Spatial structure and resource potential of heat storage in Nanmeng geothermal field

Xiaowei Zhang\textsuperscript{1,a}, Yichen Wang\textsuperscript{2}, Zhou Jiang\textsuperscript{1}, Jianmin Li\textsuperscript{3}, Jun Zhu\textsuperscript{4}, Lei Zhao\textsuperscript{1,b*}, Yingchao Jia\textsuperscript{1}

\textsuperscript{1}Exploration and Development Research Institute of Huabei Oilfield Company, Petro China, Renqiu, Hebei Province, China
\textsuperscript{2}Research Institute of Petroleum Exploration & Development, PetroChina, Beijing, China
\textsuperscript{3}Huabei Oilfield Xiong’an Green Energy LTD, Renqiu, Hebei Province, China
\textsuperscript{4}Inspection and Testing Center of Huabei Oilfield Company, PetroChina, Renqiu, Hebei Province, China
\textsuperscript{a}Email:yjy_zxw1@petrochina.com.cn
\textsuperscript{b*}Email: yjy_zhaol@petrochina.com.cn

\textbf{Abstract:} The geothermal conditions in Jizhong Depression are superior, and the area has many years of geothermal development history at present. Nanmeng geothermal field is located in the dominant area of geothermal resources in Jizhong depression, most of which is suitable for large-scale geothermal development. The main reservoirs in Nanmeng geothermal field include pore sandstone reservoirs of Neogene Guantao Formation and bedrock reservoirs of Jixian System. The Jixian System is the main thermal reservoir in the region, with a buried depth of 2000-4000 meters, a thickness of 500-700 meters, and a heat storage temperature of 70-105°C. It is characterized by large amount of water, good water quality and easy recharge of reservoirs. According to the difference of overlying strata structure, the buried depth of the main reservoirs in Nanmeng geothermal field gradually increases from south to north. In this paper, the annual geothermal recoverable resource of Nanmeng geothermal field is calculated as $0.3 \times 10^{16}$J by the heat storage method, and the produced water temperature and the dynamic fluid level of the produced water are analyzed by the numerical simulation method. Finally, the most favorable well spacing of Nanmeng geothermal field is determined as 4A, which lays a foundation for the geothermal resource planning and development in Nanmeng.

\textbf{1. Introduction}

Geothermal resource is a clean, environmentally friendly renewable energy with the characteristics of large reserves, wide distribution, good stability, and recyclability. Reasonable and effective utilization of geothermal resources plays an important role in improving China's energy structure and promoting sustainable economic and social development. Carbonate rocks, as the main reservoir of geothermal resources, are characterized by good reservoir conditions, multiple reservoir systems, large thickness and wide distribution, and are distributed in major sedimentary basins throughout the country\textsuperscript{[1-3]}. In Jizhong Basin, they are also the main target for searching for high-quality geothermal resources.
2. Overview of the study area

2.1. Geothermal background
The Nanmeng geothermal field is located in the north of the downtown area of Bazhou, close to the Xiongan New Area and belonging to Nanmeng Town. The ground is 6.8 meters above sea level. Nanmeng geothermal field thermal development is concentrated in Hualong mining area of Huabei oilfield, mainly heating. Water volume of geothermal Wells in carbonate reservoirs of Wumishan Formation, Jixian System, Nanmeng area is 80-100 m³/h, and wellhead temperature is 70-105°C. At present, a number of Wells in the study area have been drilled into the Wumishan Formation thermal reservoir with a depth from 2000 to 4000m. During the heating period, the water production is more than 300,000 m³, basically achieving the balance of injection and production. The hot water produced mainly provides winter heating service for Hualong mining area.

2.2. Regional structure
Nanmeng geothermal field is a secondary structure of Baxian Sag of Jizhong Depression, centered on Nanmeng Buried Hill. It is close to Niutuo Town Uplift in the north and Baxian Sag in the south (Fig. 1).

![Fig.1 Tectonic map of the study area](image)

The regional geothermal background of this area is the hot basin area in the eastern part of North China, with a relatively high heat flow background [4]. The trend of Nanmeng Buried Hill is nearly east-west, which is consistent with the direction of the main tectonic faults in the region. The buried depth of bedrock in the geothermal field area is greater than 2,000 meters. Because of the destruction of the craton, heat from deep by heat conduction to the surface in the forms of transmission, formed in the carbonate rocks of the heat conductivity thermal refraction, to play with low thermal conductivity of sedimentary cover formation heat reflection, and composite regional groundwater circulation and water rock heat exchange, multiple trap heat mode to form a stable high-quality thermal reservoir [5]. This region has the highest geothermal gradient in Hebei Province, and the main direction of geothermal distribution is northeast. The side of platform arch or bulge is generally the high temperature center. The geothermal anomaly generally presents a banded distribution between high and low, and the long axis direction is consistent with the regional tectonic line [6].

