

Guidelines for Geothermal Energy Development Technology

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ABSTRACT

Geothermal energy is a kind of energy with great potential for development. Nevertheless, if improperly exploited, it will cause damage to geothermal resources, trigger environmental pollution, and make geothermal energy unsustainable. It is necessary to formulate a unified technical guideline for geothermal energy development in the whole industry to realize the sustainable development and utilization of geothermal energy. This, ensuring the development of utilization geothermal energy is sustainable after following this guide. The guideline includes four requirements to realize the sustainable development of geothermal energy projects and life cycle management. Firstly, the calculation and evaluation of geothermal recovery resources. Second, design and formulation for the reasonable development plan. Then, that is conducting systematic dynamic monitoring. Finally, scientific reinjection that ensures recycle utilization. It is necessary for this guideline to be jointly formulated by geothermal energy-related organizations and institutions all over the world, and followed by worldwide geothermal energy projects and investors.

1. INTRODUCTION

The characteristic of geothermal water is a deep burial, slow compensation, and slow regeneration. Owing to this, large-scale centralized exploitation of geothermal water will result in the declined geothermal water level and land subsidence. The random discharge of geothermal tailwater will pollute the water, soil, and atmosphere. It is necessary to implement reinjection to maintain the reservoir pressure, to ensure the geothermal resources sustainable development and utilization, and to reduce the thermal and chemical pollution. At present, reinjection has become the main way to dispose of geothermal tailwater in China, but the national standard "*Geologic Exploration Standard of Geothermal Resources*" (GB/T 11615-2010) issued in 2010 does not consider reinjection system. So, the geothermal national standards, which consider reinjection, should be issued as soon as possible.

The National Energy Administration of China authorized Sinopec Star Co., Ltd to set up the Geothermal Energy Standardization Technical Committee on Nov. 2016. It has issued 51 standards from 2017 to 2019. This paper will introduce the development of technical guidelines (considered reinjection system) written by Geothermal Energy Standardization Technical Committee, including geothermal resource evaluation, design of development plan, dynamic monitoring system, and a reinjection project.

2. EVALUATION OF GEOTHERMAL RESOURCES BASED ON BALANCED REINJECTION

Geothermal resource evaluation refers to the estimation of the quantity and quality of geothermal energy and geothermal fluids in geothermal fields, and the assessment of the exploitable reserves. The geothermal resource evaluation methods consist of heat flux method, volumetric method, statistical method, Monte Carlo method, and numerical simulation method, etc. In recent years, geothermal space heating has become the main way of geothermal utilization in China. The reinjection of space heating tailwater has been implemented to improve geothermal reservoir pressure. Therefore, the numerical simulation method mentioned in the "*Geologic Exploration Standard of Geothermal Resources*" (GB/T 11615-2010) should be improved. The reinjection should be included in the updated geothermal resource evaluation technical standard.

2.1 Geothermal Resources Evaluation Method

A dynamic calculation method, the numerical modeling method is proposed to achieve the sustainable development and utilization of geothermal resources. The proposed numerical modeling method uses professional technical software to calculate the number of geothermal fluid resources without a temperature drop in production well for several years.

The basic steps of establishing the numerical model, as shown below:

(1) Design of the geological conceptual model

After a comprehensive analysis of the collected data and conceptualized the geothermal field geological condition, it will be designed a three-dimensional conceptual model. The conceptual model reflects the thermal reservoirs and cap rocks distribution, the recharge source of geothermal water, the heat source of the geothermal system, important thermal fluids and heat transfer mode, and hydrodynamic characteristics.

(2) Geological body mesh generation

Based on the conceptual model, the simulated geological body will be divided into several units, such as cubes, cuboids, and prisms. The way of mesh generation depends on the model solving method and the calculation program requirements. The size of the unit depends on the degree of exploration and the amount of available information. The grids should be relatively dense in the concentrated production area, while the grids can be relatively sparse not only in the periphery of the geothermal field but also where the reservoir pressure changes are not obvious.

