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Factors affecting the fluid temperature of geothermal energy wells converted from abandoned oil and gas wells

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Abstract:
The transition from fossil energy to clean energy is an ongoing trend. Because geothermal energy is buried beneath oil and gas wells, it is desirable to convert abandoned oil and gas wells to geothermal energy wells. The candidate wells can be dry holes in oil and gas exploration or end-of-life oil and gas wells in depleted oil and gas reservoirs. There is a knowledge gap to fill between the oil and gas wells and geothermal wells in the well conversion engineering, that is, factors affecting the performance of the geothermal wells are not fully understood. This work investigated the factors affecting the temperature of produced water of geothermal energy wells converted from abandoned oil and gas wells. Both vertical and horizontal well options were considered. The result of the field case study using the data for a well in the Songliao Basin of Northeastern China shows that, without pipe insulation, the temperature of the returned water is very close to that of the injected water, regardless of vertical or horizontal wells. With pipe insulation, the temperature of the returned water in the horizontal well is higher than that in the vertical well. The temperature of the returned water declines quickly as the thermal conductivity of pipe insulation increases in the low-thermal conductivity region. The temperature of the returned water in horizontal wells is affected by the horizontal hole section length for heat transfer. But this effect levels off after about 1,000 m of horizontal hole section is reached, meaning that 1,000 m of horizontal hole section is adequate for heat transfer from the geothermal zone to the injected water. This paper provides an analytical method for the technical feasibility assessment of converting abandoned oil and gas wells to geothermal energy wells.

1. Introduction

The transition from fossil energy to clean energy is an ongoing trend (Ayres and Ayres, 2009; Abas et al., 2015; York and Bell, 2019; Holechek et al., 2022). Because geothermal energy, which is one of the major clean energy resources (Kazemi and Ehyaei, 2018), is also buried at the bottom of abandoned oil wells, it has been promoting the penetration of the geothermal energy industry into the oil and gas industry (Caulk and Tomac, 2017; Lin et al., 2021). Since it will take some time to replace fossil energy smoothly with clean energy without hurting the economy, the fossil energy industry will still be a major industry to sustain the energy supply to mankind. The co-production of fossil energy and thermal energy has become a realistic option today. Typically, oil production declines while water increases in the lifetime of the well. The water produced from deep reservoirs is up to 90 °C at the surface. This hot water is usually reinjected into the reservoir to enhance production and maintain pressure. This means that the heat energy stored in the water is wasted. An alternative is to extract the heat prior to reinjection, for direct heat, or electricity production. Some abandoned oil and gas wells were tested for geothermal energy production back a decade ago (Bu et al., 2012; Santos et al., 2022). This technology has been proven viable in some areas in the past five years (Shmeleva, 2018; Kharseh et al., 2019).

For instance, the U.S. Department of Energy selected four new projects to receive up to $8.4 million to establish new geothermal energy and heat production from abandoned oil

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and gas wells in 2021 (Song et al., 2022). This funding allowed existing well owners and operators to use their idle or unproductive wells to access otherwise untapped geothermal potential and convert oil wells into geothermal wells, supporting the nation's goal of a carbon-free grid by 2035. The conversion means transforming suspended oil wells directly into geothermal wells. The candidate wells are not producing enough oil anymore and therefore became uneconomic, but they still produce a lot of hot water (Hu et al., 2020; Harris et al., 2021).

Globally, recent data reveals that up to 20 countries are actively harnessing geothermal energy for electricity production, resulting in an impressive annual output of 73.7 terawatt-hours (TWh) (Coro and Trumpy, 2020). Additionally, geothermal energy is being extensively utilized for direct applications, including cooling, heating, and various industrial processes, in more than 80 countries, accounting for approximately 163 TWh/year (Trumpy et al., 2015; Bertani, 2016). Moreover, between 2015 and 2020, the capacity for geothermal power generation has experienced a substantial growth of 27%, equivalent to 3.65 gigawatts. Notable expansions have been observed in Turkey, Indonesia, and Kenya. The adoption of geothermal energy is projected to continue its upward trajectory. By 2050, it is anticipated that geothermal power generation will reach an impressive range of 800 to 1,300 TWh, with direct thermal usage estimated at 3,300 to 3,800 TWh/year (Van Der Zwaan and Dalla Longa, 2019).

