Exploration and practice of centralized sandstone geothermal well group deployment

ZHOU Hong[1], LI Hongda[2], ZHAO Pengfei[3], ZHANG Jichang[1], CHEN Xuanyi[4], SU Na [5], Wu Shaokun[1]

(1. Liaohe Oilfield Environmental Engineering Company, Panjin 124010

2. Geothermal Project Department of Jidong Oilfield, Tangshan, 063004

3. China Coal Xi'an Design Engineering Co., Ltd., Xi'an 710000, China

4. College of New Energy and Environment, Jilin University, Changchun, 130012

5. Tangshan Jidong Geothermal Energy Development Co., Ltd., Tangshan, 063004).

Abstract: In recent years, people have paid more and more attention to the development of medium and deep sandstone-type geothermal resources, and centralized mining has gradually become the norm. In the deployment process of centralized sandstone geothermal well groups, well spacing and well network not only determine the temperature and water level changes of geothermal wells after many years, but also affect the life and economy of geothermal projects. Taking the geothermal project of Caofeidian New City in eastern Hebei as an example, this paper studies the optimization of centralized sandstone-type geothermal mining well network. On the basis of geothermal investigation in the study area, the extraction and recharge test was used to determine that the mining capacity of geothermal wells was 100m^3/h and the recharge capacity was 80m^3/h. Numerical modeling was used to optimize the distance between geothermal recharge wells to 450 meters, and the network of geothermal recharge wells was deployed according to staggered arrangement. The multi-well pilot test was used to verify the rationality of geothermal well exploitation and recharge, and the operation and maintenance system of geothermal well exploitation and recharge was formulated. Using the modeling of multi-year recharge production data of well groups, it was predicted that the thermal storage seepage field would form a small-scale drop funnel (maximum range of about 300m) during the heating period, and the water level would quickly recover to the initial water level state during the non-heating period. When the model was in operation for 30 years, the temperature drop in the recharge area in the thermal reservoir was 10-40°C, the temperature drop in most areas was about 15°C, and the temperature change at the mining well location was less than 0.5°C. Production practice and numerical model results confirm that the well distance of the project is 450m, and it is feasible to deploy the well

network according to staggered arrangement, which provides technical support for the large-scale development of geothermal resources in the future.

Keywords: centralized; Medium and deep; sandstone-type thermal storage; Well network optimization; Numerical simulation

1. Introduction

At present, the development and utilization of geothermal resources has emerged in the world, and as a country rich in medium and low temperature geothermal resources [1], China's direct utilization of geothermal energy is in the forefront of the world. In recent years, due to its advantages of economic benefits, the use of medium and deep sandstone geothermal resources has developed rapidly, and the development mode has gradually transitioned from scattered to centralized. In production practice, geothermal mining well spacing is small, easy to cause thermal breakthroughs, large well spacing, which is not conducive to centralized development, and has low economic benefits.

Zhu Jialing et al. [2] focused on the pore strata of the Guantao Formation in Tanggu area (533km^2) of Tianjin Binhai New Area, and used numerical simulation methods to study the influence of geothermal well spacing on pore thermal storage temperature field and pressure field, based on the simulation calculation of well spacing. Considering the influence on the pressure compensation effect and temperature field of well recharge, it is recommended that the spacing of pore thermal storage geothermal production and recharge wells should not be less than 500m. Zhang Hongbo[3] Taking the heat storage of the lower section of Dongying Formation and Guantao Formation of the central uplift of Dongying sag as an example, a model evaluation method for recyclable wells for geothermal resources was established, and a reasonable well spacing of about 800m was determined through the evaluation of the well network model. Many scholars [4-8] took shallow groundwater as an example and used numerical simulation methods to study the well spacing, well network deployment, thermal breakthrough, and temperature field of recharge and production wells.

The Code for Geological Exploration of Geothermal Resources (GB/T 11615-2010) mentions that the distance between the mining well and the recharge well in the well recharge test should be greater than twice the radius of exploitation influence [9]. The Technical Requirements for Geothermal Reinjection (NB/T 10099-2018) mentions that the design requirements of recharge wells require that well location layout should avoid the close distance between the wells and the recharge wells to prevent thermal breakthroughs [10].

Geothermal heating projects generally need to be close to residential gathering areas, the ground space is relatively small, and geothermal recharge wells need to be arranged in the form of cluster wells, which requires that the spacing between the bottom of the wells should not be too large. Therefore, the optimization of the well network for geothermal resource exploitation is a very important work, which is related to the success or failure of the entire geothermal heating project.

The following is an example of the $230\times10^4 m^2$ geothermal heating project in Caofeidian in eastern Hebei, see Figure 1. From the aspects of resource exploration, recharge and mining experiment, well network optimization, production practice, model prediction, etc., the optimization and practice process of centralized medium and deep sandstone geothermal mining well network is elaborated, which provides reference and reference for large-scale geothermal resource exploitation in the future.