(3) Conduct simulation in un-production condition

The pressure, temperature, flow state of the thermal fluid, and heat conduction of the geothermal field before the development will be simulated.

(4) History matching

Using history matching to achieve the accurate model by matching both pressure and temperature based on geothermal field dynamic monitoring data. There are two methods of history matching: direct method and indirect method. Because of the poor stability of the direct method, the indirect method should be used to adjust the model parameters step by step. That way, the results calculated by the model can approach the actual dynamic monitoring data. As for pressure history matching, the fitting error between the observed and simulated pressure values in observation wells should be under 10% of the variation of water level during the fitting calculation. When the pressure change is small, the pressure fitting error should be less than 1.0 m of water column height.

(5) Application of model prediction

The numerical model is used to estimate the geothermal field resources, to predict the production and reinjection program, to optimize the geothermal space heating project program, and to calculate the amount of geothermal field recoverable resources. The prediction results will depend on the rationality of the geothermal field conceptual model, the accuracy of calculation parameters, and the accuracy of dynamic monitoring data.

2.2 Case study— Xiaotangshan Geothermal Field, Beijing, China

The exploration and development history in the Xiaotangshan geothermal field starts in 1956. At present, there are more than 100 geothermal wells with a depth of 70 m ~ 3500 m. The main geothermal reservoir is Jx and Cambrian, and the production water temperature is 40°C ~ 70°C, the production rate is 1000 m³/day to 2000 m³/day. The geothermal resources in the Xiaotangshan geothermal field are mainly used for space heating, greenhouse planting, and bathing. The reinjection rate reaches 100%. The Xiaotangshan geothermal field has a high research level, early development and utilization, several monitoring projects, abundant monitoring data, good resource conditions, and large heating demand. Therefore, the Xiaotangshan geothermal field is selected as the research object.

The following is a typical geothermal project in Xiaotangshan. This project has two production wells one reinjection well, and the geothermal reservoir is the Jx, the production rate and reinjection rate is 110m³/h. The production water temperature is 69°C, the reinjection water temperature is 30°C, and the distances between the two production wells and reinjection well are 300 m and 500 m, respectively. This project started space heating in 2004. The dynamic monitoring data showed that the water level of the production well and production water temperature did not decrease. This indicated that the geothermal reservoir pressure remained stable, and the production wells could be not influenced by the reinjection water.

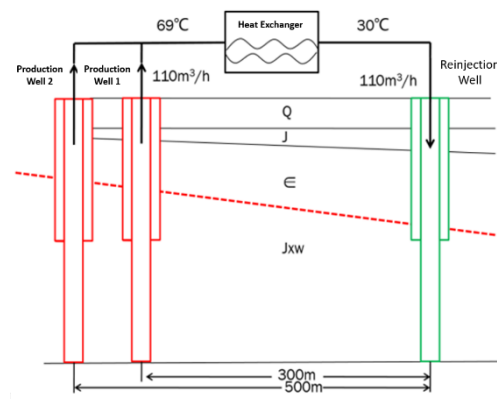


Figure 1 Typical geothermal project in the Xiaotangshan geothermal field

The above evaluation method is applied in the Xiaotangshan typical geothermal field to simulate and predict the production water temperature under different production rates. The prediction results are shown in Figure 2, Figure 3, and Table 1.

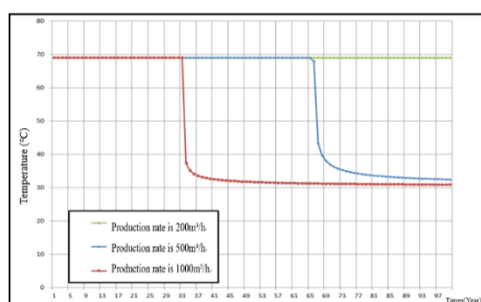


Figure 2 Well #1 (well spacing 300 m)

