Development and Design of High-angle Deviated Geothermal Well Extraction and Reinjection in Sandstone Types Thermal Storage

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Abstract. High-angle deviated wells have a larger contact area with the reservoir compared to conventional vertical wells. As extraction and injection wells, they can significantly enhance extraction efficiency. Additionally, an integrated geological engineering design allows for large platform implementation, reducing surface construction costs and increasing overall project returns. However, due to the inter-layer and intra-layer heterogeneity of sandstone types thermal storage, high-angle deviated wells are prone to issues such as uneven vertical utilization and cold breakthrough in high-permeability layers. Moreover, predicting water extraction temperatures becomes more challenging. This paper is based on implemented project examples to optimize the design of high-angle deviated geothermal wells and screen casing. The integrated geological engineering approach aims to reduce costs and increase efficiency by optimizing well trajectories considering inter-layer heterogeneity, ensuring effective water extraction deeply. Additionally, we establish a QS flow equation and use the harmonic level KH method for temperature prediction, achieving a 10% increase in thermal storage thickness utilization with measurement and temperature errors within 3%. A modeling system for thermal storage temperature fields throughout the lifecycle is developed, providing a solid foundation for parameter optimization in project planning. Real-time monitoring of field operations is conducted to provide early warnings for cold breakthrough risks, ensuring stable operation of public welfare projects.

Keywords: Sandstone types thermal storage, Geothermal, High-angle deviated Wells, Extraction and injection, development.

1. Overview

The study area is located in the northeastern part of the eastern depression of the Liaohe fault basin [1], adjacent to the central uplift. The exposed strata, from bottom to top, include the Neogene-Paleogene Shahejie Formation (E2s3 and E3s1), Dongying Formation (Ed), Neogene Guantao Formation (Ng), Minghuazhen Formation (Nm), and Quaternary Alluvial Plain Formation (Qp). The target formation for this study is the Dongying Formation.

The Dongying Formation (Ed) is divided into three sections: East 1, East 2, and East 3, from top to bottom. The East 1 and East 2 sections primarily consist of light gray conglomerates, gray-green mudstones, and gray siltstone mudstones. The East 3 section exhibits stable development of extensive volcanic rocks throughout the area. The Dongying Formation has a considerable thickness ranging from 800 to 1000 meters.

The Dongying Formation in the study area represents sedimentation in a near-source fluvial environment, with material sources originating from the western and northern uplifts, resulting in northeast-southwest trending sand bodies. Due to its proximity to the source, the lithology is predominantly coarse, mainly consisting of light gray conglomerates and gravelly sandstones. The sandstone composition is primarily quartz and feldspar, with particles being sub-angular to rounded, exhibiting variable sorting from poor to good, and are loosely cemented by clay.

Reservoir development is primarily controlled by sedimentation. The long axis of the thermal reservoir sand bodies in the Dongying Formation trends northwest-southeast. The Ed2 thermal reservoir is thicker in its central part, measuring between 200 and 300 meters, while it thins towards the west and south. In contrast, the southern part of the Ed3 section has a thickness ranging from 50 to 110 meters; however, it thins in the north due to gas layer development and basalt presence. The temperature gradient in this block is measured at 2.8°C per hundred meters, with temperatures in the Ed2 thermal reservoir ranging from 40 to 56°C and those in Ed3 ranging from 51 to 62°C. Total mineralization ranges between 855 and 1103 mg/L, classified as $NaHCO_3$ type water.

The thermal reservoir area of the study site covers approximately 30.85 km², with resource estimates of 552 million GJ for Ed2 and 256 million GJ for Ed3.

2. Design of High-angel Well Extraction and Injection

Based on existing data, the extraction and injection parameters from the similar physical property X well area were referenced and validated through numerical simulation methods [2]. Initially, two wells were implemented for extraction and injection testing, and design parameters were optimized based on the test results. Considering factors such as hotspot distance and surface conditions, the A block was preferentially selected for deployment near the boiler room in a horizontal layout. Vertically, a significant portion of the northern area is developed with large sections of basalt, primarily focusing on Ed2 for development.

