to Giant Oil Fields, SPE Reservoir Simulation Symposium Proceedings, 2009; pp 160–167.

(14) Olasolo, P.; Juárez, M. C.; Morales, M. P.; Damico, S.; Liarte, I. A. Enhanced geothermal systems (EGS): A review. *Renewable Sustainable Energy Rev.* 2016, 56, 133–144.

(15) Ma, Y.; Li, S.; Zhang, L.; Li, H.; Liu, Z. Numerical simulation on heat extraction performance of enhanced geothermal system under the different well layout. *Energy Explor. Exploit.* 2020, 38, 274–297.

(16) Noorollahi, Y.; Pourarshad, M.; Jalilinasrabad, S.; Yousefi, H. Numerical simulation of power production from abandoned oil wells in Ahwaz oil field in southern Iran. *Geothermics* 2015, 55, 16–23.

(17) Liao, Y.; Sun, X.; Sun, B.; Gao, Y.; Wang, Z. Transient gas–liquid–solid flow model with heat and mass transfer for hydrate reservoir drilling. *Int. J. Heat Mass Transfer* 2019, 141, 476–486.

(18) Zhang, J.; Wang, Z.; Liu, S.; Zhang, W.; Yu, J.; Sun, B. Prediction of hydrate deposition in pipelines to improve gas transportation efficiency and safety. *Appl. Energy* 2019, 253, No. 113521.

(19) Huang, Y.; Zhang, Y.; Gao, X.; Ma, Y. Thermal disturbance analysis in rock-soil induced by heat extraction from the abandoned well. *Geothermics* 2022, 101, No. 102374.

(20) Barnard, A. C. L.; Hunt, W. A.; Timlake, W. P.; Varley, E. A. Theory of Fluid Flow in Compliant Tubes. *Biophys. J.* 1966, 6, 717–724.

(21) Lurie, M. V. Modeling of Oil Product and Gas Pipeline Transportation; Wiley-VCH Verlag GmbH & Co. KGaA: Weinheim, 2008.

(22) Gnielinski, V. On heat transfer in tubes. *Int. J. Heat Mass Transfer* 2013, 63, 134–140.

(23) Wang, W. Study On Simulation And Heat Removal Performance Of Deep U-shaped Geothermal Well. *Acta Energ. Sol. Sin.* 2022, 43, No. 477.

**NOTE ADDED AFTER ASAP PUBLICATION**

This paper was published ASAP on November 3, 2022 with an incorrect spelling of an author’s name. The corrected version was reposted on November 7, 2022.