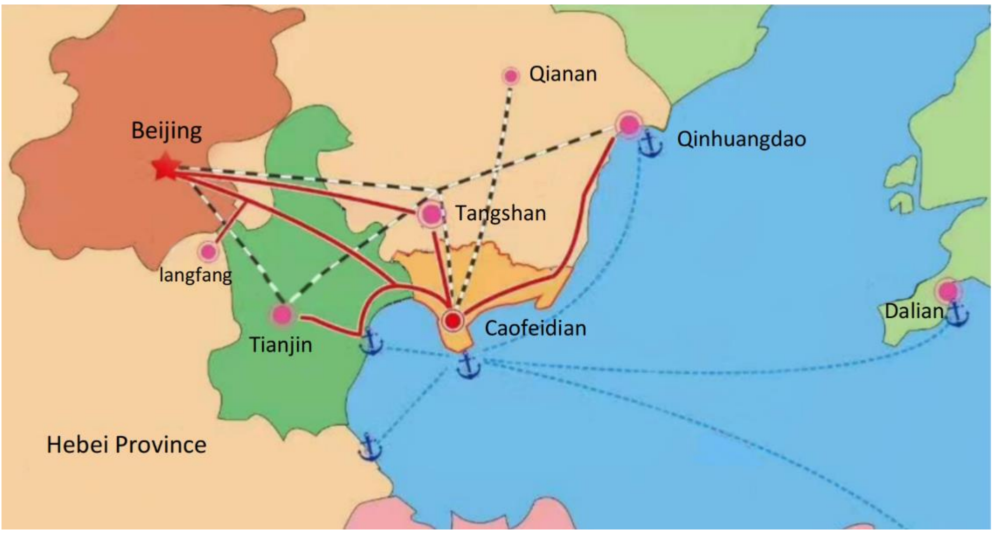


Figure 1 Schematic diagram of the traffic location of the study area

2. Theory and methodology

Hydrogeological conceptual model, mathematical model, three-dimensional hydrothermal coupling numerical model were established[11] . The mathematical model of groundwater flow can be expressed as follows:

The water flow motion control equation takes the general form of a continuity equation:

$$\mu_s \frac{\partial h}{\partial t} + \frac{\partial q_i}{\partial x_i} = 0 \qquad (1)$$

where is the water storage rate [μ_s 1/m], the water head [m], the time h [d], the square distance, t and the directional flow x_i rate i q_i , i According to Darcy's Law, it can be written:

$$q_i = -k_{ij} f_\mu \left(\frac{\partial h}{\partial x_i} + \frac{\rho - \rho_0}{\rho_0} e^j \right) \qquad (2)$$

where k_{ij} is the permeability coefficient [m/d], the viscous equation, the direction vector, the f_μ fluid density e^j [kg/m ρ ³], and ρ_0 the reference temperature (15°C) Fluid density [kg/m³]. The density is temperature dependent, and its linear model is:

$$\frac{\rho - \rho_0}{\rho_0} = -\beta \frac{T - T_0}{T_0} \qquad (3)$$

where β represents the coefficient of thermal expansion, usually 10^{-4}1/°C.

Heat transfer satisfies the conservation of energy, and its control equation can be expressed as:

$$C \frac{\partial T}{\partial t} = \nabla(\lambda \nabla T) - C q_i \nabla T \qquad (4)$$

where C is the equivalent volume specific heat capacity [MJ/m³/K]; λ is the thermal conductivity [W/m/K]. The left end of the equation represents the heat change term over time, the first term on the right is heat transfer under heat conduction control, and the second term is heat transfer under convection control.

The flow velocity field is obtained by calculating the water flow equation, which is used to calculate the heat transfer equation to obtain the three-dimensional temperature spatial distribution and the time-dependent evolution process. The temperature field affects the density of the fluid, causing the density flow, which is fed back to the water flow movement process.

3. Characteristics of thermal reservoirs in the study area

Caofeidian in eastern Hebei is located in the northern part of the North China Plain, and the structural location is located in the Gaoshangbao Structural Zone of the Nanbao Depression in the northern part of the Huanghua Depression in the Bohai Bay Oil and Gas Basin. The heat storage of the Cenozoic Neogene Pavilion is widely distributed in the whole area, and it is fluvial sedimentary sandstone, with large thickness of single sand body and good connectivity, see Figure 2. The lithology is gray-white unequal grained fine sandstone, medium sandstone, conglomerate, with unequal thickness interbedded. The composition of sandstone is mainly quartz, followed by feldspar, containing a small amount of dark minerals, sub-round, well sorted, argillaceous cementation, loose. It belongs to porous heat storage.

