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Geothermal In-Situ Heat Transfer Control Factor Simulation and Numerical Analysis

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ABSTRACT

Geothermal energy, as a renewable and clean energy source, holds immense potential in meeting energy demands and reducing carbon emissions. Its unique sustainability and environmental friendliness make it an important complement to addressing today's energy challenges. Coaxial tubing in-situ heat exchange technology for geothermal wells, as a key extraction method for geothermal energy, is subject to control by multiple critical factors that directly relate to its efficiency and feasibility. This paper aims to delve into the technology of coaxial tubing in-situ heat exchange for geothermal wells through numerical simulation analysis, with a focus on studying the impacts of three key factors on its performance: heat transfer medium flow rate, inlet water temperature, and cement thermal conductivity. Through numerical analysis, this study aims to reveal the variations of these factors to provide more refined control methods and optimize the coaxial tubing in-situ heat exchange technology for geothermal wells. By conducting experimental simulations and numerical analysis on these key factors, this paper aims to provide strong support for optimizing the coaxial tubing in-situ heat exchange technology for geothermal wells, which will contribute to advancing geothermal energy technology and promoting the sustainable utilization of clean energy.

KEYWORDS

Medium-depth geothermal wells; In-situ heat exchange technology; Numerical simulation; Geothermal well outlet temperature.

1. INTRODUCTION

Geothermal in-situ heat exchange technology, as a cutting-edge engineering related to underground thermal energy resources, aims to fully tap into the Earth's internal heat to meet the ever-growing energy demands of human society. Faced with escalating energy needs and increasingly severe environmental issues, geothermal in-situ heat exchange technology demonstrates its unique advantages – it is a renewable, clean, and sustainable energy option. Against the backdrop of the necessity to build a clean, low-carbon, safe, and efficient energy system and achieve the goals of "peak carbon" and "carbon neutrality," it is imperative to delve into and explore this immensely potential energy resource.

In terms of hydrothermal geothermal resources, China's hydrothermal geothermal resources equivalent to standard coal reserves have reached 1.25 trillion tons, with an annual exploitable amount equivalent to 1.865 billion tons of standard coal. Among them, high-temperature geothermal resources are mainly distributed in the southwest Tibetan-Yunnan region and Taiwan, with a potential of 8,460 megawatts of electricity generation. Medium and low-temperature geothermal resources are widely distributed in large and medium-sized sedimentary basins and orogenic belts such as the Bohai Bay Basin, Northern Jiangsu Basin, Songliao Basin, Fenwei Rift, and South China Fold Belt. With vast resources, the equivalent standard coal reserves are as high as 1.23 trillion tons, with an annual exploitable amount equivalent to 1.85 billion tons of standard coal and a power generation potential of 1,500 megawatts.

The annual exploitable amount of shallow geothermal resources in 336 cities at or above the prefecture level in China is equivalent to 700 million tons of standard coal, while the prospective resources of hot dry rocks reach an astonishing 8.56 trillion tons of standard coal. This series of figures undoubtedly showcases the immense potential of China's geothermal resources.

2. NUMERICAL SIMULATION AND CONTROL MECHANISM OF IN-SITU HEAT EXCHANGE

2.1. Geological Characteristics

The Weihe Basin is located within the structural framework of the project area, situated in the Xi'an Depression of the Interrupted Step Zone. In terms of its tectonic origin, the Weihe Basin is a Neogene faulted-faulted basin formed during the rifting and extension processes of the Xishan tectonic movement. Its characteristics include deep depression, young strata, and relatively late formation. The sedimentary cover in the southern part of the basin is the thickest, reaching about 7000 meters, exhibiting an asymmetric graben shape with a steep slope in the south and a gentle slope in the north. The structural zoning of the Weihe Basin is mainly based on fault and fold structures, with the main structural units including the Xi'an Depression and the Gushi Depression, while the slope belts on the north and south sides of the basin form the two wings of the depression, with the northern part being a gentle slope belt and the southern part being a steep slope belt.