2.3. Groundwater flow field
The regional bedrock fissure karst thermal reservoirs are mainly carbonate Marine sedimentary rocks, which are widely leached by palaeo-precipitation. Since the Cenozoic, the bedrock fissured karst thermal reservoir has been covered, but the bedrock in the western mountainous area is still exposed, and it is easy to receive meteoric water recharge, making the bedrock hot water become the deep circulating water originated from the infiltration of meteoric water. Five wells in the study area have been tested on the Wumishan formation, and the results show that the chloride content is
300-1450mg/L, the total salinity is 2800-2950mg/L, and the water type is NaHCO3.

3. Heat storage characteristics
The top to bottom heat storage of Nanmeng geothermal field is mainly the pore sandstone heat storage of Neogene Guantao Formation and the bedrock heat storage of Jixian System.

(1) Neogene heat storage: it is the sandstone pore type heat storage of Guantao Formation. Most of the pore types of sandstones are primary pores, which are mainly intergranular pores, with high face ratio and good connectivity. Electrically, the resistivity curve is concentrated in the middle and high resistance peaks. The reservoir is mainly composed of medium and fine lithic sandstone with medium to good sorting, and the grinding round is subcircular to subsharp. The cementation type is mainly pore type, secondary is pore-contact type, and the cementing material is mainly argillaceous and secondary is calcareous. The content of cuttings is from 7% to 16%, and the content of feldspar is generally more than 20%. According to the petrophysical analysis of the well drilled in this area, the average porosity is 19%, the average permeability is from 60 to 1050mD, and the average permeability is 900 mD. It is a medium to high porosity and high permeability reservoir.

(2) Jixian System thermal reservoir: The carbonate rock in Jixian System is the main thermal reservoir, including two layers of Wumishan Formation and Gaoyuzhuang Formation, which is a deep circulation structural fracture type heat reservoir formed under the combined action of heat conduction and heat convection [7]. The lithology of Wumishan Formation is brownish gray, grayish brown, light gray, light gray and light gray dolomite interbedded with thin layers of argillaceous and limestone dolomite, interbedded with chert bands, and containing calcite veins and masses. Gaoyuzhuang Formation is dominated by dolomite, intercalated with argillaceous dolomite and limey dolomite. Quartz sandstone is found in the lower part. The strata in this section have experienced denudation, weathering and leaching in a long geological period, and the rock dissolving and fissured are relatively developed, providing a good storage space for groundwater [6]. The burial depth of Wumishan Formation in Nanmeng geothermal field is generally between 2000 and 4000 meters. A total of 8 Wells in the study area have been drilled into the Wumishan Formation with a depth of 15-700 meters and an average depth of 220 meters. The fractures in the Wumishan Formation are well developed. Leakage and venting occurred in several Wells during drilling. Among them, well B9 was tested on the Tieling Formation-Wumishan Formation. The daily water output was 1300 m³, the wellhead water temperature was 90°C, the chloride content was 1442mg/L, and the water type was NaHCO3.

4. Resource potential assessment

4.1. Basic principles
In view of the carbonate reservoirs in Nanmeng area, the evaluation method of geothermal resources sustainable development under the condition of balanced production and irrigation is provided with support for the exploitation and utilization planning of geothermal resources by fully combining the development characteristics of regional thermal reservoirs.

On the basis of geothermal field zoning, the amount of static geothermal resources and geothermal fluid storage are calculated according to different depths. Based on the long-term dynamic detection data, the dynamic evaluation was carried out to determine the amount of geothermal resources exploitation in the study area. Taking the depth of 4000 meters as the boundary, the Jixian system heat reservoir is evaluated by dividing into two layers of 2000-3000 meters and 3000-4000 meters. Considering the factors of water balance, the recharge rate of geothermal water in the study area is not less than 90%, and the annual drop of water level is controlled within 2 meters.