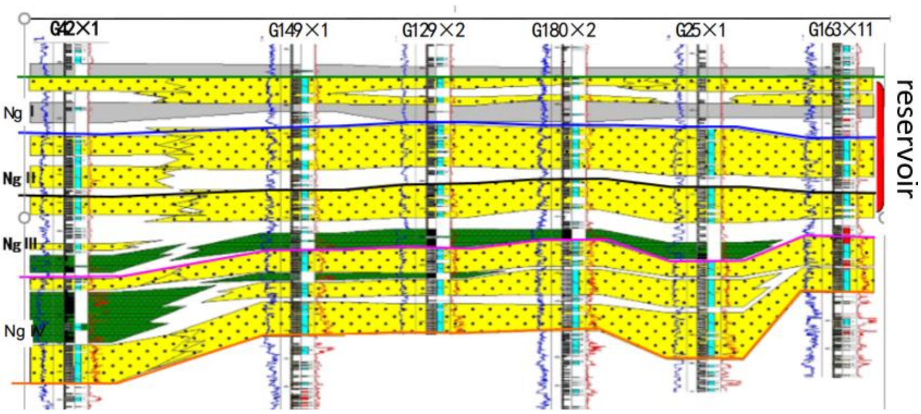


Figure 2: **Comparative stratigraphy of the Guantao Formation in the study area**

Through logging interpretation and prediction of seismic properties, the buried depth of the thermal storage roof plate is 1900-2100m, the depth of the floor is 2100~2700m, and the thickness is 120~300m. The average porosity of the reservoir is about 26%, and the average permeability is about 630mD, which is a highly porous and permeable reservoir. The depth of the thermostatic zone in this area is 30 meters, the thermostatic layer temperature is 13.5 °C, the geothermal gradient is 3.0-4.0 °C/100m, and the temperature of the thermal reservoir is 70~ 110℃。 Geothermal water chemistry type HCO_3· Cl-Na type, the total salinity is 1.0~3.0g/L.

Through the investigation and evaluation of the water collection area of Caofeidian 230×10^4m 2 geothermal heating project, 11.7km 2 within[the] scope of Guantao Group [12], the heat energy recovery rate is calculated at 25%, and the hot water recovery rate is calculated at 20% [1]. 3], the available geothermal resources in the water extraction area are 0.94×10 ^{8}GJ, and the available geothermal water capacity is 1.17×10 ^{8}m^3。 The annual utilization of geothermal water of the project is 386.5×10^4m^3, and the geothermal resources can meet the heat demand of the project for 30 years.

The nearby scrapped oil wells were converted into geothermal wells with a height of 12 9×2 and a height of 149×1. The pumping test test has a maximum stable mining capacity of 97m^3/h, and the wellhead outlet temperature is 75°C. Aquifer test software was used to find parameters[14-16]: the water conductivity of the thermal reservoir T=83.20m^2/d, permeability coefficient K=0.91m/d, elastic water release coefficient S=9.75×10^{-5}, influence radius R= 1274m。

4. Design and optimization of centralized geothermal mining mode

4.1 Geothermal well spacing optimization

According to the resource investigation results, combined with the recharge test data, the geothermal production and recharge well distance was optimized based on FEFLOW software. One mining well and one recharge well were set up, with a mining well production capacity of 100m 3/h and a recharge well recharge capacity of 80m^3/h The well spacing is 300m, 400m, 500m, 600mm and 700m, respectively, and wells are opened in one year 136 days, closed well for 229 days, numerical simulation with a cycle of 30 years, the trend of head and temperature change with different well spacing was obtained, see Figure 3.

After 30 years of mining, when the well spacing is 600m~700m, the reservoir temperature drop is not more than 1 °C; When the well spacing is 500m~600m, the temperature drop of the reservoir is not more than 2.5 °C. When the well spacing is 400m~500m, the temperature drop of the reservoir is not more than 6.5 °C; When the well spacing is 300m~400m, the temperature drop of the reservoir is not more than 11.5 °C. When the well distance is 450m, the reservoir temperature drop is not more than 4°C.

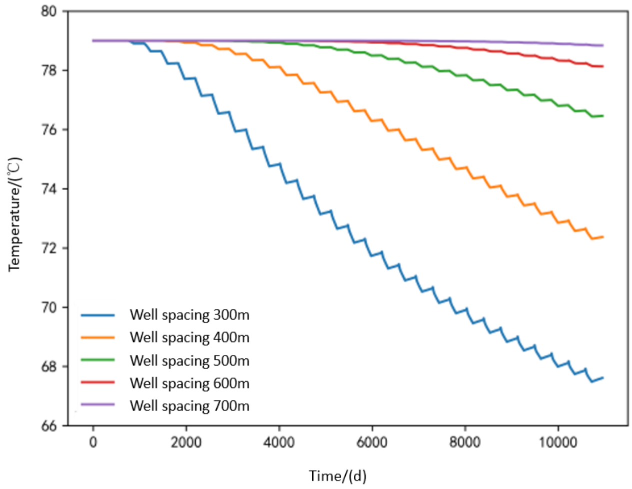


Figure 3: Variation curve of wells with well spacing during 30 years of operation

According to the geothermal well pumping test, recharge production test, well spacing optimization comparison, combined with geothermal well drilling trajectory design, surface drilling platform location and other factors, the geothermal well spacing was finally determined to be 450m.