Based on the existing logging data, the thermal reservoir conditions in the project area can be clearly delineated. Along the northern fault zone of the Weihe River, geothermal resources are relatively abundant. The main thermal reservoir layers include the Zhangjiapo Formation, Lantian-Bahe Formation, and Gaoling Group, each with its unique characteristics, detailed as follows:

The Quaternary insulation cover has a thickness of 845.70 meters, comprising light yellow and grayish-yellow loess, powdery clay, clay, as well as gray-black and gray-white medium-coarse, medium, and medium-fine sand, sandstone, and gravel. This massive Quaternary sediment layer plays a role in thermal insulation during the formation of geothermal resources. The thermal storage conditions of the fine-grained clay layers are relatively poor, hence they are typically considered as insulation layers.

The Upper Tertiary Upper Pliocene Zhangjiapo Formation thermal reservoir layer is buried at depths ranging from 845.70 meters to 1676.70 meters, with a total thickness of 831 meters. The sandstone porosity of this thermal reservoir layer ranges from 14.37% to 25.99%, with permeability between 13.48mD and 131.98mD. The measured top temperature is approximately 45.277°C, the bottom temperature is about 61.057°C, and the average temperature is 53.167°C.

The Upper Tertiary Upper Pliocene Lantian-Bahe Formation thermal reservoir layer is buried at depths ranging from 1676.70 meters to 2576.70 meters, with a total thickness of 900 meters. The sandstone porosity of this thermal reservoir layer ranges from 9.72% to 23.66%, with permeability between 5.29mD and 89.44mD. The sandstone has an average thickness of about 24%. The measured top temperature is 61.057°C, the bottom temperature is 85.123°C, and the average temperature is 73.09°C. This thermal reservoir segment exhibits good aquifer characteristics and belongs to low-pressure, low-permeability thermal reservoirs.

The Middle Tertiary Gaoling Group thermal reservoir layer is buried at depths ranging from 2576.70 meters to 3094.70 meters, with a total thickness of 581 meters. The sandstone porosity of this thermal reservoir layer ranges from 9.72% to 24.90%, with permeability between 3.50mD and 65.64mD. The sandstone has an average thickness of about 23%. The measured top temperature is 85.123°C, the bottom temperature is 111.575°C, and the average temperature is 98.349°C. The sandstone of this thermal reservoir segment generally exhibits moderate aquifer characteristics and also belongs to low-pressure, low-permeability thermal reservoirs.

The geothermal resources within the Weihe Basin are abundant, with the Zhangjiapo Formation, Lantian-Bahe Formation, and Gaoling Group being the main thermal reservoirs. The characteristics of these thermal reservoirs are of significant reference value for geothermal energy development, aiding in guiding the implementation of future geothermal projects to meet energy demands and promote the utilization of clean energy.

2.2. Analysis of Heat Transfer Performance

Assuming there is no seepage phenomenon in the rock and soil, and the thermal properties of the rock and soil are uniform. With the outer pipe material being petroleum steel pipe, and both the cementing material and the thermal conductivity of the rock and soil being 3.25 W/(m·°C), the variation of formation temperature at 2500m depth of the geothermal well with operating time is analyzed in the paper. The temperature changes at different operating times are calculated, taking operating times of 0 days, 60 days, and 120 days as examples.