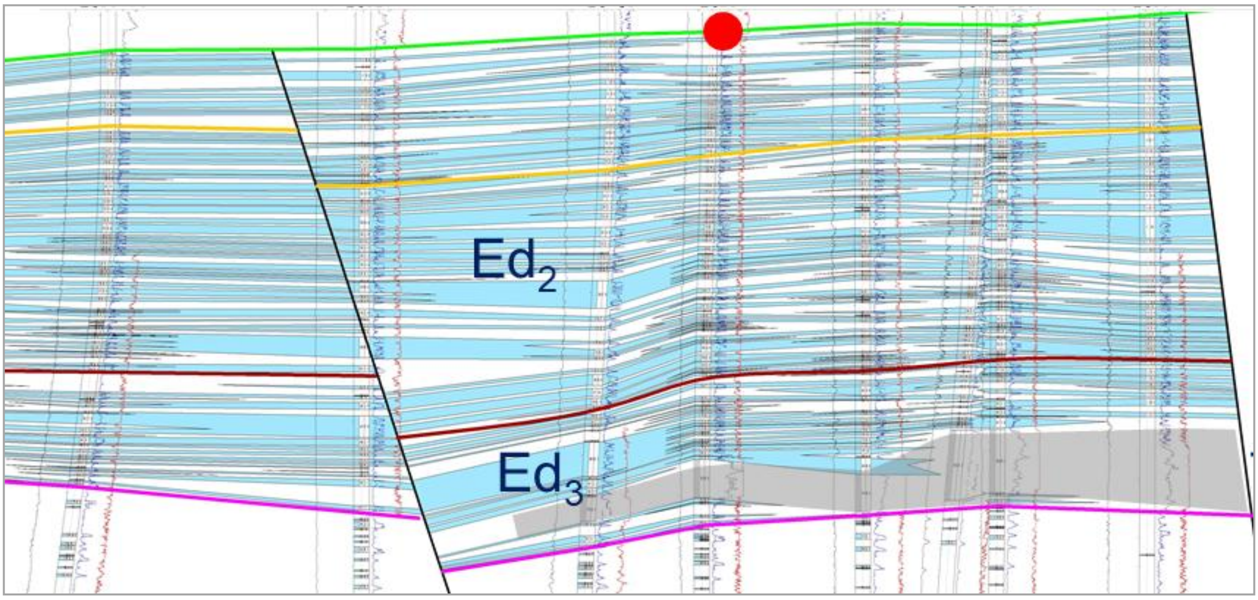

Figure 1. Typical Thermal Reservoir Profile in the Study Area

Using empirical formulas, analogy methods, and results from numerical simulations, a reasonably well spacing of 450 meters was determined for the target area. According to geothermal resource evaluation methods and estimation guidelines DZ T 0331-2020, the calculated reasonably well spacing over 50 years of operation is 453 meters (operating 151 days per year).

A geological model was established based on the geological conditions of the well area. The extraction and injection flow rates were designed according to previously validated intensities and thermal reservoir thickness (120 m³/h). Simulation results indicated that at a well spacing of 300 meters, temperatures begin to decline after 10 years; at 350 meters after 17 years; at 400 meters after 35 years; and at 450-500 meters after 50 years (operating for 151 days per year).

