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Research of Geothermal Resources on Hot Dry Rock in North Songliao Basin of China

Duo Xiao[1], Huabin Wei[1, *], Shangming Shi[1], Huanlai Zhu[1], Senlin Gan[2], Xiaoxiong Wu[3], Wei Feng[4]

[1] School of Earth Sciences, Northeastern Petroleum University, Daqing, China
[2] No.1 Oil Production Company, Daqing Oilfield, Heilongjiang Province, China
[3] Research Institute of Petroleum Exploration and Development, Qinghai Oilfield Company, Qinghai, China
[4] Daqing Drilling & Exploration Engineering Corporation, No.1 Geo-logging Company, Heilongjiang Province, China

[*] **Corresponding author**: Huabin Wei (Email: whbinemail@163.com)

Abstract: With abundant oil and gas as well as geothermal resources, Songliao Basin is a famous large continental sedimentary basin in China. So far, the research of geothermal resources in North Songliao Basin has mainly concentrated in the shallow layers where low-temperature geothermal resource is mainly developed. However, the research of deep geothermal resource in high-temperature hot dry rock is still in a blank state. Based on the Songliao Basin exploration and research achievements as well as oil exploration well data, this paper further improves geothermal resource exploration and development theories of North Songliao Basin by researching geothermal resources in high-temperature hot dry rock. Hot dry rock distribution is relatively concentrated in the North Songliao Basin, mainly in the central, southern and southeastern part of the study area, where the depth of 150 ℃ isothermal surfaces substantially less than 5km is conducive to the development of hot dry rocks. Studies have shown that two high value areas of terrestrial heat flow in the North Songliao Basin are respectively located in the southern part of the central depression area as well as the junction of three first-order tectonic belts including central depression, southeast and northeast uplift areas, where geothermal resource potential of hot dry rock is great. By using enhanced geothermal system, mining hot dry rock is feasible. This study has some guidance and reference for the development and utilization of deep geothermal resources in hot dry rock of the North Songliao Basin.

Keywords: North Songliao Basin; Geothermal resources; Hot dry rock; Enhanced geothermal system.

1. Overview of the study area

With abundant oil and gas as well as geothermal resources, Songliao Basin is a famous large continental sedimentary basin in China[1].In North Songliao Basin, heat source of hot dry rock is mainly from the deep mantle, accounting for about 60.2%. The heat from radioactive element mainly in the earth's crust accounts for about 38.4%. Heat energy of hot dry rock conducts across the mantle mainly in the form of heat conduction. In some areas, thermal convection transfer modes can be formed because the lithospheric and crustal fractures as well as shovel basement faults converged in detachment zone communicate with each other, which provides a good channel for thermal convection (Fig. 1). The formation and distribution of hot dry rock in North Songliao Basin are also affected by the deep crust and mantle structures, fractures, magmatic activities, basements, covers and hydrogeological conditions [2-3].

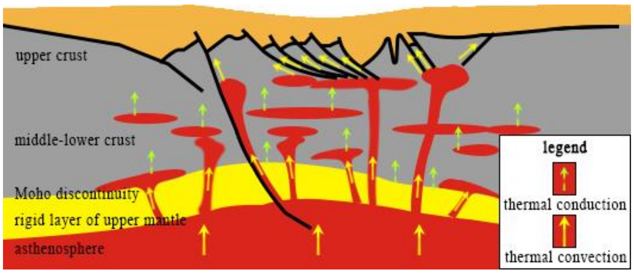

Fig.1 The heat transfer mode in North Songliao Basin

In North Songliao Basin, the buried depth ranges from 3km to 10km and total amount of hot dry rock geothermal resources whose temperature is greater than 150 ℃ is 2190.5 × 1020J, which is equal to 74507.3 × 108t standard coal. If 6km is taken as depth limit, total amount of hot dry rock geothermal resources within the range of 6km in North Songliao Basin is 372.3 × 1020J, which is equal to 12663.1 × 108t standard coal. According to 2% extraction rate, the recoverable amount of hot dry rock geothermal resources within the range of 6km in North Songliao Basin is 7.4 × 1020J, which is equal to 253.3 × 108t standard coal. It shows its reserves are very abundant. Reserve abundance of hot dry rock geothermal resources in North Songliao Basin ranges from 1065.4 to 4783.5 × 1012kJ / km2, of which the total area of reserve abundance of hot dry rock geothermal resources larger than 4000 × 1012kJ / km2 is 3360km2, mainly in Chaoyanggou terraces and South Daqing Placanticline[4-5].