Through the analysis of Figures 1, 2, and 3, the following conclusions can be drawn: At the beginning of the model operation, i.e., at a time of 0 days, the formation temperature still maintains the original formation temperature. The temperature of the formation closer to the wellbore is lower, while the temperature of the formation farther from the wellbore is relatively higher, consistent with the original formation temperature. This indicates that there is no heat exchange between the annular space of the geothermal well and the rock and soil layers in the initial stage of the model operation. As the model gradually runs to 120 days, which is the end of a complete heating season, the temperature of the formation closer to the wellbore begins to decrease, while the temperature of the formation farther from the wellbore rises, and eventually, the formation temperature returns to the original formation temperature. The results indicate that during the operation of the model, the heat exchange medium of the geothermal well gradually exchanges heat with the surrounding rock and soil layers, with the heat exchange medium starting to absorb the temperature of the formation, especially the temperature of the formation near the wellbore decreases significantly. With the increase in operating time, the range of influence on the formation temperature expands, i.e., the amplitude of the change in the formation temperature field increases. This result emphasizes the influence of operating time on the heat transfer performance of geothermal wells. With the extension of operating time, the performance of geothermal wells will significantly affect the distribution of formation temperature in the surrounding area.

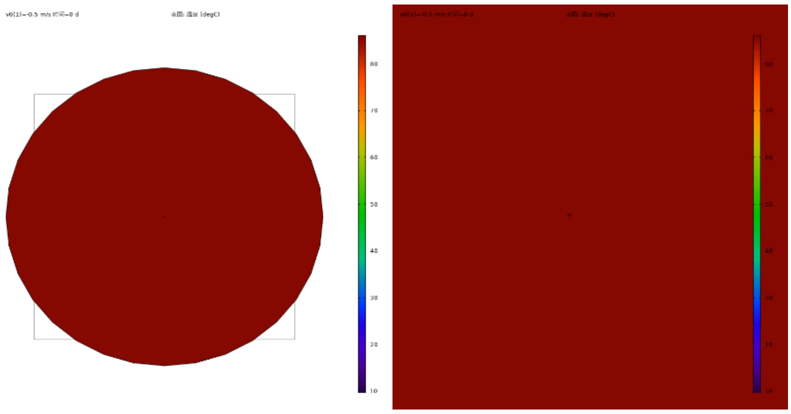

Figure 1. Initial Temperature Cloud Map and Local Magnification at the Start of Heat Exchange

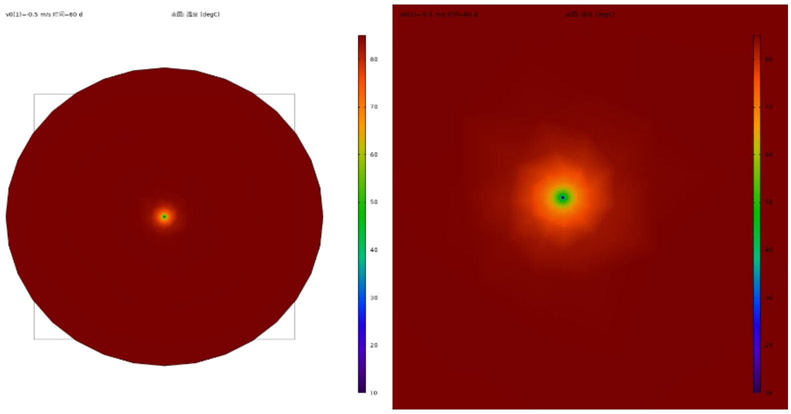

Figure 2. Temperature Cloud Map and Local Magnification 60 Days After Heat Exchange

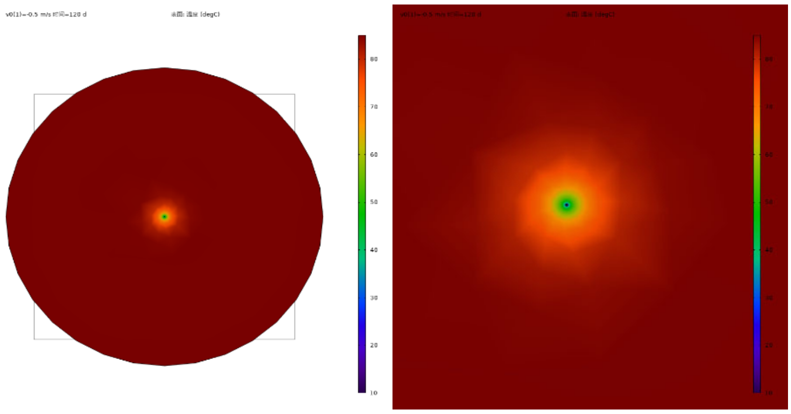

Figure 3. Temperature Cloud Map and Local Magnification 120 Days After Heat Exchange