4.2 Well network structure design

The deployment of well group network should first ensure the pressure balance of the geothermal flow field of the well group. According to the thermal reservoir connectivity, well group correspondence and single well recharge capacity, the underground recharge capacity of each block should be balanced, and the geothermal flow field pressure of the overall well group should be balanced.

Secondly, mining wells and recharge wells are not interchangeable, especially recharge wells, once determined, should be persisted as recharge wells for a long time, and cannot be easily changed to mining wells, because the temperature of geothermal tailwater after reinjection needs to be gradually restored after a long heat exchange.

The water injection method of oil well area can be divided into four-point method, five-point method, seven-point method, nine-point method, crooked seven-point method area injection and orthogonal and staggered discharge water injection according to the mutual position between oil production wells and water injection wells and the shape of the well network[17]. In the enhanced geothermal system, the well network layout methods include three-point method, five-point method, seven-point method and nine-point method [18]. Combined with the characteristics of geothermal geology, geothermal field and geothermal wells in the study area, and drawing on the water injection method of oil well development area, the deployment of the well group network in this study adopts staggered discharge distribution, that is, the staggered distribution of mining wells and recharge wells.

The geothermal well extraction capacity is 100m³/h, the geothermal well recharge capacity is 80m³/h, the ratio of geothermal mining wells to the number of recharge wells is designed to be 4:5, and the geothermal well spacing is designed 450m, according to the total heat demand of geothermal heating projects, 16 geothermal mining wells, 20 recharge wells and 3 reserve wells were designed, a total of 39 The mouth, mining and recharge layers are all heat storage of the pavilion pottery group. The location of the well is shown in Figure 4.

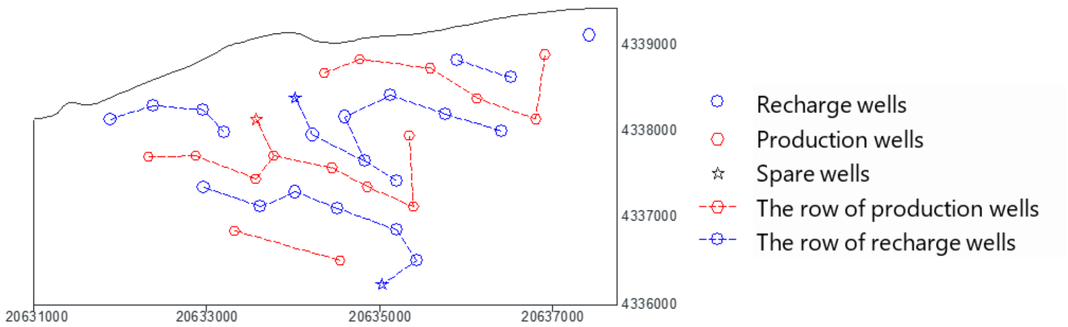


Figure 4: Deployment diagram of centralized sandstone geothermal well group

4. 3. Practice and analysis of recharge and harvesting production

In the early stage of project construction, pilot test wells of 6 wells were first constructed. From drilling, completion, well washing, recharge and production testing, production and operation have invested a lot of research work, received good results, and provided an important guarantee for later production. For example, drilling mud, cementing method, screen pipe type, well washing method, etc. are reasonable and efficient, to ensure the completion quality of geothermal wells, good sand prevention effect, mining capacity (100m^3/h), recharge amount (80m ^{3}/h) all meet the design requirements, and form a full chain of replicable geothermal drilling and completion technology. Six geothermal wells were used to carry out productive pumping tests and reinjection tests, and a reasonable lifting perimeter, lifting amount and operation and maintenance system were formulated, which provided a guarantee for the long-term and stable operation of the entire geothermal project, and formed a reasonable sandstone geothermal well production and recharge technology.

After the formal production, it has been implemented in accordance with the well spacing and well network determined above, and operated and maintained in accordance with the reasonable recharge system. Up to now, the four heating periods of geothermal mining wells and recharge wells have operated smoothly, and there has been no major change in the amount of extraction, recharge, water temperature and water level, and 100% natural recharge of the same layer has been achieved for four consecutive years.

The numerical model is corrected based on the dynamic monitoring data of water level and water temperature in the geothermal mining cycle in 2018~2021. After adjusting the parameters of the model, the temperature, water level values and change trends obtained by the simulation are basically consistent with the actual situation, and the fitting effect is good, see Figure 5~6.