4.2. Geothermal resource evaluation
At present, there are two kinds of methods for evaluating geothermal resources. One is to calculate the amount of geothermal resources by heat storage method based on volumetric method, such as surface heat flow method, volume method, hydrothermal balance method, analogy method, etc. The other is to
establish the mathematical model of hot water system flow or heat transport to simulate and predict the exploitation of underground hot water. In this study, the heat storage volume method is used to calculate geothermal resources. This method will heat reservoir rock and their occurrence and migration of the geothermal fluid in porous media as a whole, the calculation of relative to the local reference temperature (local average temperature), the entire heat store contain all the heat energy in the body, and then according to the hydrogeological conditions and mining technical and economic level estimation can be mined reserves stored heat. In fact, volume method is a calculation method of static reserves, which equates geothermal energy with general solid mineral resources and basically regards them as non-renewable resources. From the point of view of the medium in which geothermal fluid occurs and migrates, this method is generally applicable to various types of heat reservoirs such as pore type, fissure type and karst type. The basic formula is as follows: 

\[ Q = Ah(t_r-t_0) \rho_r C_r (1-\psi) + Ah(t_r-t_0) \rho_w C_w \psi \]

In the formula, \( Q \) is the heat stored in the heat storage (J); \( A \) is the area of the calculation area \((m^2)\); \( H \) is heat storage thickness \((m)\); \( T_r \) is the average temperature of heat storage \( (^\circ C)\); \( T_0 \) is the reference temperature \( (15 ^\circ C)\); \( \rho_r \) is the density of heat storage rock \((kg/m^3)\); \( C_r \) is the specific heat of heat reservoir rock \((J/kg•^\circ C)\); \( \psi \) is the porosity (dimensionless). The rock density during calculation is 2600kg/m³.

The Nanmeng geothermal field in the research area covers an area of 5km². After stratified calculation, the geothermal resources in Jixian System in the research area are \( 6\times10^{16} \)J, the geothermal fluid storage is \( 1.5\times10^8 m^3 \), the recoverable geothermal resources in the whole area are \( 7.5\times10^6 m^3/a \) and the recoverable heat of geothermal fluid is \( 0.3\times10^{16}J/a \) under the condition of balanced water production and injection.

4.3. Numerical Simulation

The numerical model of hot reservoir is the most effective method to evaluate geothermal resources at present [8]. In this study, the STARS module in CMG software was used to establish the geological model of Nanmeng geothermal field. According to the geothermal resources calculated by the heat storage method and combined with the number of Wells required by the project, the plane grid of the geological model is defined as 50m×50m. Meanwhile, the porosity is selected as 60%, the permeability is 1000mD, and the calculated depth range is from 2000m to 4000m. The daily production and injection water of a single well were defined as 2000m³/d, and the well spacing was defined as five schemes A, 2A, 3A, 4A and 5A to verify the optimal well spacing suitable for the study area and guide the development and utilization of geothermal resources in the study area. According to the simulation calculation, when the well spacing is greater than or equal to 4A, the water production temperature of the production well is basically maintained at about 95°C within 20 years, and the dynamic liquid level of water production is maintained at about 230m within 20 years (Figure 2 and Figure 3). Within the range of annual recoverable geothermal resources, when the daily production water and temperature of a single well are constant, the more injection and production Wells, the more objective the economic benefit will be. Therefore, the optimal well spacing in the study area by comprehensive determination is 4A.

![Fig.2 Water temperature change diagram of five different conditions](image1)

![Fig.3 Water depth change diagram of five different conditions](image2)
5. Conclusions and recommendations
Nanmeng geothermal field has good conditions of thermal resources, which is conducive to the large-scale development and utilization of geothermal resources. The whole geothermal field heat reservoir includes the pore sandstone heat reservoir of Neogene Guantao Formation and the bedrock heat reservoir of Jixian System. The Jixian System is the main thermal reservoir in the region, with a buried depth from 2000 to 4000 meters and a thickness from 500 to 700 meters, a heat storage temperature from 70 to 105°C, a large amount of water and good quality. The reservoirs are easy to be reinjected, which is conducive to large-scale and centralized development and utilization.

The recoverable resource of geothermal fluid in Nanmeng geothermal field is $7.5 \times 10^6$ m$^3$/a, and the recoverable heat of geothermal fluid is $0.3 \times 10^{16}$ J/a.

Within the annual recoverable range of geothermal resources, the optimization of resources and benefits can be achieved when the well spacing is 4A by constructing a numerical model.

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