2.3. The Control Mechanism of Heat Transfer Medium Flow Rate on Heat Extraction Performance

The flow rate of the heat transfer medium significantly affects the performance of geothermal wells. The flow rate of the heat transfer medium determines the heat transfer rate through the geothermal well per unit time, thereby affecting the heat extraction performance. This paper will analyze the outlet temperature of geothermal wells under different flow rate conditions when steel pipe material is used as the outer pipe, to further understand the impact of this key parameter on the performance of the geothermal system.

Considering the case where steel pipe is used as the outer pipe material, with an outer diameter of 177.8mm and a wall thickness of 9.19mm. In the simulation, the flow rate is divided into different conditions, ranging from 0.5m/s to 1m/s, with increments of 0.05m/s. Other simulation conditions include a temperature gradient of 0.03°C/m, a thermal conductivity of 40 W/(m·°C) for the outer pipe, and constant dimensions for the geothermal well outer pipe, with an outer diameter of 177.8mm and a wall thickness of 9.19mm. Additionally, the thermal conductivity of the rock mass is 3.25 W/(m·°C), and the thermal conductivity of the cementing material is 0.73 W/(m·°C).

From the results in Figure 4, it can be observed that under different inlet flow rate conditions, the outlet temperature of the geothermal well gradually decreases with increasing operation time. This indicates that higher flow rate conditions can more effectively extract underground thermal energy, resulting in a lower outlet temperature of the geothermal well. After stable operation for 120 days, there is approximately a 7°C temperature difference between the outlet temperatures of the geothermal well under the conditions of inlet flow rates of 0.5m/s and 1m/s. Under different inlet flow rate conditions, the outlet temperature of the coaxial tubing in-situ heat exchange geothermal well exhibits a power function-like decreasing trend. Comparing the cases of 11 different flow rates ranging from 0.5 to 1.0m/s, it is found that an increase in flow rate leads to a decrease in outlet temperature.

Higher flow rate conditions can improve the heat extraction efficiency of geothermal wells but may also lead to a decrease in outlet temperature. Therefore, in practical applications, it is necessary to choose an appropriate flow rate based on specific requirements and the conditions of geothermal resources.

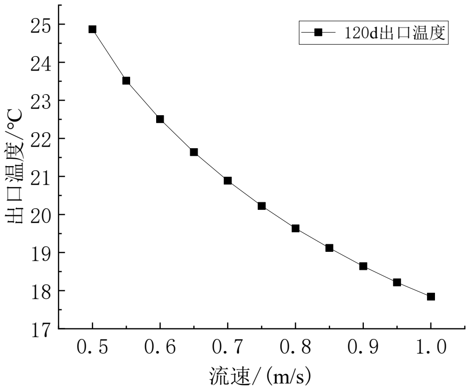

Figure 4. Outlet Temperature at Different Flow Rates

2.4. The Control Mechanism of Inlet Water Temperature on Heat Extraction Performance

To investigate the impact of inlet water temperature on the heat extraction performance of geothermal wells, simulations were conducted using COMSOL with a simulation period of 120 days. Inlet temperatures of 10°C, 15°C, 20°C, 25°C, and 30°C were considered, and their respective outlet temperatures were analyzed using in-situ heat exchange technology. Other simulation conditions included a temperature gradient of 0.03°C/m, an outer pipe thermal conductivity of 40 W/(m·°C), and constant dimensions for the geothermal well outer pipe, with an outer diameter of 177.8mm and a wall thickness of 9.19mm. Additionally, the thermal conductivity of the rock mass was 3.25 W/(m·°C), and the thermal conductivity of the cementing material was 0.73 W/(m·°C).