2. Heat Mining calculation model

When geothermal wells are explored, produced heat is related to production and wellhead temperature.

2.1. Productivity calculation method

In Enhanced geothermal systems, the productivity of production wells is closely related to the injection volume of injection wells. However, due to the uncertainty of artificial geothermal reservoir, injected fluid may not be mined. Therefore, we use conversion to calculate the productivity of production wells by a conversion coefficient called the fluid leakage rate.

Productivity is calculated as follows:

$$q = q_{in} \cdot \delta \cdot t \tag{1}$$

Where:
- The productivity of production wells, m3/D;
- Injection volume, kg / s;

- Production time, s;
- Fluid leakage rate,%.

2.2. Wellhead temperature calculation method

In the process of production well fluid migrating from the horizontal section to the upward section, there exists temperature difference between the well fluid and the surrounding formation in the vertical section. Therefore, the migration process will have heat loss. The essence problem of wellhead temperature calculation is that the fluid heat of target layers minuses the heat loss in the wellbore during the mining process [6].

During the process of geothermal fluid, the relationship between the wellbore and the surrounding formation (Figure 2) is as follows:

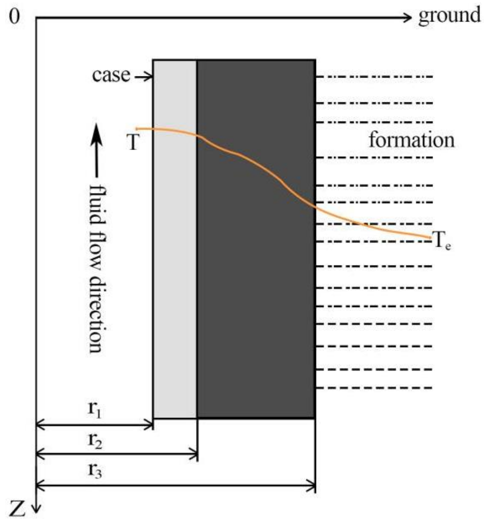

Fig.2 Body structure diagram of geothermal wells

According to thermodynamic equilibrium principle, the heat loss of the fluid is equal to the heat transferred to the cement sheath:

$$dq = -W \cdot CdT_1 \quad (2)$$

In the above formula: $dq = 2\pi r_3 U(T_1 - T_2)(-dZ)$

The heat transferred from the cement sheath into the formation can be expressed as:

$$dq = 2\pi k \cdot \frac{T_2 - T_e}{f(t)}(-dZ) \quad (3)$$

Where: $T_e = a \cdot (z - z^*) + b$

Showing undisturbed temperature in geothermal field, the following equation can be established:

$$\frac{dT}{dZ} + \frac{T}{A} - \frac{a \cdot (z - z^*) + b}{A} = 0 \quad (4)$$

In the above formula: $A = \frac{W \cdot C \cdot (\lambda + r_3 U f(t))}{2\pi r_3 U \lambda}$

Computing above integrals can be obtained:

$$T(z,t) = e^{\frac{z - z_0}{A}} \times [T_0 - a(z_0 - z^*) - b - aA] + a(z - z^*) + b + aA \quad (5)$$

Where:

- Water temperature at the depth of z_0, °C;
- Water temperature calculated at the depth of Z, °C;
- Geothermal gradient, m / °C;
- The temprature of constant temperature layer °C;
- The depth of constant temperature layer, m;
- Water production, kg / s;
- Depth, m;
- Formation thermal conductivity, W / (m · °C);
- Heat capacity of water, J / (kg · °C);
- Radius, m;
- The total heat transfer coefficient, W / (m2 · °C);
- Time function can be calculated as follows when time is more than 7 days:

$$f(t) = ln \frac{2\sqrt{\alpha \cdot t}}{r_3} - 0.29 \quad (6)$$

Where:
- Rock diffusion coefficient, m2 / s;
- Time, s.