Given the promising future of geothermal energy, a significant amount of effort has been dedicated to research on heat transfer modeling, heat production potential assessment, and sensitivity analyses or operating condition optimization. Davis and Michaelides (2009) focused on estimating the geothermal power production from abandoned oil wells in the South Texas region. They developed a mathematical model by considering principles of energy, mass, and momentum conservation. Isobutene was chosen as the heat-transferring fluid in their simulations due to its superior thermodynamic properties, making it more suitable for efficient heat extraction. Their findings highlighted that the extracted power is influenced by various factors, including the downhole temperature, injection pressure, fluid velocity, and pipe size.

Ghoreishi-Madiseh et al. (2012) employed finite volume discretization to simulate heat transfer and solve the equations of mass, energy, and momentum conservation. They observed that natural convection can be disregarded when the heat exchange medium's conductivity is below a specific threshold. Furthermore, they identified the thermal and hydraulic conductivity of the medium, along with the rate of heat extraction, as the most significant parameters influencing the performance of geothermal wells. In a subsequent study by Ghoreishi-Madiseh et al. (2014), they delved into the long-term sustainability of heat extraction from abandoned petroleum wells. Their findings indicated that sustainability hinges upon achieving a balance between the extraction rate and the natural replenishment process of geothermal heat within the reservoir.

Wight and Bennett (2015) examined the feasibility of utilizing abandoned petroleum wells for geothermal heat extraction, employing water as the working fluid. Through their calculations, they determined that a well situated in Texas at a depth of 4,200 m could generate a power output of 109 KW with a mass flow rate of 2.5 kg/s. They further demonstrated that increasing the mass flow rate leads to higher power output. However, achieving this requires greater depths for the wellbore to obtain the necessary fluid temperature.

Ahmadi and Dahi Taleghani (2016) conducted a numerical investigation using the finite element method to assess the heat extraction potential in fractured reservoirs. Through their simulations, they observed that the presence of fractures in the wellbores increased the contact area between the wellbore and the formation, leading to enhanced heat extraction capabilities. This indicated that a greater amount of heat could be extracted from the fractured wellbores compared to non-fractured ones.

Alimonti and Soldo (2016) utilized a numerical model to estimate the potential heat extraction from abandoned petroleum wells in the Villafortuna Trecate oilfield. They examined two types of working fluids, water, and diathermic oil, and investigated various internal pipe diameters to optimize the system's geometric configuration for efficient heat extraction. Their findings indicated that water is the most effective working fluid for heat extraction. Additionally, the authors determined that a pseudo-stationary condition would be achieved after 5 years of exploitation, resulting in a reduction of the initial power by 45%.

Cheng et al. (2019) assessed the improvement in heat transfer by employing a novel well bottom curvature design inside the wellbore, utilizing computational fluid dynamics analysis. Different designs of well bottom curvature were examined, and the impact of working fluid inlet temperature and flow rate was also investigated. To optimize the parameters, the Taguchi Statistical Method was utilized to identify the optimal combination of parameters and their interactions. The findings revealed that a 0.5 m well bottom curvature design yielded higher output temperature and heat transfer rate, while a 0.8 m well bottom curvature design was recommended for reducing pressure drop and achieving higher performance.

In addition to the aforementioned electricity production, recent studies have, specifically, developed a momentum of using geothermal energy to improve gas and oil from unconventional resources such as gas hydrate reservoirs and shale oil reservoirs. Fu et al. (2021) proposed a new technique to develop gas hydrate reservoirs using geothermal energy as a driving mechanism. The technique involves pairs of y-shaped wellbores for transferring geothermal energy from a deeper geothermal zone to a gas-hydrate-bearing zone using a working fluid to release the natural gas in the gas hydrates. A lower horizontal wellbore located in the geothermal zone heats the working fluid. A vertical wellbore transfers the hot fluid to an upper horizontal wellbore where the heat in the fluid is partially released to the gas hydrate reservoir for hydrate dissociation. A mathematical model was developed to obtain the temperature profiles of the working fluid along the wellbores. The result of mathematical modeling suggests that the proposed technique can transfer hot fluid from the lower horizontal wellbore in the geothermal zone to the upper horizontal wellbore in the gas hydrate reservoir. However, the developed mathematical model does not consider the effect of