Figure 5 illustrates the variation in geothermal well outlet temperature under different inlet water temperature conditions. From the graph, it is evident that the trend of geothermal well outlet temperature varies significantly under different inlet water temperature conditions. On the first day of operation, the temperature rapidly increases and reaches its peak due to the rapid transfer and accumulation of underground thermal energy. As the operation continues, the outlet temperature gradually decreases and eventually stabilizes, a stable state typically observed after approximately 20 days of operation.

Furthermore, it is apparent that the inlet water temperature has a notable influence on the geothermal well outlet temperature. With an increase in inlet water temperature, the geothermal well outlet temperature also rises. This is because the elevation of inlet water temperature directly affects the temperature of underground thermal energy, thereby raising the working temperature of the heat extraction system. Specifically, taking the example of inlet water temperatures of 30°C and 10°C, after stable operation for 120 days, there is a temperature difference of approximately 13°C between the outlet temperatures under these two conditions. Under different inlet water temperature conditions, the outlet temperature of the coaxial tubing in-situ heat exchange geothermal well also exhibits a power function-like decreasing trend. Comparison of five groups of different inlet temperatures ranging from 10°C to 30°C reveals that an increase in inlet temperature results in a corresponding increase in outlet temperature.

Higher inlet water temperature enhances the heat extraction efficiency of geothermal wells, enabling them to reach a stable state more quickly and obtain higher outlet temperatures during operation. This is crucial for improving the overall performance and efficiency of geothermal systems and requires selecting an appropriate inlet water temperature based on specific application requirements and underground thermal energy resource conditions.

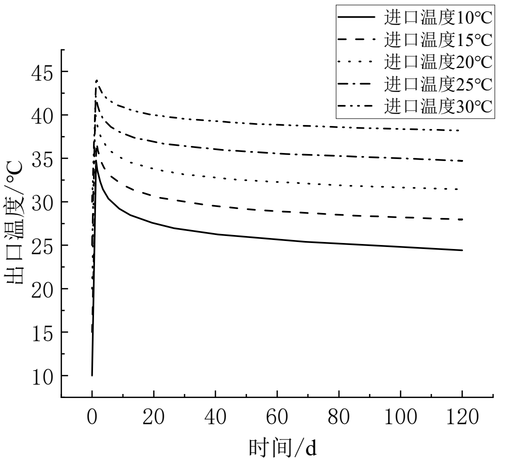

Figure 5. Simulated Outlet Temperature Curve at Different Inlet Temperatures

2.5. The change in thermal conductivity of the well cement controls the heat extraction performance

When conducting software simulations, while keeping other parameters constant, the thermal conductivity of the well cement was set to 0.5 W/(m·°C), 1 W/(m·°C), 2 W/(m·°C), and 3 W/(m·°C), respectively, to analyze its impact on the heat transfer performance of mid-deep geothermal well heat exchangers. Figure 6 illustrates the effect of varying thermal conductivity of the well cement on the outlet temperature.

From Figure 6, it can be observed that under different thermal conductivity conditions of the well cement, the outlet temperature of the geothermal well gradually decreases with increasing operation time. Furthermore, the lower the thermal conductivity, the smaller the decrease in outlet temperature. Taking the example of well cement with a thermal conductivity of 0.5 W/(m·°C), the difference between the highest temperature and the stable temperature is approximately 1°C. In contrast, when the thermal conductivity of the well cement is 3 W/(m·°C), the difference between the highest temperature and the stable temperature is approximately 10°C. It is noteworthy that even after reaching stable operation, there remains a difference of about 10°C between the temperatures of the well cement with a thermal conductivity of 3 W/(m·°C) and 0.5 W/(m·°C).