2.3. Calculation method of extracting heat energy

Heat formula of produced heat energy:

$$Q = q \cdot (T - T_0) \cdot c \cdot \rho \quad (7)$$

Where:
- Produced heat, J / D;
- The productivity of production wells , m3 / D;
- Wellhead temperature, °C;
- Tail water temperature, °C;
- Produced water specific heat, J / (kg · °C);
- Produced water density, kg / m3.

2.4. Computation results

According to the above formula, 30kg/s constant flow of injection wells and 25% fluid leakage rate, computation results of the heat produced from hot dry rock of artificial geothermal reservoir each year (365 days) are as follows:

Table 1. Forecast table of wellhead temperature and extraction heat

Time	Bottom hole temprature (°C)	Wellhead temprature (°C)	Produced heat ($\times 10^8$kJ)	Produced heat (MWe)	Conversion standard coal ($\times 10^4$t)
From the 1st year to the 13th year	200	188	52152.7	16.54	1.77
The 14th year	195	184	47682.4	15.12	1.62
The 15th year	190	179	46490.4	14.74	1.58
The 16th year	183	173	45298.3	14.36	1.54
The 17th year	175	166	43510.2	13.80	1.48
The 18th year	165	157	41424.1	13.14	1.41
The 19th year	155	148	38742.0	12.29	1.32
The 20th year	145	139	36357.9	11.53	1.24

The first stage was from one to thirteen years. The bottom hole temperature of production wells stabilized at 200 °C and wellhead temperature stabilized at 188 °C. According to tail water temperature of 25 °C, the annual heat mined from the geothermal reservoir is 52152.7 × 108kJ, equivalent to 16.54MWe, which is equal to approximately 1.77 × 104t conversion standard coal.For 13 years, the total produced heat is 67.8 × 1012kJ, equivalent to 215.02MWe, which is equal to 23.01 × 104t conversion standard coal. The second stage was from 14 to 20 years. Bottom hole temperature, wellhead temperature and produced heat have decreased year by year. At the time of the 20th year, bottom hole temperature of production wells has dropped to 145 ℃ and wellhead temperature has dropped to 139 ℃. In the second stage, the total produced heat is 30 × 1012kJ, equivalent to 94.94MWe, which is equal to 10.19 × 104t conversion standard coal.

During 20 years of the entire enhanced geothermal systems mining the numerical simulation, the cumulative produced heat from the geothermal reservoir was 97.8 × 1012kJ, equivalent to 310MWe, which converted into standard coal of approximately 33.2 × 104t. By estimation, the total amount of the hot dry rock geothermal resources at 4-5 depth is 1.04 × 1016kJ in the entire test area. Without considering the surrounding rock supplies, produced heat energy of 20 years accounts for about 0.94%. Thus, if a reasonable plan is made to shut wells intermittently to recover formation temperature, dynamic balances between recovery and supply can be achieved in enhanced geothermal system. Finally, sustainable exploitation can be realized.

According to statistics, burning standard coal per ton can produce 2620kg carbon dioxide, 8.5kg sulfur dioxide and 7.4kg nitrogen oxides. Therefore, emission gas of coal-fired boiler is one of the main atmospheric pollution sources. From the above calculation results, the cumulative emission reduction of carbon dioxide is 86.984 × 104t, sulfur dioxide is 0.283 × 104t and nitrogen oxides is 2.456 × 104t.

3. Utilization modes

There are many utilization modes of geothermal energy, which can be widely used in power generation, geothermal heating, bath, health spa, planting and plant breeding, etc [7-9]. The use of geothermal resources with different temperature has different focuses. Through simulation, when the injection flow rate is 30kg / s, the formation fluid loss rate is 25% and the daily output of the geothermal water is approximately 1944m3. In the course of 20 years' mining, wellhead temperature of production wells higher than 100 ℃ can be used for geothermal power generation. Geothermal power generation can only use 5% to 20% geothermal water energy. After power generation, the temperature is about 90 ℃ in the tail water, where there are still a considerable amount of heat. If these tail water discharges directly into or recharge to the ground, it will cause a great waste of geothermal resources. Meanwhile, thermal pollution will be formed to impact on the surrounding environment.