temperature prediction curve

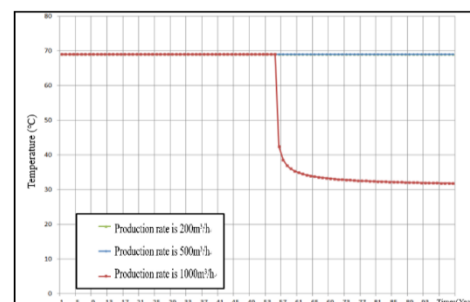


Figure 3 Well #2 (well spacing 500 m)

temperature prediction curve

Table 1. Numerical Simulation Results

Production rate m ³ /h	Well #1 Temperature	Well #2 Temperature
200	100 yrs not decline	100 yrs not decline
340	100 yrs began to decline	100 yrs not decline
500	66 yrs began to decline	100 yrs not decline
1000	34 yrs began to decline	55 yrs began to decline

By calculating the temperature prediction curve and numerical simulation, when the production rate is 200 m³/h and 340 m³/h, the production water temperature of production well #1 and production well #2 will not decrease within 100 years. When the production rate reaches 500m³/h, the temperature of production well #1 begins to decrease after 66 years, the temperature of production well #2 would not change within 100 years. When the production rate reaches 1000 m³/h, the temperature of production of well #1 begins to decrease after 34 years, the temperature of production well #2 began to decline after 55 years. After a comprehensive analysis, the geothermal wells recoverable production rate should be 340 m³/h to ensure the temperature unchanged after 100 years.

3. PREPARATION GEOTHERMAL RESOURCES DEVELOPMENT PLAN

Based on the balanced reinjection geothermal resource evaluation method and geothermal reservoir description, preparing the optimum geothermal resource development plan resulted in the achievement of geothermal resources thermal balance, pressure balance, and chemical balance. In order to further promote scientific exploration and development of China geothermal resources, to ensure the reasonable, scientific, and sustainable development and utilization of geothermal resources.

The development plan should follow the following principles: ① Fully consider the characteristics of the geothermal reservoir. ② Based on the prediction results from the geothermal resources evaluation method mentioned in the last part, choose the reasonable production rate. ③Reasonable reinjection rate and temperature. ④Reasonable well spacing and ratio of production and reinjection to prevent a thermal breakthrough. ⑤Make full use of similar geothermal field development experiences.

The sustainable geothermal resources development plan consists of the following parts:

3.1 Selection of Favorable Area

The determination of the favorable area should consider the effective reservoir thickness, vertical distribution, porosity, permeability, geothermal field temperature gradient, the ground conditions, and other indexes.

3.2 Evaluation of Production Capacity and Reinjection Capacity

Based on the yield test data of drilled geothermal wells, using analogy method, empirical formula calculation method, and numerical simulation to predict the geothermal well productivity, temperature, and maximum reinjection capacity in the favorable area.

3.3 Development and Deployment

(1) Well type

Analyze the adaptability of various well types and optimize the production well and reinjection well types, such as vertical wells, directional wells, and horizontal wells.

(2) Determine the well spacing

The optimum well spacing will be determined based on geothermal reservoir heterogeneity, the formation of physical property, connected conditions, and exploitation method. It will use a hydrological empirical formula method, numerical simulation method, and other methods. It will consider reservoir protection, economic, sustainable development, and the thermal breakthrough time to calculate the geothermal well influence radius.

(3) Well pattern deployment

The geological structural conditions, reservoir characteristics, geothermal resources, and surface conditions should be considered into the deployment of the well's pattern. The optimum well pattern should be determined by production rate, fracture distribution, and well interference degree.

3.4 Design and Optimization of Development Plan

(1) Design development plan

Determine the reasonable well production rate, well number, reinjection well rate, and temperature and production scale, then choose at least three optimum development plans.

(2) Prediction of development plans

Based on the geological modeling, the numerical simulation model will be used to predict more than 100 years of production performance of each development plan. The prediction includes the change of geothermal field and single well's production rate, the change of well production temperature, reinjection well rate, and temperature, formation pressure, etc. The optimum development plan and alternative plans will be chosen after comparison.