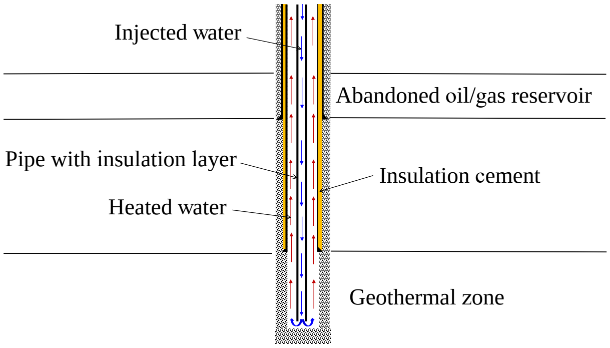

Fig. 1. A sketch of a vertical geothermal well converted from an abandoned vertical oil and gas well.

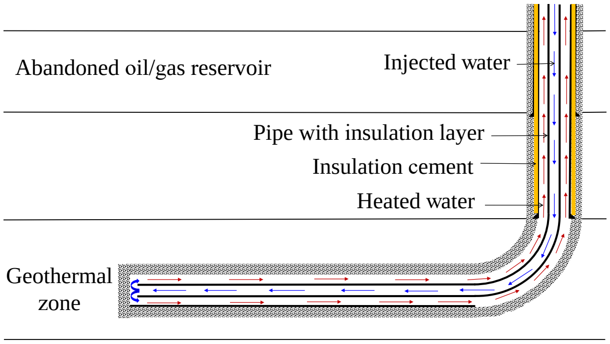

Fig. 2. A sketch of a horizontal geothermal well converted from an abandoned vertical oil and gas well.

pipe and wellbore insulation on the efficiency of heat transfer. Also, the model does not describe the heat transfer from the upper horizontal wellbore into the gas hydrate reservoir.

Guo and Zhang (2022) modified Fu et al. (2021)'s mathematical model by adding an analytical solution for heat transfer from the upper horizontal wellbore into the gas hydrate reservoir. The result of the analytical model is consistent with that of a numerical model. A model study of the case for the gas hydrate reservoir in the Shenhu area, Northern South China Sea, predicted the dynamic temperature profile in the gas hydrate reservoir.

Guo et al. (2022) proposed to use the y-shaped wellbores for storing carbon dioxide (CO_2) in gas hydrate reservoirs while producing natural gas. The process involves displacing the methane gas in the gas hydrates by geothermal-heated CO_2 and storing the latter in the hydrate reservoirs. The heat convection-diffusion equation was solved numerically for predicting the heat transfer from the wellbore into gas hydrate reservoirs during the CO_2-methane displacement. A case study using the data from the gas hydrate reservoir in the Shenhu area, Northern South China Sea indicates that the reservoir temperature can be controlled in a range suitable for methane gas production and CO_2 storage.

Zhang (2022) proposed using the y-shaped wellbores to heat a shale oil reservoir with geothermal energy for lowering oil viscosity and thus improve well productivity. A case study for the Tuscaloosa Marine Shale (TMS) suggests that using a y-shaped wellbore to transfer the geothermal energy in a deeper depth to the TMS can reduce TMS oil viscosity from 0.5 to 0.22 cp and thus increase the initial oil production rate from 140 to 320 stb/day.

However, the reliability of model prediction for the y-shaped wellbores is limited by the fact that the mathematical model does not consider the effect of thermal insulation on the efficiency of heat transfer. Therefore, Wei and Guo (2022) model is utilized instead in this paper. To investigate factors affecting geothermal well performance, a case study on a well drilled in the Songliao Basin of Northeastern China was performed. Comparison and sensitivity analysis are focused on well configuration, the thermal conductivity of pipe insulation, and the length of the horizontal wellbore. It is anticipated that the injection rate of working fluid is another critical aspect, however, in contrast to other factors, it was not analyzed in this study due to its prompt adjustability.

2. Conversion of abandoned wells

An abandoned oil and gas wellbore can be perforation-sealed and deepened into a geothermal zone to convert it to a geothermal energy well (Fig. 1). The advantage of using a vertical geothermal well is its simplicity in well construction engineering. Its disadvantage is that the vertical section of the wellbore in the geothermal zone may not be long enough to allow adequate retention time for heat transfer. The reachable well depth depends mainly on the thermal stabilities of drilling fluids and tools used for well logging.