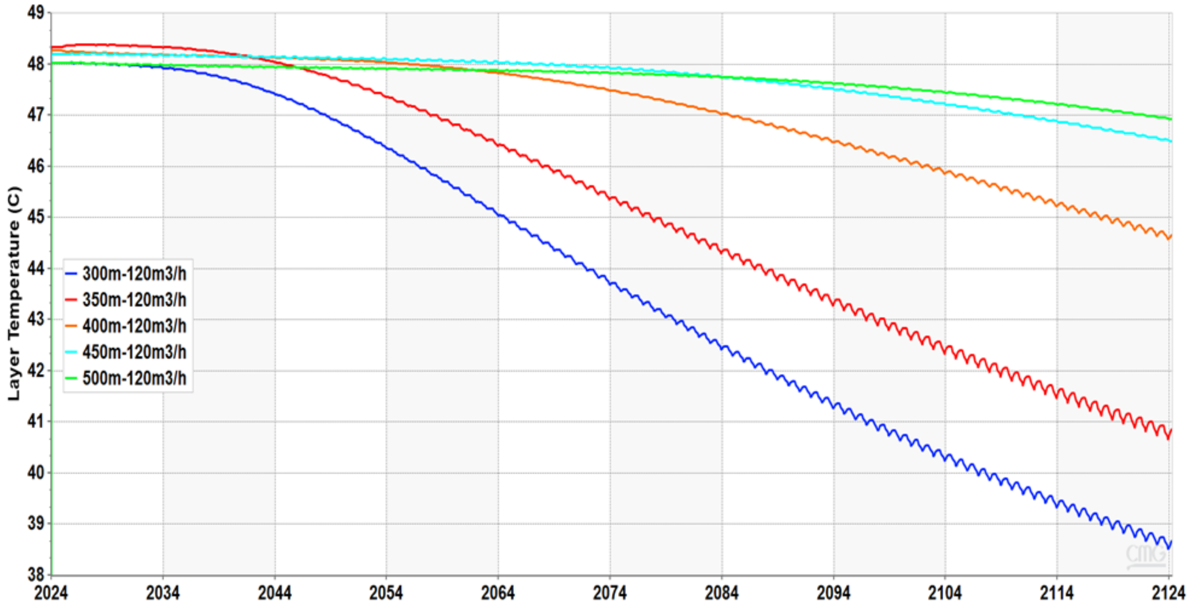

Figure 2. Relationship Between Extracted Temperature and Time at Different Well Spacings from Numerical Simulations

Considering the required ratio of injection to extraction wells and combining it with the characteristics of thermal reservoir fractures, a staggered grid layout was adopted to ensure multidirectional connectivity among the injection and extraction wells [3-4].

