Water Circulation of Geothermal System in Kaifeng Depression

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Abstract. Kaifeng is rich in geothermal resources. It is important to clarify its genetic model for its further sustainable utilization. In this paper, the geothermal geological conditions of Kaifeng Depression are analyzed, the circulation of geothermal water in Kaifeng area are discussed by using hydrochemical and isotopic data, and the conceptual model of geothermal system is preliminarily established.

1. Introduction
Geothermal energy is a priority development direction of renewable energy in the 13th five-year Plan. Kaifeng Depression is one of the best geothermal resources in Henan Province. Geothermal resources in Kaifeng has been used for recreation, bathing, swimming, heat supply, health care, etc. In this paper, hydrochemical and isotopic methods are used to analyze the origin of geothermal system in Kaifeng Depression, which has certain guiding significance for further development and utilization of geothermal resources in Kaifeng Depression.

2. Geothermal geological characteristics of Kaifeng Depression

2.1. Structural feature
Kaifeng Depression is located in the southeast of Jiyuan-Kaifeng Depression. Jiyuan-Kaifeng Depression belongs to Meso-Cenozoic Depression. Due to the long-term influence of deep fault activity in Jiyuan-Xinxian-Shangqiu, Jiyuan-Kaifeng Depression presents a dustpan-like depression with high middle, deep east end, deep west end, shallow south and deep north. It belongs to Meso-Cenozoic fault depression (Fig.1). [1]
Within the tectonic unit, faults are crisscrossed and complex, with NW and EW directions as the main extension directions, followed by NE direction. These small structures are the extension of peripheral structures. Kaifeng Depression is located in the crisscross and composite parts of EW-trending and NE-trending structures [9]. These structures provide a good channel for the circulation of geothermal water.

2.2. Geothermal reservoir and caprock

The geothermal reservoir and caprock of Kaifeng geothermal system is Quaternary sediment. Its main lithology is interbedded with sub-sandy soil, sub-clay, medium coarse sand and fine sand. Its thickness is about 300 m. The thickness of clay layer accounts for 58.9% of the total thickness of the caprock, and the thermal insulation performance is good [2].

The Neogene Minghuazhen Formation and Guantao Formation consist of a series of clay and sand layers (semi-consolidated clay rocks and sandstones) overlapping each other, forming a multi-layer aquifer group (geothermal reservoir). There are clay interbeds with thickness of more than 20 m between geothermal reservoirs, and there is no obvious hydraulic connection between them according to water level monitoring data. Geothermal water mainly moves horizontally and receives lateral recharge.

2.3. Characteristics of geothermal field

According to statistics, the average value of Kaifeng urban area is 3.460 °C/100 m, and the average geothermal flow value is 57.688 mW/m² (Table 1). Surface geothermal flow value in depression area belongs to conductive geothermal flow value, which varies slightly with the development of basement structure.

Geothermal distribution in Kaifeng Depression is controlled by tectonics, which is consistent with the regional NE-trending structure. Local geothermal distribution is affected by deep geothermal water activity. The hot water rises along the fissures and dissolution fissures in the structural development area, and is blocked by Neogene mudstone, which concentrates at the bottom of Neogene and forms a high geothermal anomaly area.

Fig. 1 Structure plan of Kaifeng Depression
Table 1. Geothermal data of Kaifeng Depression

| Name of well                  | Depth m | Water temperature °C | Geothermal gradient °C/100 m | Temperature °C | Heat flux (mW/m²) |
|-------------------------------|---------|-----------------------|-----------------------------|----------------|------------------|
| Thermal Power Plant 7#        | 445     | 27                    | 3.62                        | 58.61          | 60.729           |
| Electric Power Bureau 2#      | 550.7   | 30                    | 3.25                        | 54.25          | 54.779           |
| County Land Bureau            | 650     | 35                    | 3.60                        | 58.38          | 60.727           |
| Thermal Power Plant 5#        | 709     | 35.5                  | 3.35                        | 55.43          | 56.431           |
| Longsh Company                | 860     | 40.5                  | 3.19                        | 53.54          | 56.176           |
| Bianjing Hotel               | 1200    | 50.5                  | 3.39                        | 55.90          | 60.545           |
| Water Saving Office (West) 1# | 1231    | 49                    | 3.13                        | 52.83          | 55.848           |
| Xiao Bei Gang                | 1302    | 51.5                  | 3.19                        | 53.54          | 56.272           |

3. Characteristics of geothermal water cycle in Kaifeng Depression

Hot water samples from the interior of Kaifeng Depression were collected and analyzed by hydrochemical and isotopic analysis. Stable isotopic methods (δD, δ18O) can be used to effectively determine the origin and recharge source of hot water; and radioisotopic methods (T, 14C) can determine the age and cycle of hot water [3].