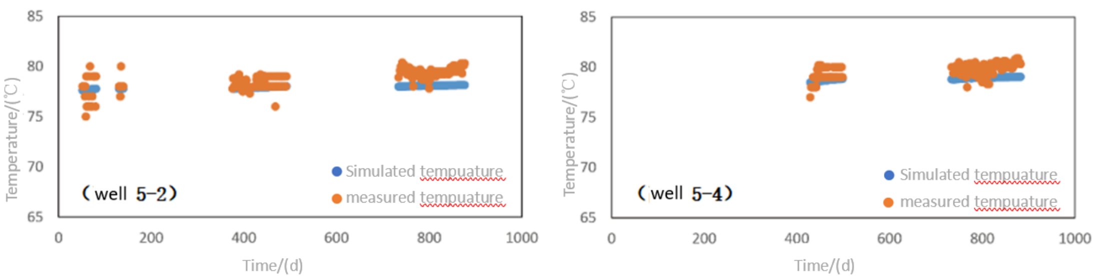


Figure 5 Partial well temperature fitting plot

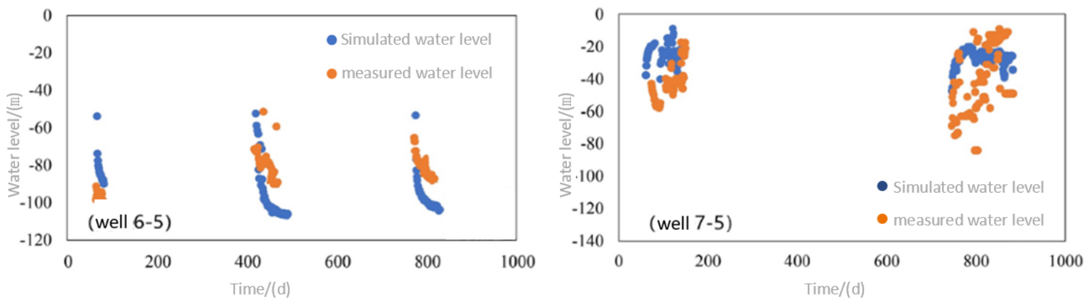
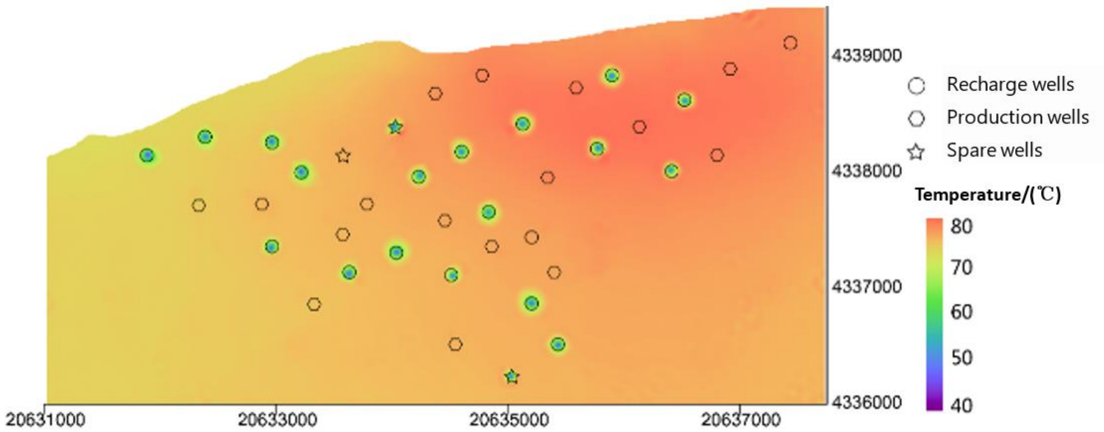
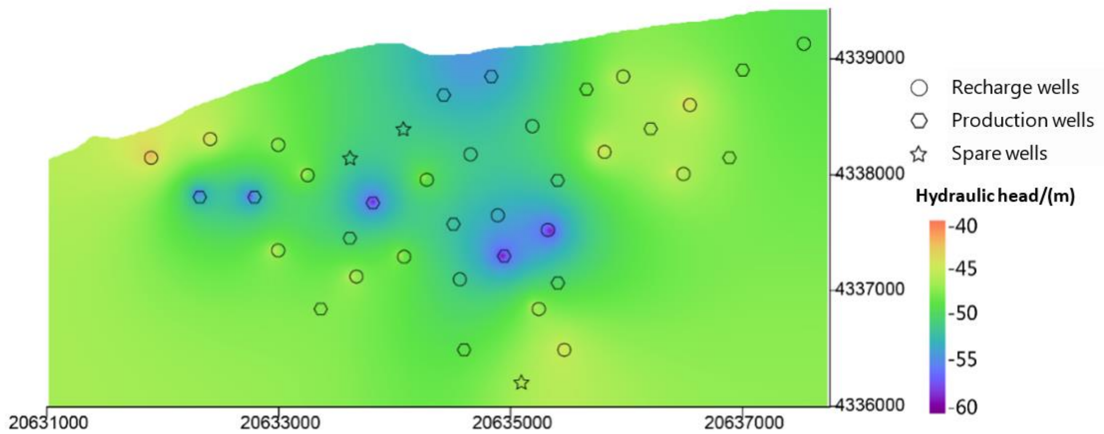


Figure 6 Part of the well water level fitting diagram

After adjusting the model fitting, the parameters of the model were determined, and the changes of temperature and water level in the study area after three years (883 days) of recharge from 2018 to 2021 were obtained, as shown in Figure 7.