An abandoned oil and gas wellbore can be perforation-sealed, deepened to the top of a geothermal zone, and kicked out to convert it to a horizontal geothermal energy well (Fig. 2). The advantage of using a horizontal well is that it allows a longer time of heat transfer in the geothermal zone at a lower temperature as compared to the vertical well. The vertical depth of the horizontal well depends mainly on the thermal stabilities of drilling fluids and tools for well logging.

In both cases of vertical and horizontal geothermal energy wells converted from abandoned oil and gas wells, it is essential to maintain the high temperature of the returned water for heat energy delivery. Therefore, thermal insulation is critical for converted wells. Use of insulation cement is necessary and insulated pipe may be needed. Determination of insulation cement and pipe requirement is a prior task in planning well conversion.

3. Mathematical model

Steady fluid temperature profiles in geothermal wells can be predicted using previous mathematical models. The mathematical model derived by Fu et al. (2021) considers a general well configuration containing a down-ward pipe flow, counter-current vertical flow, counter-current horizontal flow, and horizontal pipe flow. Although this model has been used by several investigators to simulate inter-wellbore heat transfer (Guo and Zhang, 2022; Guo et al., 2022; Zhang, 2022), the model is over-complicated for simulating water flow in geothermal wells. The simplified model derived by Wei and Guo (2022) was used in this study. This mathematical model is briefly summarized as follows.

The temperature of the injected water inside the pipe (T_p) at length L is expressed as:

Table 1. Data for an example case of well conversion in northeastern China.

Parameter	Value
Total vertical depth (m)	4,000
Horizontal wellbore length (m)	1,000
Borehole diameter (m)	0.20
Outer diameter of casing (m)	0.14
Outer diameter of cement sheath (m)	0.20
Outer diameter of pipe (m)	0.089
Inner diameter of pipe (m)	0.078
Thickness of pipe (m)	0.0055
Geothermal temperature at surface (°C)	20
Geothermal gradient (°C/m)	0.03
Thermal conductivity of pipe with insulation (W/(m·°C))	0.03
Thermal conductivity of insulation cement sheath (W/(m·°C))	0.5
Thermal conductivity of pipe (W/(m·°C))	45
Fluid flow rate (m^3/s)	0.05
Temperature of injected fluid (°C)	30
Heat capacity of injected fluid (J/kg·°C)	4,184
Density of injected fluid (kg/m^3)	1,000

$$T_p = A\alpha_p e^{R_1 L} + B\alpha_p e^{R_2 L} + GL + \frac{\alpha_p G + \alpha_p \alpha_a T_{g0} - G(\alpha_a + \beta_a)}{\alpha_p \alpha_a} \tag{1}$$

The temperature of the returning water in the annulus (T_a) at length L is expressed as:

$$\begin{aligned} T_a &= A(\alpha_p + R_1)e^{r_1 L} + B(\alpha_p + R_2)e^{r_2 L} + GL \\ &+ \frac{\alpha_p G + \alpha_p \alpha_a T_{g0} - G\beta_a}{\alpha_p \alpha_a} \end{aligned} \tag{2}$$

where

$$A = \frac{\alpha_p \alpha_a(\alpha_p \Delta T_b - G) - [\alpha_p \alpha_a T_{p0} - \alpha_p \alpha_a T_{g0} - \alpha_p G + G(\alpha_a + \beta_a)] r_2 e^{r_2 L_{\max}}}{\alpha_p^2 \alpha_a (r_1 e^{r_1 L_{\max}} - r_2 e^{r_2 L_{\max}})} \tag{3}$$

$$B = \frac{-\alpha_p \alpha_a(\alpha_p \Delta T_b - G) + [\alpha_p \alpha_a T_{p0} - \alpha_p \alpha_a T_{g0} - \alpha_p G + G(\alpha_a + \beta_a)] r_2 e^{r_2 L_{\max}}}{\alpha_p^2 \alpha_a (r_1 e^{r_1 L_{\max}} - r_2 e^{r_2 L_{\max}})} \tag{4}$$

$$R_1 = \frac{\alpha_a + \beta_a - \alpha_p + \sqrt{(\alpha_a + \beta_a - \alpha_p)^2 + 4\alpha_p \alpha_a}}{2} \tag{5}$$

$$R_2 = \frac{\alpha_a + \beta_a - \alpha_p - \sqrt{(\alpha_a + \beta_a - \alpha_p)^2 + 4\alpha_p \alpha_a}}{2} \tag{6}$$