Combined the actual situation of the test area with the thought of applying geothermal resource cascade utilization, we drew the test area schematic diagram of geothermal resource cascade utilization (Figure 3).

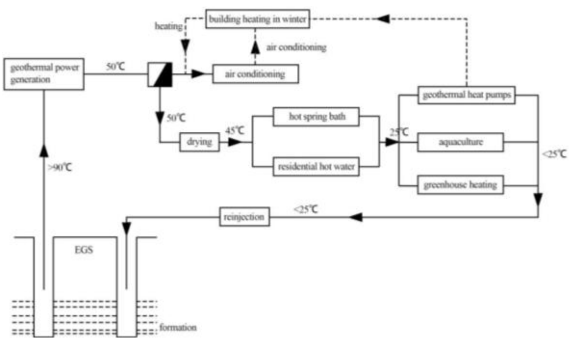

Fig.3 Schematic diagram of geothermal resource cascade utilization

In order to avoid geothermal energy waste, the heat of mined geothermal water is extracted several times from high to low temperature, which can maximize the geothermal water use of various temperature levels and achieve cascade utilization of geothermal water resources. There are four ideal utilization modes for mined geothermal water as follows:

The 1st level of geothermal utilization mode: geothermal water whose temperature is higher than 90 ℃ can be used for geothermal power generation;

The 2nd level of geothermal mode: geothermal water whose temperature is between 50 ℃ and 90 ℃ can be used for building heating in winter, air conditioning and drying;

The 3rd level of geothermal mode: geothermal water whose temperature is between 45 ℃ and 50 ℃ can be used for hot spring bath and residential hot water;

The 4th level of geothermal mode: geothermal water whose temperature is between 25 ℃ and 45℃ can be used for greenhouse heating, aquaculture and geothermal heat pumps.

After four levels of cascade utilization, geothermal water heat has been fully utilized and the geothermal tail water has lower temperature, usually about 25 ℃. The tail water whose temperature is lower than 25 ℃ can be dealt with and then is reinjected into artificial heat reservoir by injection wells again. Therefore, the development of geothermal cascade utilization technology has more important significance for promoting the development of the geothermal industry.

4. Conclusions

This paper took dry hot geothermal resources of North Songliao Basin as the object. According to the research of hot dry rock formation, distribution, potential and mining, we can mainly get the following conclusions:

(1) The heat source formed by hot dry rock of North Songliao Basin is mainly deep mantle heat source, accounting for about 60.2%. Radiogenic heat is mainly in the earth's crust, accounting for 38.4%. Heat energy of hot dry rock mainly comes from the deep heat source and is transferred by way of heat conduction and heat convection. Hot dry rock distribution is mainly by the impact of regional tectonic background and deep structure of the crust and mantle.

(2) Based on numerical simulation, in the mining process of enhanced geothermal systems, the fluid temperature of the production wells can be divided into two stages. The first stage from 1 to 13 years is a stable period. During this period, the temperature of production wells is maintained at 200℃. The second stage from 14 to 20 years is a decreasing period. During this period, the temperature of the production wells began to drop. At the 20th year, the fluid temperature of the production wells has dropped to 145 ℃. If a reasonable way is made to shut wells intermittently to recover formation temperature, dynamic balances between recovery and supply can be achieved in enhanced geothermal system. Finally, sustainable exploitation can be realized.

(3) According to 30kg/s constant flow of injection wells and 25% fluid leakage rate, the total produced heat is 97.8×1012kJ, which is equal to 33.2×104t conversion standard coal. Cumulative emission reduction of carbon dioxide is 86.984 × 104t, sulfur dioxide is 0.283 × 104t and nitrogen oxides is 2.456 × 104t, which is significant to protect the environment and reduce PM2.5 greenhouse gas emissions.

(4) In order to maximize the heat use of geothermal water, we have made cascade utilization plans for mined geothermal water, which are divided into four stages. After cascade utilization of four stages, the heat of geothermal water has

been used fully. It has an important significance to efficiently use the geothermal resource and promote the development of geothermal industry.

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