(a) Temperature field distribution diagram



(b) Flow field distribution map

Figure 7 Distribution of temperature field and flow field in simulation area

4.4 Analysis of future hydrothermal evolution trends

The annual heating and recharge scheme after 2021 was collated, and the recharge data of each well with one year of complete operation was obtained, and it was repeatedly extended to

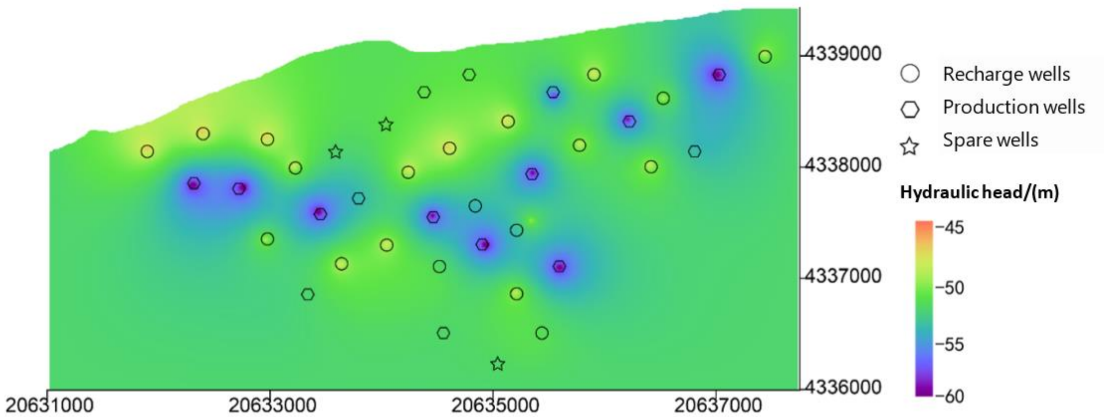
30 years as the recharge scheme of the prediction model. The 2021 head distribution and temperature field distribution obtained by the simulation were used as the initial head and initial temperature conditions of the prediction model.

For a given mining scenario, numerical simulations yielded a head distribution map when the mining and recharge wells were running and when all wells were closed, as shown in Figure 8.

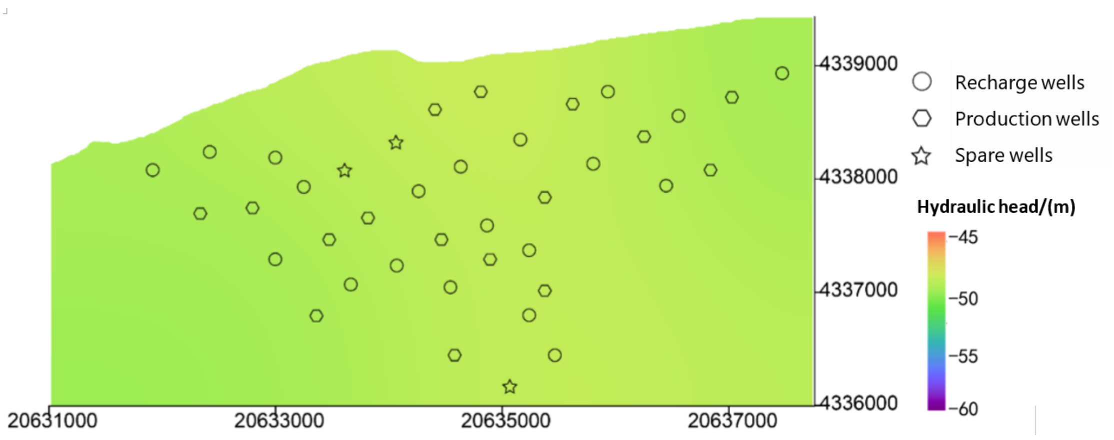
As can be seen from Figure 8(a), during the heating period, the water head in the recharge well area is high, and the water head in the mining well area is low, which is due to the increase in the water level in the recharge well area after filling the low-temperature water, and the surrounding fluid cannot be quickly replenished due to the large amount of mining in the mining well area, forming a small-scale landing funnel (maximum range approx 300m）。

As can be seen from Figure 8(b), during the shutdown of heating, driven by the difference in head between the recharge well and the mining well, the fluid flows from the area with a high head to the area with a low head, so that the water level quickly returns to the initial water level state.

In summary, after many years of operation of the geothermal project, the geothermal flow field of thermal storage in the study area always maintained a dynamic equilibrium state, and a small-scale landing funnel was formed during the heating period, and the heating stopped quickly returned to the initial water level.