4. GEOTHERMAL DYNAMIC MONITORING SYSTEM

At present, the dynamic monitoring of geothermal well still obeys the previously issued groundwater standards. The most direct and important reason for changing the geothermal system stability is a large-scale human-made exploitation and geothermal water reinjection. The "Standard for Geothermal Resources Performance Monitoring" has been formulated based on the dynamic monitoring experience in Beijing and Tianjin to strengthen the dynamic monitoring of the geothermal water and to master the dynamic change rule of the geothermal water in a certain time and space range. This standard will unify the principle of arranging dynamic monitoring networks, dynamic monitoring contents, and other necessary parts related to the dynamic monitoring.

4.1 Design and Arrangement of Dynamic Monitoring Network

The quality of monitoring the network directly affects the accuracy of geothermal water production data and input of manpower, financial and time. The excessive density of geothermal monitoring points will cause the over-waste of monitoring resources. The low density of geothermal monitoring point may lead to the loss of valuable data and information, resulting in a large difference between the monitoring data and the actual situation. The quality of monitoring data will also be influenced by monitoring frequency, backward monitoring equipment and monitoring technology (Baocheng et al., 2013).

The main principles of dynamic monitoring network arrangement are as follows: ①Dynamic monitoring points should be arranged as earlier as possible. ②Geological structure and geothermal reservoir types of the region should be considered, then form the 3D layout in the plan and vertical direction. ③Significant geological structural positions and key pay zone require intensive monitoring. ④The boundary of the geothermal reservoir should be controlled under the dynamic monitoring network. ⑤The continuity and stability of dynamic monitoring data should be guaranteed. ⑥The coordination and unification of economic and technological should be followed (Guang H., Li L., 2014).

Dynamic Monitoring points should be appropriately increased at the stage of geothermal field exploitation. The density of dynamic monitoring networks should higher than (3 ~ 5) points /100km² as required in GB/T 11615-2010. According to the different properties of geothermal dynamic monitoring points, monitoring points should be divided into three categories: key monitoring points, common monitoring points, and unified test monitoring points.

(1) Key monitoring points

Key monitoring points should respond sensitively to the dynamic change of geothermal reservoir and play an important and controlling role in the dynamic characteristics of the different geothermal reservoir, the understanding of the geological structure, and the evaluation of geothermal resources (Baocheng et al., 2013).

The requirements of arranging key monitoring points are ①Close to the great deep fault zone. ②Geothermal wells, which is shut off for a long time, should be selected as a key monitoring point to avoid interference from human activities. ③Choose the geothermal wells with continuous dynamic monitoring and performance data. ④Geothermal wells should be perpendicular and parallel to the recharge and discharge direction of geothermal fluid. ⑤The representative geothermal wells. ⑥ Account for about 30% of monitoring wells (Sumin et al., 2013).

(2) Common monitoring points

Common monitoring points must be arranged based on the key monitoring well points to improve the accuracy of the monitoring system.

(3) Unified test monitoring points

The unified test monitoring points should be the monitoring wells except for the key monitoring points and the common monitoring points. The unified monitor test will be conducted twice a year, with a time interval of 6 months. The unified monitor test should be completed 15 days before and after heating every year, that is, in April and October every year in China. This, considering that the opening and closing of geothermal wells have a greater impact on the geothermal water level. The collected data could be used to draw the geothermal water level contour map.

4.2 Main Dynamic Monitoring Contents

4.2.1 Geothermal water pressure

Geothermal reservoirs pressure can be obtained by measuring the water level of geothermal wells. The monitoring frequency of key monitoring points is generally controlled twice a month. Normal monitoring points are generally controlled once a month. The static water level would be measured in the non-heating season, while the dynamic water level would be measured in the heating season. The reinjection well measure method is the same as the production well.