where $\alpha_a = (\pi d_c K_c)/(c_a \dot{m}_a t_c)$, $\alpha_p = (\pi d_p K_p)/(c_p \dot{m}_p t_p)$, $\beta_a = (\pi d_p K_p)/(c_a \dot{m}_a t_p)$, G is the geothermal gradient, T_{g0} is the geothermal temperature at the top of the section, T_{p0} is the temperature of the water inside the pipe at the top of the section, d_c is the inner diameter of insulation-cement sheath, K_c is the thermal conductivity of the insulation-cement, c_a is the heat capacity of water in the annulus, $\dot{m}_a$ is the mass flow rate in the annulus, t_c is the thickness of the cement sheath, d_p is the inner diameter of the pipe, K_p is the thermal conductivity of the insulation pipe, c_p is the heat capacity of water inside the pipe, $\dot{m}_p$ is the mass flow rate in the pipe, and t_p is the thickness of the pipe, ΔT_b is the temperature difference between fluids in the annulus and pipe at the bottom of the section, $L_{\max}$ is the maximum length of the wellbore. This mathematical model can be applied to different sections of a wellbore with some modifications in boundary conditions. Details are shown in the work of Wei and Guo (2022).

4. Field case study

A well drilled in the Songliao Basin of Northeastern China was for the exploration of oil and gas and found to be a 7-7/8" dry hole at the designed total depth of around 2,500 m. Because of the high geothermal gradient of 0.03 °C/m in the area, it was considered to be converted into a geothermal well. The drilling fluids available in the area can resist temperatures up to 140 °C without losing their thermal stability. This allows for deepening the well down to 4,000 m. Both vertical and horizontal well structure options were considered. The vertical well option was planned to drill to 4,000 m and case with 5-1/2" casing from 3,000 m to the surface. The horizontal well option was considered to drill to about 4,000 m, kick off to create a horizontal borehole, and case with 5-1/2" casing from the total depth to the surface. Factors affecting the temperature of the returned water were investigated with the mathematical model. Table 1 shows a data set for the case.

Insulation of pipe reduces heat transfer from the water in the annulus to the water in the pipe in the cased hole section

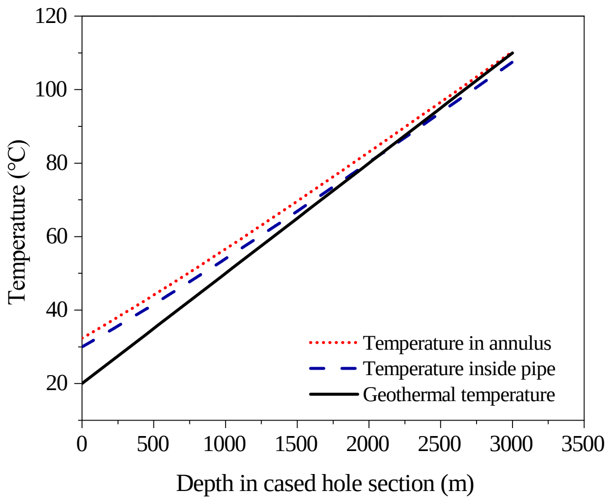

Fig. 3. Predicted temperature profiles in the cased hole section of the vertical wellbore with non-insulated pipe.

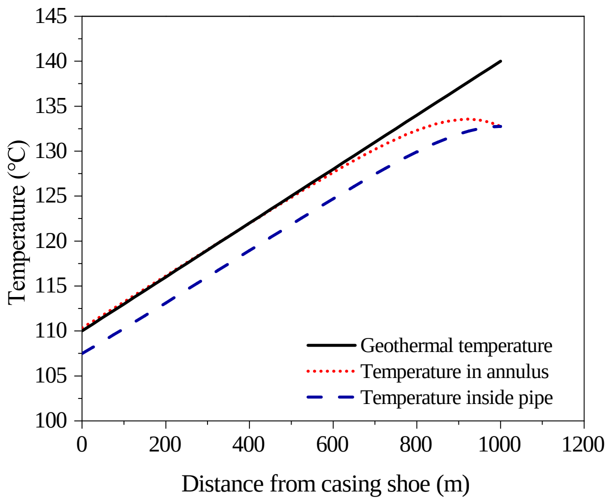

Fig. 4. Predicted temperature profiles in the open hole section of the vertical wellbore with a non-insulated pipe.