(a) During the heating period



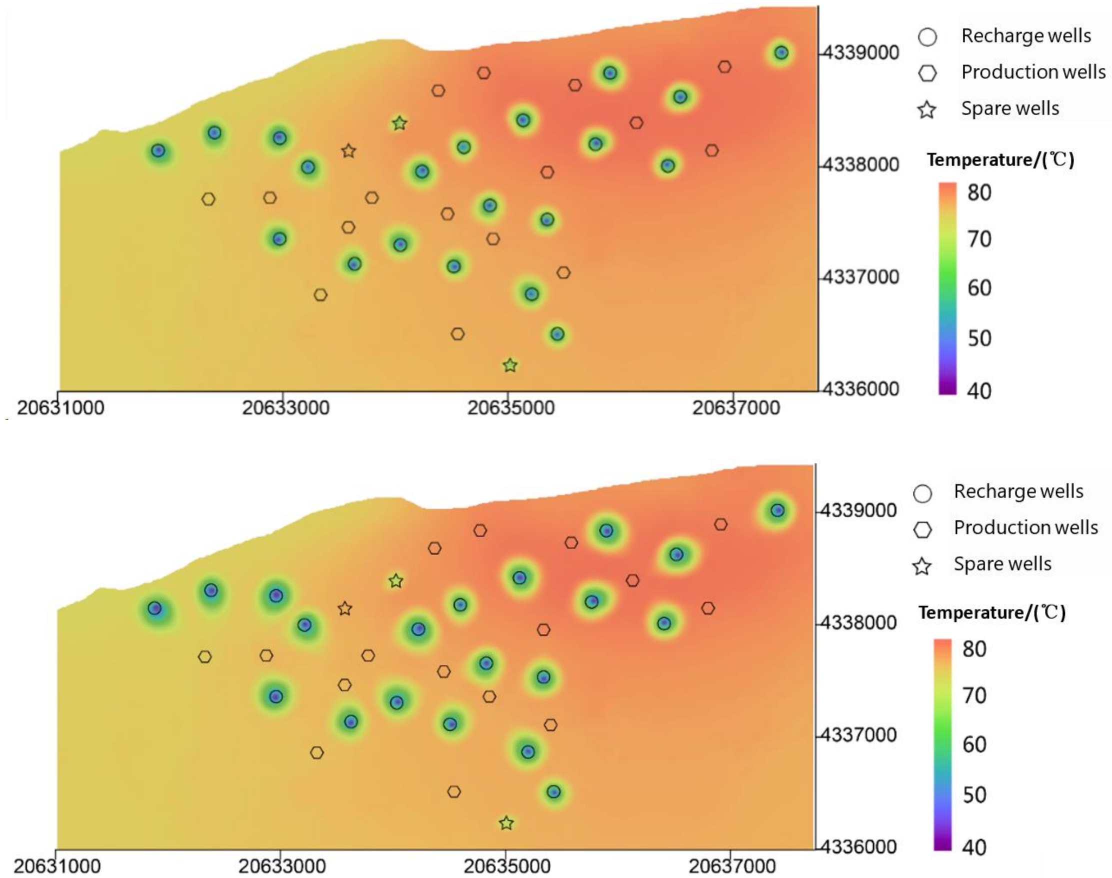
(b) During the period when the heat supply is stopped

Figure 8: Distribution **of water heads under different working conditions after 20 years of operation**

Under the above mining conditions, the evolution of the temperature field over time under 30-year recharge conditions was simulated. It can be seen from Figure 9(a) that in the fifth year of mining reinjection in the model, the temperature of the thermal reservoir in the recharge well area decreases due to the reinjection of the low-temperature fluid, and as the injection fluid continues to migrate around, a concentric circle is formed in the hot reservoir with a radius of about 100m. With the increase of time, the influence of recharge of low-temperature water from recharge wells increases, see Figure 9(b). At the 30th year of the model's mining recharge, the cold area of the thermal reservoir was increased compared with the 5th year, when the cold water affected area was about 300m.

When the model was in operation for 30 years, the temperature drop in the recharge area in the thermal reservoir was 40°C and the minimum drop was 10°C, and most of the areas dropped by about 15°C. However, the temperature variation at the location of the well is less than 0.5°C. It can be seen that the recharged low-temperature water is heated by convective heat conduction during the movement to the mining well, and the temperature is basically consistent with the reservoir temperature when it reaches the mining well.

In summary, when the geothermal project has been in operation for 30 years, the area of the low temperature area of the thermal reservoir increases year by year, and the influence range of cold water is about 300m, and the change range of the thermal storage temperature at the location of the mining well is less than 0.5 °C, and no thermal breakthrough occurs Phenomenon.



(b) 20 years of operation

Fig. 9 Temperature **field distribution of thermal reservoirs at different operating times of geothermal wells**

5. Conclusions and Recommendations

(1) It is feasible to simulate and optimize the geothermal well spacing of 450m, which solves the problem of the deployment of centralized sandstone-type geothermal well groups in Caofeidian in eastern Hebei, where the distance between geothermal production and recharge wells is small and prone to thermal breakthrough. The problem that the large well spacing cannot meet the drilling trajectory requirements of cluster wells.