The thermal conductivity of the well cement similarly exhibits a power function-like decreasing trend for coaxial tubing in-situ heat exchange geothermal wells. Comparison of four groups of different well cement thermal conductivity values ranging from 0.5 to 3 W/(m·°C) reveals that an increase in the thermal conductivity of the well cement leads to an increase in the outlet temperature.

The thermal conductivity of the well cement has a significant impact on the performance of mid-deep geothermal well heat exchangers. In engineering applications, it is advisable to choose well cement materials with higher thermal conductivity, as this helps optimize the heat transfer performance of geothermal wells, enhance energy utilization efficiency, and meet heating demands under different environmental conditions.

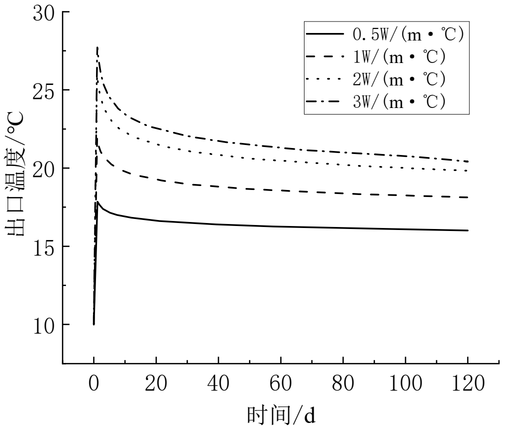

Figure 6. Simulated Outlet Temperature Curve at Different Cement Thermal Conductivities

3. CONCLUSION

This study aimed to establish and analyze a numerical model of coaxial double-U tube in-situ heat exchange geothermal wells to investigate its performance in geothermal heating applications. The study focused on exploring the controlling effects of three key factors - inlet flow velocity, inlet temperature, and thermal conductivity of well cement - on the heat transfer performance of coaxial double-U tube geothermal wells. The following main conclusions were drawn:

Initially, there was no heat exchange between the geothermal well and the surrounding geological strata. However, after 120 days of operation, heat exchange began between the geothermal well and the surrounding strata, with a noticeable decrease in temperature in strata near the wellbore. Moreover, with increasing operation time, the radius of influence on strata temperature gradually increased.

Under different inlet flow velocity conditions, the outlet temperature of the coaxial double-U tube in-situ heat exchange geothermal well decreased exponentially. Comparing 11 sets of different flow velocities ranging from 0.5 to 1.0 m/s, it was found that increasing flow velocity led to a decrease in outlet temperature. This suggests that higher flow velocities may weaken the heat exchange effect inside the geothermal well, thus lower flow velocities should be selected in practical applications to improve outlet temperature and ensure heat exchange efficiency.

Under different inlet temperature conditions, the outlet temperature of the coaxial double-U tube in-situ heat exchange geothermal well also decreased exponentially. Comparing five sets of different inlet temperatures ranging from 10 to 30°C, it was observed that increasing inlet temperature led to higher outlet temperatures. Therefore, selecting higher inlet temperatures can effectively improve outlet temperature and further enhance the performance of geothermal wells whenever feasible.

The thermal conductivity of well cement also exhibited an exponential decrease in performance of the coaxial double-U tube in-situ heat exchange geothermal well. Comparing four sets of different thermal conductivities ranging from 0.5 to 3 W/(m·℃), it was found that increasing the thermal conductivity of well cement resulted in higher outlet temperatures. This underscores the importance of selecting appropriate thermal conductivity well cement materials in engineering applications to optimize heat transfer performance of geothermal wells, thereby improving energy utilization efficiency and performance stability.

This study provides important theoretical and practical guidance for optimizing the performance of coaxial double-U tube in-situ heat exchange geothermal wells under various engineering conditions. It is expected to play a significant role in the sustainable application of geothermal energy, providing strong technical support for future geothermal well projects to meet energy demands, reduce environmental impacts, and promote the development of clean energy technologies.

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