The density of water decreases with the increase of temperature. It means that when the pressure of the water column in the well is constant, different water densities will correspond to different water levels. This is called the wellbore thermal effect (Zhitao & Zhisheng, 2014). The depth of geothermal wells used for space heating is generally more than 1500 meters. Therefore, the thermal effect of wellbore should be considered to ensure the accuracy of dynamic monitoring data. To eliminate the wellbore thermal effect, the average temperature method could be used to uniformly calibration of the water level data at different water temperatures (Formula 1). The method assumes that geothermal fluid density and temperature are a linear relationship.

$$h = H - \frac{\rho_{ave}(H - (h_1 - h_0))}{\rho_1} \quad (1)$$

Where, h , H , ρ_{ave} , h_1 , ρ_1 , h_0 are at calibrated water level (m), depth at the middle point of the pay zone (m), average density of water column in a geothermal well (kg/m^3), depth of observed water level (m), density of standard temperature (kg/m^3), the height at base point(m), respectively.

4.2.2 Geothermal water temperature

The measurement of geothermal water temperature should be measured while being synchronized with the monitoring of water pressure. The monitoring frequency of key monitoring points is generally controlled twice a month, normal monitoring points is generally controlled once a month. The reinjection well measure method is as same as the production well.

4.2.3 Production/reinjection rate of geothermal wells

It should be conducted monitoring and recording of instantaneous production/reinjection rate and the amount of cumulative production/reinjection. Instantaneous production/reinjection rate should be monitored once a day, and measurement should be conducted twice to three times. The amount of cumulative production/reinjection should be measured once a month, and the change of the total amount of production/reinjection geothermal fields should be analyzed in terms of the calendar year (month).

4.2.4 Geothermal water quality

To determine the degree of influence of artificial exploitation, monitoring of geothermal water quality mainly conducts a full analysis of sampling and regularly testing, including regular monitoring of special components in the geothermal water (such as sulfur, iron, isotopes, dissolved and spilled gases, etc.). The monitoring of geothermal water quality should be measured twice a year. Sampling and testing time is recommended in April and October.

As for reinjection wells, regular or irregular testing of suspended substances and microorganisms should be included in the geochemical monitoring. Pump lifting water quality of reinjection wells should be tested if it is necessary (Baocheng et al., 2013).

5. DESIGN OF REINJECTION PROJECT

It is generally agreed that the geothermal reinjection is an effective method of alleviating thermal and chemical pollution caused by the discharge of geothermal wastewater. Reinjection plays an important role in maintaining geothermal reservoir pressure and ensuring the sustainable development and utilization of geothermal resources. Currently, reinjection has become a daily operation work in the important geothermal fields worldwide and has been widely implemented in more than ten countries, including the United States, New Zealand, Iceland, Italy, France, Japan, Romania, Denmark, the Philippines, and El Salvador. In China, geothermal reinjection in Beijing, Tianjin, Hebei, and other provinces have been implemented successfully. After the reinjection, the water level of The Jxw formation in Beijing went up in 2005. It is shown that the geothermal reinjection has an obvious effect, and the reinjection is an inevitable choice for the sustainable development and utilization of geothermal resources.

The “*Technical Specification of Geothermal Reinjection*” has been issued to guide the reinjection work of geothermal enterprises and to ensure that the exploitation and utilization of geothermal resources obey the environmental protection. This technical specification gives specific requirements related to the design of reinjection well, design of reinjection system, etc.

5.1 Design of Geothermal Reinjection Well

The main principles should be followed in geothermal reinjection wells design: ①Select reservoirs with good conditions and high permeability, and a thermal reservoir thickness should more than 60m. ②The channeling will cause pollution and reinjection not to be in the same layer, the target layer and non-target layer has to be separated. ③Strengthen the stability of the wellbore wall, prevent formation plugging caused by the sand formation and formation collapse. ④The implementation of high overflow-area technology will result in reducing pressure damage, improving reinjection, and exploiting more geothermal resources (Fengnian et al., 2019).

The geothermal reservoir protection should also be concerned. The drilling fluid is the primary issue to be solved. The performance of drilling fluid should be strictly controlled to reduce pollution caused by the loss of drilling fluid. After the well completion, the wellbore should be washed to remove the plugging materials such as mud, cuttings and rock powder to improve the reinjection effect.