(2) In this study, the well group network deployment adopts staggered displacement distribution, that is, the staggered displacement distribution of mining wells and recharge wells, which is a simple and practical well position deployment method.

(3) The geothermal heating project in Caofeidian in Jidong has achieved 100% natural recharge in the same layer for four consecutive years; During the heating period, a small-scale landing funnel (maximum range of about 300m) is formed, and the heating is stopped and quickly restored to the initial water level; In the 30th year of operation, the temperature change of heat

storage at the location of the mining well was less than 0.5°C, and no thermal breakthrough occurred. It has obtained objective understanding in survey, design, test, well network optimization, production operation and maintenance, simulation and prediction, and is a successful optimization and practice of centralized medium and deep sandstone geothermal mining well network. It can provide reference for large-scale geothermal development and utilization in the future.

(4) It is recommended to carry out long-term dynamic monitoring and regular evaluation of the geothermal wells of the geothermal project in the future.

Further reading:

[1] Wang J, Qiu N, Hu J, et al Progress and development trend of geothermal research in oilfields in China[J]. Earth Science Frontiers,2017,24(03):1-12

[2] ZHU Jialing, ZHU Xiaoming, LEI Haiyan Analysis of the influence of pressure difference compensation between geothermal recharge wells on recharge efficiency[J]. Journal of Solar Energy,2012,33(1): 56-62

[3] Zhang Hongbo Evaluation method of well network model for recyclable geothermal resources[J] Petroleum Geology and Recovery Efficiency, 2017, 24(1): 86-91

[4] GAO Qing,ZHOU Xuezhi,JIANG Yan,CHEN Xiangliang Thermal penetration and quantitative analysis of pumped and irrigated well area in geoenergy utilization process[J] Journal of Basic Science and Engineering, 2012,20(3): 447-453

[5] ZHANG Yuandong, WEI Jiahua, LI Yu, LI Shi Numerical simulation of water-heat coupling of groundwater source heat pump energy collection[J]. Journal of Tianjin University,2006,39(8): 907-912

[6] Ni Long, Ma Zhiliang Effect of aquifer parameters on heat pump of groundwater source recharge in the same well[J]. Journal of Tianjin University,2006,39(2): 229-234

[7] Zhang Yuandong Study on the influence of single (multiple) well pumping and recharge on the submerged geothermal field[D]. Beijing: Graduate School of Chinese Academy of Sciences, 2003: 1-120

[8] ZHANG Yuandong, WEI Jiahua, WANG Guangqian Influence of regional flow field on geothermal field of aquifer energy mining area[J] Journal of Tsinghua University (Natural Science Edition), 2006, 46(9): 1518-1521

[9] Standardization Administration of China Code for geological exploration of geothermal resources: GB/T 11615-2010[S]. Beijing: China Standards Press, 2011

[10] National Energy Administration Geothermal reinjection technology: NB/T 10099-2018[S] Beijing: China Petrochemical Press, 2018

[11] XUE Yuqun, XIE Chunhong, ZHANG Zhihui, et al Numerical simulation study of three-dimensional unstable flow aquifer energy storage[J]. Geological Review,1994,40(1):74-81

[12] Wang Shejiao, Li Feng, Yan Jiahong, et al Evaluation method and application of geothermal resources in oilfield[J]. Acta Petrolei Sinica,2020,41(5): 554-564

[13] Dong Yuexia, Huang Hongxiang, Ren Lu, et al Characteristics and development practice of geothermal field in the northern Bohai Bay Basin--- a case study of Caofeidian geothermal heating project in Tangshan City,

Hebei Province[J]. Petroleum Exploration and Development, 2021, 48(03): 666-676

[14] ZHANG Wenwen, LIANG Xing, JIN Menggui, et al Fundamentals of hydrogeology [M]. Beijing: Geological Publishing House, 2011

[15] Xue Yuqun Groundwater dynamics [M]. Beijing: Geological Publishing House, 1997

[16] HE Manchao, LIU Bin, YAO Leihua, et al Study on permeability coefficient during underground hot water recharge[J] Journal of Jilin University(Earth Science Edition),2002,32(4):374-377

[17] YANG Yanlin,JING Jing,WANG Fugang Study on well network spacing optimization in CO2-enhanced geothermal system[J]. Journal of Solar Energy, 2014, 35(7):1130-1137

[18] CHEN Taoping, HU Jingbang Petroleum Engineering [M]. Beijing: Petroleum Industry Press, 2000

Fund: Supported by PetroChina's major scientific and technological research project "Research on Key Technologies for the Development and Utilization of Geothermal Resources" (2021DJ5502).

First author profile: Zhou Hong, born in December 1966, male, Changchun Institute of Geology, senior engineer, mainly engaged in groundwater and geothermal development.

Mobile: 15804278246

Address: No. 140, Xinglong Street, Xinglongtai District, Panjin City, Liaoning **Province Zip code: 124010**

Email：lh_gszh@cnpc.com.cn