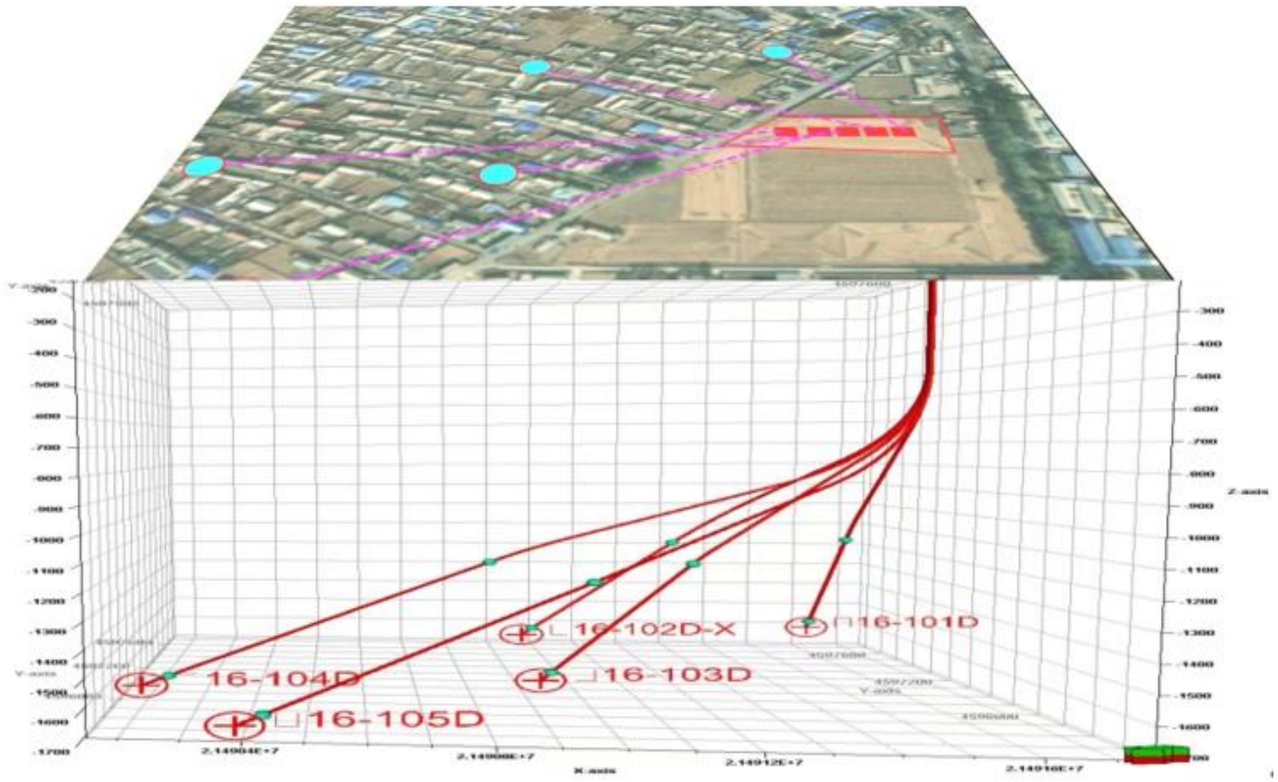

Figure 3. Schematic Diagram of High-Inclination Extraction and Injection Deployment in the Study Area

Based on previously validated extraction and injection capacities, single-well extraction and injection parameters were designed using an injection-determined extraction approach with a balance principle. The single-well injection flow rate is set at 80 m³/h, while the single-well extraction flow rate is set at 120 m³/h, resulting in a total extraction-injection scale of 240 m³/h. The expected extraction temperature at the wellhead is 45°C with an injection temperature of 10°C, covering a heating area of approximately 284,000 m². The geothermal load supported is estimated at 12.1 MW, with a heating output during the heating season of around 105,000 GJ. This setup is projected to reduce CO2 emissions by approximately 4543 tons annually and save about 3582 tons of standard coal per year.

3. Optimization Design of Trajectory and Screen-Casing Combination

Compared to conventional vertical wells, high-angle geothermal wells have a larger contact area with the thermal reservoir section. As extraction and injection wells, they can significantly enhance extraction and injection efficiency. Additionally, an integrated geological engineering design facilitates large platform implementation, reducing surface construction costs and increasing overall project returns. However, due to the inter-layer and intra-layer heterogeneity of sandstone-type thermal reservoirs, high-angle wells may encounter issues such as uneven vertical utilization and cold breakthrough in high-permeability layers during extraction and injection.

In the study area, the Ed2 thermal reservoir is buried at depths of 1150 to 1680 meters, with porosity generally ranging from 22% to 29.7%, averaging 26.4%. The permeability typically ranges from 600 to 1800 mD, with an average of 1226 mD. For the Ed3 thermal reservoir, buried at depths of 1480 to 1900 meters, secondary interpretation results indicate porosity ranging from 20% to 28.8%, averaging 22.5%, while permeability ranges from 427 to 1226 mD, averaging 657.5 Md. To address this issue, we consider the heterogeneity of the thermal reservoir and the differences in permeability between the upper and lower sections of the main thermal reservoir layer in relation to high-angle well extraction and injection. The overall layout of the extraction and injection well network for high-angle wells adopts an upper injection and lower extraction approach, with reinjection wells positioned as high as possible in structural highs to facilitate gravitational movement of reinjection water into lower extraction wells. In addition, well spacing is increased by 10-20% in the upper high-permeability sections while reduced by 10-20% in the lower low-permeability sections, ensuring uniform utilization across different permeability layers within the thermal reservoir.