3.1. Source of hot water

According to the isotopic data of 57 samples collected from Zhengzhou atmospheric precipitation isotopic sampling sites (3 KM south of Zhengzhou, 34.72° of north latitude and 113.65° of east longitude) from September 1985 to July 1992, the "atmospheric precipitation line" in Kaifeng area is established by statistical analysis (Fig. 2). The linear equation is as follows:

\[ \delta D = 8.013\delta^{18}O + 8.275 \quad (1) \]

It can be seen that most of the points are near the atmospheric precipitation line, and a few of them are slightly deviated. Therefore, we can judge that the geothermal water is closely related to the atmospheric precipitation. At the same time, according to the hydrochemical data analysis of the samples, we can conclude that the geothermal water of the geothermal system in the study area comes from the atmospheric precipitation.

![Fig.2 The relationship curves of precipitation, geothermal water and δD-δ18O in Kaifeng geothermal system](image)
3.2. Geothermal water recharge elevation
According to the principle of elevation effect of stable isotopes, the value of δD decreases with the increase of elevation of groundwater recharge area [4]. The formula for calculating the elevation of geothermal water recharge area is as follows:

\[ H = H_r + \frac{(D - D_r)}{\text{grad}D} \]

(2)

Where in: 
- \( H \) - elevation of geothermal water recharge area (m);
- \( H_r \) - elevation of geothermal water sample points (m);
- \( D \) - the δD value of recharge water (‰);
- \( D_r \) - the δD value of geothermal water (‰);
- \( \text{grad}D \) - the gradient of δD decreasing with elevation (‰/100 m).

The value of δD of recharge water in Kaifeng city can be determined by the intersection point between the equation of atmospheric precipitation line and the δD-δ18O relation line of geothermal water. According to the δD-δ18O relation line of the collected geothermal samples: \( \delta D = 5.7396 \delta^{18}O - 16.112 \), and the intersection point with the atmospheric precipitation line is (\( \delta^{18}O = -10.729 \text{‰}, \delta D = -77.696 \text{‰} \)) (Fig. 2). The gradient value of δD in this area is \(-2.25 \text{‰}/100 \text{m}\). The recharge elevation calculated according to formula (2) is as shown in Table 2. The recharge elevation of geothermal storage hot water in Guantao Formation of Kaifeng Depression is about 145-280 m. According to the analysis of regional topographic map, there may be two recharge areas: the southwest mountain area of Zhengzhou and the northeast mountain area of Jiaozuo.

| \( H_r / \text{m} \) | \( D_r / \text{‰} \) | \( H / \text{m} \) |
|----------------|----------------|----------------|
| 75            | -76.14         | 144.16         |
| 75            | -76            | 150.38         |
| 75            | -73.14         | 277.49         |

3.3. Circulation rate of geothermal water
The age of geothermal water, which is the storage time of water in thermal reservoir, can be measured and calculated by radioisotope.

\[ t = 1.443 \cdot T \cdot \ln \left( \frac{A_o}{A} \right) \]

(3)

Wherein: 
- \( t \) - Age (year) of geothermal water;
- \( T \) - Half-life (year) of radioisotopes;
- \( A_o \) - the initial concentration of radioisotopes, %14C;
- \( A \) - concentration of radioisotope t or measured radioisotope concentration of geothermal water, % (14C).

Using the measured value of 14C, the age of geothermal water in sub-thermal reservoirs can be calculated according to formula (3) (where the initial concentration of 14C is 100% and the half-life T is 5730 ±40a).

The geothermal water age of the same geothermal reservoir increases from west to east, for example, the distance from water saving office (western suburbs) 1 #to water saving office (eastern suburbs) in the same geothermal reservoir is about 6 km, and the age of geothermal water increases from 22090 a to 24120 a. According to the calculation, the permeability rate is 8.1 mm/d, which indicates that geothermal water migrates slowly from west to east. The average age of geothermal water in the whole area is 20440 a. According to the calculation of 8.1 mm/d, the geothermal water recharge area should be outside 60 km.
According to the above calculation, combined with the geological map of Kaifeng area, the geothermal storage and recharge area of Guantao Formation in Kaifeng Depression is located in the southwestern mountainous area of Zhengzhou that is about 60 km away from the urban area of Kaifeng. Geothermal water migration rate is 8.1 mm/d. Geothermal water is gradually formed through long runoff heating, which indicates that the geothermal water supply is weak, and the main geothermal water is static reserves.

4. Conclusion
The isotopic data are used to identify the related problems of geothermal water cycle in Kaifeng Depression. δD-δ18O relationship shows that geothermal water in Kaifeng area originates from atmospheric precipitation, and 14C shows that the average recharge age of geothermal level is more than 20,400 years. The precipitation is in the southwest mountainous area of Zhengzhou, 60 km away from Kaifeng city, and then moves slowly from west to east along the strata of Guantao Formation with a migration rate of 8.1 mm/d. During the migration process, it is heated by heat flow and the heat storage temperature reaches 53 ℃. The overlying Quaternary sediments form caprocks.

Acknowledgments
This study has been supported financially by the Shandong Provincial Natural Science Foundation of China (Grants ZR2017LD005), the Fundamental Research Funds for the Central Universities (16CX05003A), Science for Earthquake Resilience (XH17021YSX), The Science Foundation of Kaifeng (1708001).

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