5.2 Design of Geothermal Reinjection System

Geothermal water from the production well will be transferred to the reinjection well after heat exchanges. The natural or pressurized reinjection should be applied to achieve the reinjection of raw water in the same layer. The sand removal equipment, filtration equipment, exhaust and other equipment would be included in the reinjection system. The process diagram is shown in figure 4 (Fengnian et al., 2019).

In order to alleviate wellbore plugging, geothermal reservoir plugging, and air locking phenomenon, filtration precision should be guaranteed, so as to the water quality purification treatment of reinjection water should meet the following requirements: ①For fractured geothermal reservoir, the filtration precision should be less than 50 μm . ②For porous geothermal reservoir, the two-stage filtration system should be installed in the reinjection system, and the filtration accuracy will be determined by the particle size of the reinjection water. ③The gas exhaust equipment will be applied to prevent gas plugging (Fengnian et al., 2019).

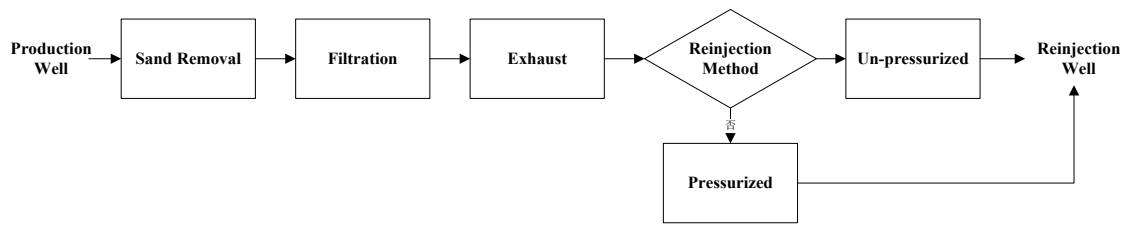


Figure 4. Process diagram of reinjection system

Besides, the reinjection system should improve the dynamic monitoring to master the operation condition of geothermal wells and provide the basic data for the management department.

6. CONCLUSIONS

“Guidelines for Geothermal Energy Development Technology” sets the standards for the geothermal resources evaluation method, geothermal resources development plan, dynamic monitoring system, and design of the reinjection project. There are several key aspects as follows:

- (1) The numerical modeling method can be applied in the evaluation of the production reinjection balanced geothermal resources;
- (2) The reasonable well spacing and the ratio of production and reinjection should be determined to prevent thermal breakthrough;
- (3) The monitoring points are divided into three categories: key monitoring points, common monitoring points, and unified test monitoring points;
- (4) Dynamic monitoring content includes geothermal water pressure, geothermal water temperature, geothermal fluid production rate, geothermal water quality. Dynamic monitoring contents of the reinjection system are basically the same as that of the production well.
- (5) To ensure the accuracy of geothermal water pressure data, it is necessary to consider the wellbore thermal effect;
- (6) The geothermal reinjection system has sand removal equipment, filtration equipment, exhaust equipment, and other equipment to achieve the reinjection of raw water in the same layer.

“Guidelines for Geothermal Energy Development Technology” will play a leading role in the life cycle management of geothermal development and utilization. It will achieve scientific evaluation, standardized design, modular operation of geothermal projects, realize the sustainable development and utilization of geothermal resources based on protecting geothermal resources and the environment. It will reach a first-class international level and occupy key points in the worldwide geothermal industry.

REFERENCES

- Binde Z., Yanzhong L., Keyan D.: GB/T 11615 Geologic Exploration Standard of Geothermal Resources, *Standardization Administration* (2010).
- Sumin Z., Baocheng S. et al.: *Exploitation and Utilization of Sedimentary Basin Geothermal Fields*, (2013), 198-214.
- Guang H., Li L.: Arrangement of Shallow Geothermal Energy Dynamic Monitoring Pattern in Tianjin, *Geology in China* (2011).
- Zhitao L., Zhisheng Z.: Research on the Geothermal Wellbore Thermal Effect, *Shandong Land and Resources*, (2014)
- Fengnian Z., Ye X. et al.: Technical specification for geothermal reinjection engineering, *Energy Industry Geothermal Energy Standardization Technical Committee*, (2019).