To address the challenges associated with predicting water temperature in high-angle wells, we established a QS flow equation and developed a rhythmic KH method for temperature prediction, achieving a 10% increase in utilized thermal reservoir thickness with measurement errors for volume and temperature within 3%. The QS flow equation is primarily calculated based on current geothermal standards, determining the relationship between depth reduction and flow rate during onsite extraction tests to ensure that both pump efficiency and flow requirements are maintained during actual production; further details are not elaborated here. Onsite measurements indicated an extraction well temperature of 45°C; using the QS method, a depth reduction of 40 meters would achieve the designed extraction volume.

An innovative rhythmic KH method was developed for predicting extraction temperatures by comprehensively considering the physical properties and thickness of the thermal reservoir's contribution to water extraction. The specific steps include resampling permeability curves at ten points per meter along both screen pipes and repeated segments of the reservoir, summing these data points to calculate each point's contribution weight; then multiplying sampled thermal reservoir temperatures by their respective weights for summation to achieve temperature predictions using the rhythmic KH method. Onsite tests confirmed that increasing utilized thermal reservoir thickness by 10% resulted in measurement errors for volume and temperature within 3%.

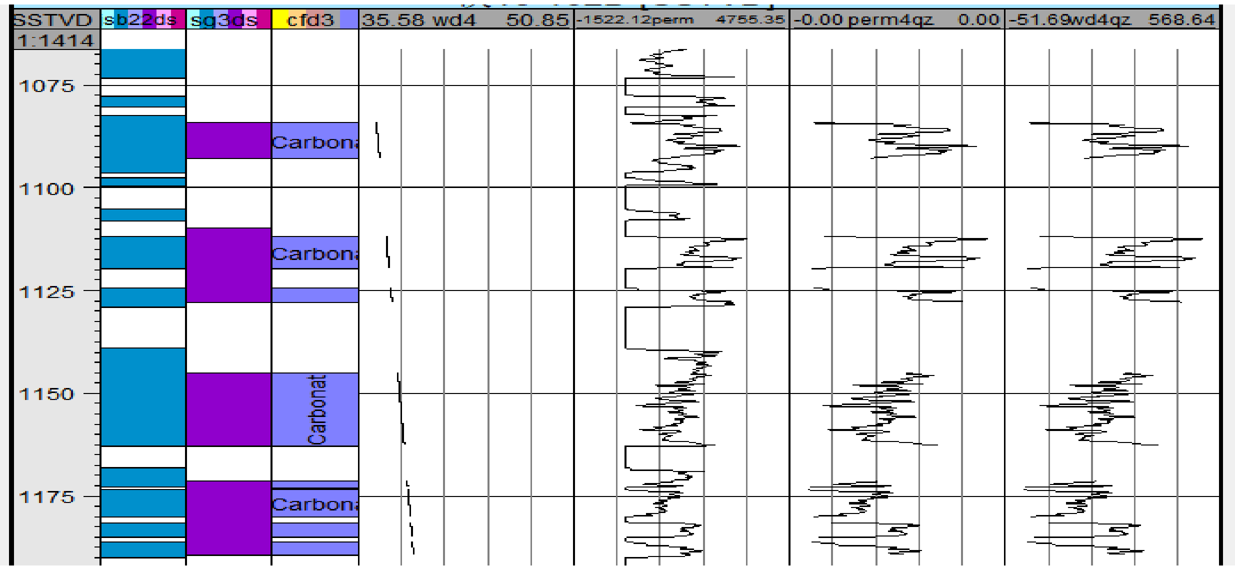

Figure 4. Interface for Predicting Extraction Temperature Using the Rhythmic KH Method in Typical Wells of the Study Area.

4. Research on Physical and Numerical Modeling of Geothermal Full Lifecycle

This study conducts firstly the series of physical simulation experiments for multiple geothermal development methods, quantifying the fluid replacement period for vertical wells, the “thermal breakthrough” period, and the “cold breakthrough” injection pv limits. Different horizontal well extraction designs were compared, simulating the temperature field changes during energy exchange and material transfer between reinjection fluids and geothermal reservoirs.