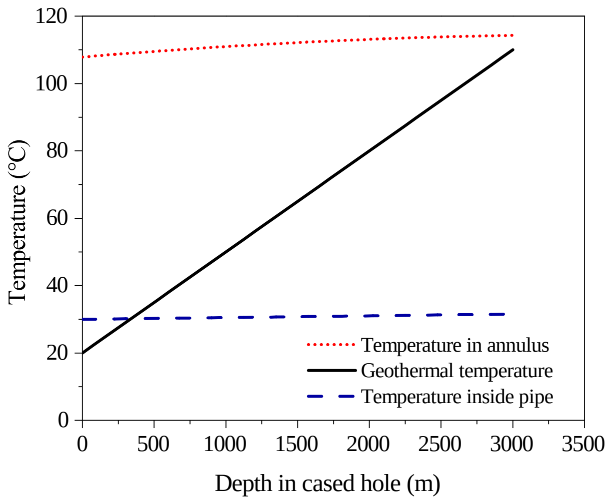

Fig. 5. Predicted temperature profiles in the cased hole section of the vertical wellbore with a pipe insulated by polyurethane foam.

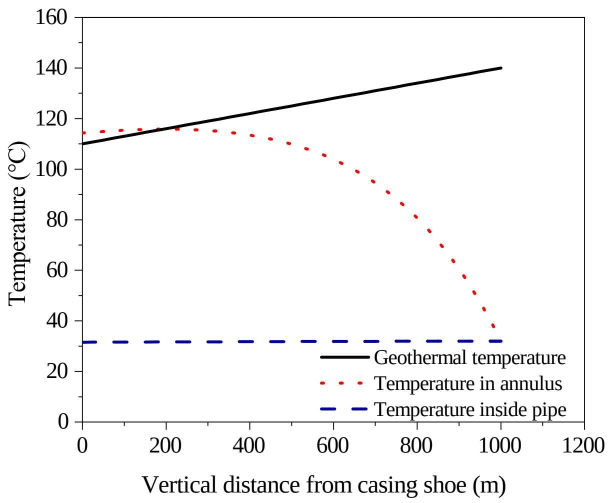

Fig. 6. Predicted temperature profiles in the open hole section of the vertical wellbore with a pipe insulated by polyurethane foam.

so that the temperature drop of the returned water is reduced. The polyurethane foams used in pipeline applications have thermal conductivity values between 0.02 and 0.04 W/(m·°C), averaging 0.03 W/(m·°C). Fig. 3 shows predicted temperature profiles in the cased hole section of the vertical wellbore with a non-insulated pipe. It indicates that the temperature of the returned water is very close to that of the injected water. Fig. 4 presents predicted temperature profiles in the open hole section of the vertical wellbore with a non-insulated pipe. It implies that the temperatures of the water in both pipe and annulus are very close to the geothermal temperature.

Fig. 5 shows predicted temperature profiles in the cased hole section of the vertical wellbore with an insulated pipe. It indicates that the temperature of the returned water is about 108 °C. Fig. 6 presents predicted temperature profiles in the open hole section of the vertical wellbore with an insulated pipe. It implies that the water in the annulus is significantly heated up by the geothermal energy. Fig. 7 shows the predicted effect of the thermal conductivity of pipe insulation on the temperature of returned water. It demonstrates that water temperature declines quickly as the thermal conductivity of pipe insulation increases in the low-thermal conductivity range.

Fig. 8 shows predicted temperature profiles in the cased vertical hole section of the horizontal well with a non-insulated pipe. It indicates that the temperature of the returned water is very close to that of the injected water. Fig. 9 presents predicted temperature profiles in the open horizontal hole section of the horizontal well with a non-insulated pipe. It implies that the temperatures of the water in both pipe and annulus are much lower than the geothermal temperature. This is due to the cooling effect of the water inside the pipe on the water in the annulus.

Fig. 10 shows predicted temperature profiles in the cased vertical hole section of the horizontal well with an insulated pipe. It indicates that the temperature of the returned water is

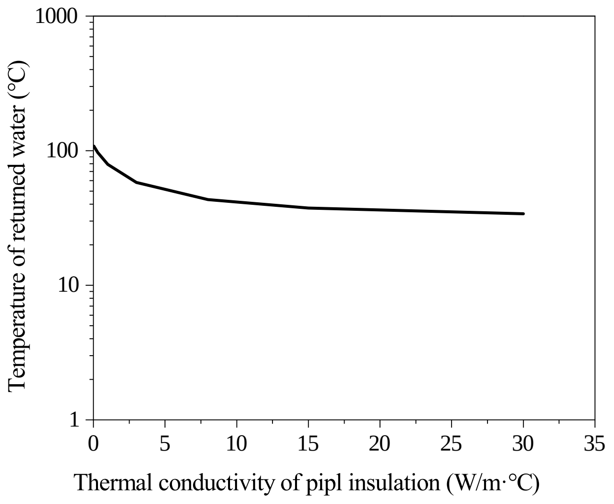

Fig. 7. Predicted effect of thermal conductivity of pipe insulation on the temperature of returned water.

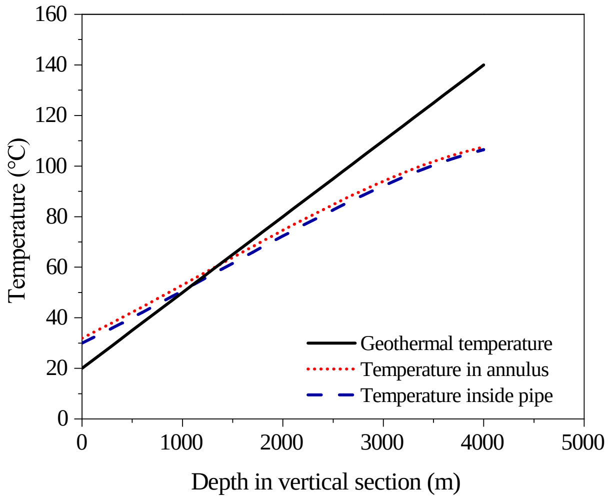

Fig. 8. Predicted temperature profiles in the cased vertical hole section of horizontal well with non-insulated pipe.

126 °C, which is higher than the 108 °C of the returned water temperature in the vertical well. Fig. 11 presents predicted temperature profiles in the open horizontal hole section of the horizontal well with an insulated pipe. It implies that the water in the annulus is significantly heated up by geothermal energy. Fig. 12 shows the predicted effect of horizontal hole section length on the temperature of returned water. It demonstrates the effect of horizontal hole section length on returned water temperature levels off after 1,000 m, meaning that 1,000 m of horizontal hole section is adequate for heat transfer from the geothermal zone to the injected water, where it reaches the in-situ geothermal temperature.

The thermal conductivity of well cement should also affect the temperature of the returned water. Normal cement concretes have thermal conductivities around 0.5 W/(m·°C), which is used in model calculations. Mortars of cement to river sand ratio of 1:2 have thermal conductivities around 1.5 W/(m·°C). Foamy cement has a thermal conductivity between 0.10 and 0.40 W/(m·°C) (Zahari et al., 2009). Because these

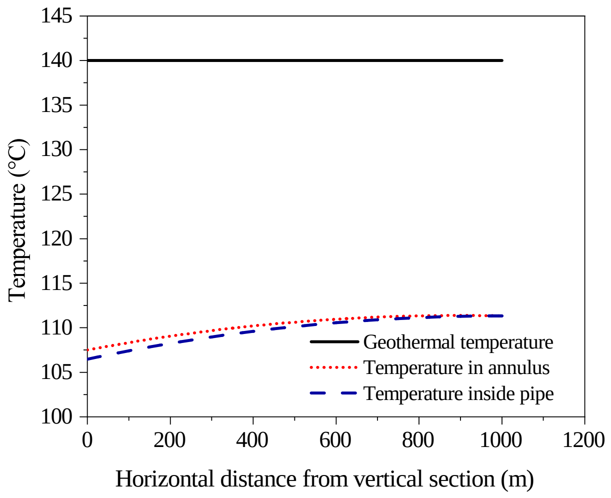

Fig. 9. Predicted temperature profiles in the open horizontal hole section of horizontal well with non-insulated pipe.