Research was conducted on the thermal breakthrough mechanisms in vertical well extraction and injection. Key points such as simplifying flow ratio to 1, strong injection and extraction material balance, and energy “thermal-cold” reverse balance were identified. Similarity criteria for thermal reservoir simulation were derived, deeply characterizing the mechanisms of mass transfer and heat transfer in fluids. This approach authentically reproduces the entire process of utilizing geothermal resources kilometers underground, leading to an innovative understanding of the “three phases” of thermal breakthrough, establishing a “breakthrough” concept distinct from oil and gas development, and redefining fluid replacement periods as well as “thermal” and “cold” breakthrough periods.

This research achieves a transformation from “detailed reservoir description” to “detailed thermal reservoir description,” constructing an integrated technical system for modeling and numerical simulation throughout the geothermal lifecycle.

A large-scale three-dimensional geological modeling technology at the depression level has been developed. Thermal reservoir descriptions have shifted from previous “depth segments” to “isochronous layers.” Using multi-machine parallel methods, large-scale three-dimensional geological modeling with one billion nodes at the depression level was achieved, dividing the depression into six zones, four layers, and 24 units with a total of 2.66 billion grid nodes to quantify geothermal resources accurately. The study conducted a bidirectional matching between surface heating target units and underground thermal reservoirs, identifying 25 favorable zone units with resource evaluation needs of 13.74 million square meters while supporting heating solutions for 4.66 million square meters.

A three-dimensional geological modeling technology for superimposed thermal reservoirs has been established. Addressing the characteristics of Paleogene superimposed thermal reservoirs, a method was employed to subdivide single sand body layers, successfully constructing layer models and completing three-dimensional geological modeling for superimposed thermal reservoirs while adjusting deployment strategies to focus on “single sand body extraction and injection.” Adjustments based on detailed thermal reservoir descriptions supported indoor studies that enhance reservoir modification and fine filtration measures, resulting in a continuous two-tier increase in extraction and injection capacity with over a 200% increase in extraction volume.

High-permeability thermal reservoir numerical simulation technology for "large platforms" and "high inclinations" has been developed. To address issues such as land acquisition for certain projects, innovative geothermal development techniques for "large platforms" and "high inclinations" were introduced, optimizing screen pipe designs to ensure effective deep-water extraction while saving surface investment costs. By integrating insights from physical simulations, numerical simulations throughout the full lifecycle optimized well networks and spacing, demonstrating no cold breakthroughs over a simulated period of 30 years while saving nearly 10% in surface construction investments.

5. Conclusions

High-angle geothermal wells have a larger contact area with the thermal reservoir compared to conventional vertical wells. As extraction and injection wells, they can significantly enhance extraction and injection efficiency. Additionally, through integrated geological engineering design, large platform implementation can reduce surface construction costs, with practical findings indicating nearly a 10% savings in surface investment.

The extraction and injection of high-angle geothermal wells should adopt an injection-determined extraction approach based on the principle of balance, taking into account the actual geological conditions of the region. This involves integrating empirical formulas, analogy methods, and numerical simulation results to determine reasonably well spacing for the target area.

The design must optimize the trajectory of high-angle wells by considering inter-layer heterogeneity to ensure effective deep-water extraction. Additionally, establishing the QS flow equation and using the rhythmic KH method for temperature prediction has shown that it is possible to increase utilized thermal reservoir thickness by 10%, with measurement errors for volume and temperature within 3%.

Research on physical and numerical modeling throughout the geothermal lifecycle serves as a foundational guarantee, leading to an innovative understanding of the "three phases" of thermal breakthrough. This research establishes a "breakthrough" concept distinct from oil and gas development and redefines fluid replacement periods as well as "thermal" and "cold" breakthrough periods.

A technical system has been developed for large-scale modeling at the depression level, three-dimensional geological modeling of superimposed thermal reservoirs, and numerical simulation techniques for "large platforms" and "high inclinations." This solidifies the foundation for optimizing parameter compilation in project planning, enabling real-time tracking of onsite operations while providing early warnings for cold breakthrough risks to ensure stable operation of public welfare projects.

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