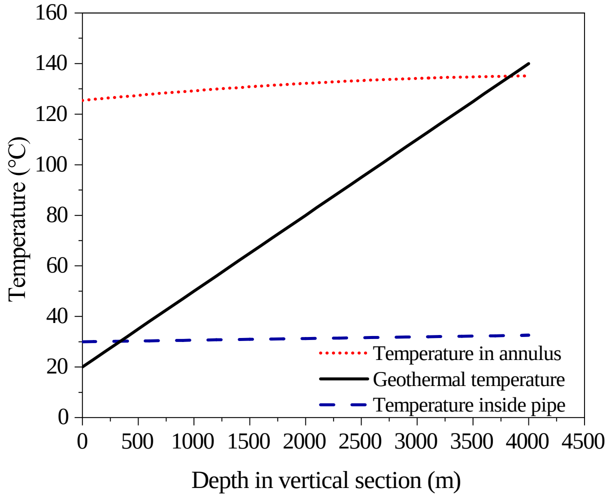

Fig. 10. Predicted temperature profiles in the cased vertical hole section of horizontal well with insulated pipe.

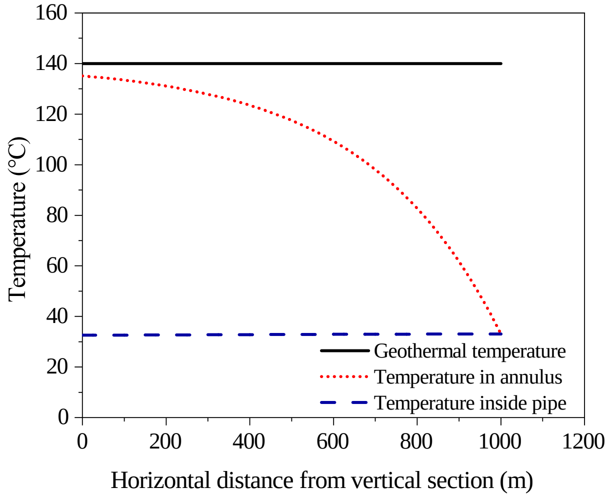

Fig. 11. Predicted temperature profiles in the open horizontal hole section of the horizontal well with an insulated pipe.

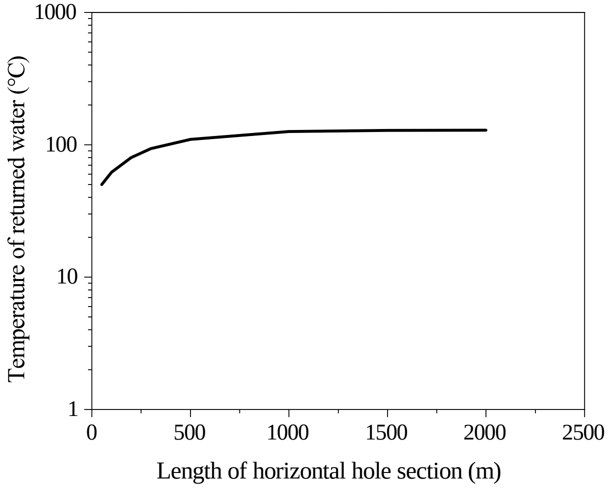

Fig. 12. Predicted effect of horizontal hole length on the temperature of returned water in a horizontal well with an insulated pipe.

values are in a narrow range, 0.5 W/(m·°C) was used in the model calculation.

The temperature of the returned water should also depend on the water flow rate due to different retention times for heat transfer from the geothermal zone to the injected water. However, this parameter was not investigated because practical values of water flow rate have to be used in real applications.

5. Conclusions

The mathematical model developed by Wei and Guo (2022) was used in this work to investigate the factors affecting the temperature of produced water of geothermal energy wells converted from abandoned oil and gas wells. Both vertical and horizontal well options were considered. The field case study using the data for a well in the Songliao Basin of Northeastern China allowed drawing the following conclusions.

1) Without pipe insulation, the temperature of the returned water is very close to that of the injected water, regardless of vertical or horizontal wells. With pipe insulation, the temperature of the returned water in the horizontal well is higher than that in the vertical well. It is therefore desirable to convert abandoned vertical oil and gas wells to horizontal geothermal wells for maximizing the production of geothermal energy.
2) The temperature of the returned water declines quickly as the thermal conductivity of pipe insulation increases in the low-thermal conductivity region, meaning that the best available insulation materials should be used for pipe insulation in geothermal energy wells.
3) The temperature of the returned water in horizontal wells is affected by the horizontal hole section length for heat transfer. But this effect levels off after about 1,000 m of horizontal hole section is reached, meaning that 1,000 m of horizontal hole section is adequate for heat transfer from the geothermal zone to the injected water.

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Conflict of interest

The authors declare no competing interest.

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