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Optimization Design of Well Spacing Pattern: A Case Study from Dongying Sag, Jiyang Depression, BBB, China

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ABSTRACT

The geothermal tail water should be reinjected back into the reservoir for the sustainable utilization of geothermal resources. It may cause temperature decrease in the production wells or pressure increase in the rejection well if the well pattern is unreasonable. The setting principle about the distance between production well and rejection well is that there should be no thermal breakthrough in the production well, meanwhile the distance should be small as far as possible to make up for the reservoir pressure decrease.

The concept model and the parameters about geological condition and exploitation situation is derived from the Central Uplift geothermal field of Dongying Sag, Jiyang Depression, Bohai Bay Basin (BBB), China. The data of pumping tests and rejection tests from 4 projects is collected to determine the water production and rejection rate, and then the ratios of production well and rejection well is obtained. The production rate is 65-75 m^3/h while the rejection rate is 30-40 m^3/h, so the ratio of production well and rejection well should be 1:2.

The change of temperature and pressure of the geothermal reservoir caused by the exploitation is mainly controlled by the reservoir characteristics and injection parameters. A series of hydro-thermal coupled simulation is carried out used the Petrasim-Tough2 Code to check the change of temperature field. The optimal distance between production well and rejection well is about 350 m.

1. INTRODUCTION

Production with reinjection is currently recognized as a sustainable way for geothermal resources, which can avoid reservoir heat and water imbalance caused by over-exploitation, as well as environmental problems such as land subsidence and water pollution (Su, et al., 2018). Under different well spacing programs, the reservoir pressure (water level), water chemistry and temperature show complex dynamic changes. Hence, scientific and rational well space programs could effectively maintain the geothermal reservoir pressure while avoiding the temperature decrease of the yielding water (thermal breakthrough), and achieving the sustainable development of geothermal resources.

In this paper, the central uplift geothermal field in Dongying Sag, Jiyang Depression, China is taken as an example. The hydrothermal coupling simulation method is adopted to study the changes of reservoir pressure and temperature under different exploitation scenes and to determine the well spacing pattern of geothermal resources in the oil and gas area.

2. CHARACTERISTICS OF GEOTHERMAL GEOLOGY

The Central Uplift geothermal field lies in the Xinzhen structure area that is the east part of the uplift fault zone of Dongying Sag (Figure 1). This geothermal field is a low-temperature conduction-type geothermal system, and the reservoir is a layered pore-type sandstone geothermal reservoir.

2.1 Reservoir-cap Association

The geothermal reservoir in this study is located in the lower Guantao Formation (Ng_2) and the Member 2 and Member 3 of Dongying Formation (Ed_2 and Ed_3). The Member 1 of Dongying Formation is not considered as geothermal reservoir for its severe erosion (Tang, 2007). The underlying Shahejie Formation is not the target of geothermal exploration because it is the main oil-bearing series of Sinopec Shengli Oilfield that must be kept off to ensure the oil production and guarantee water quality.

The caprock is the Quaternary and Neogene Minghuazhen Formation (Nm) and the underlying strata is the Member 1 of the Shahejie Formation (Es1). The formation is mainly formed with several low-permeability mudstone and siltstone, which plays a good role in separation (Figure 2).

The vertical distribution of the reservoir-cap association is shown in Figure3. All the three sets of reservoirs are lower in the south and higher in the north, and the thickness gradually increases from south to north.

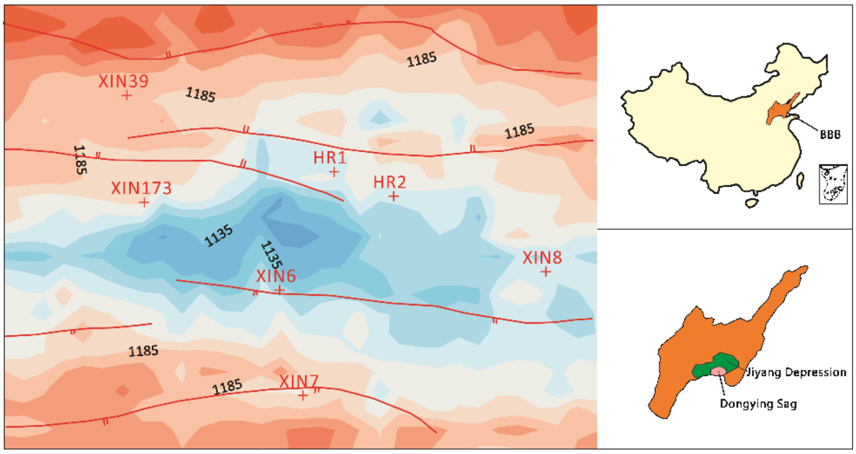

Figure 1: Location of the study area and the top of Ng.

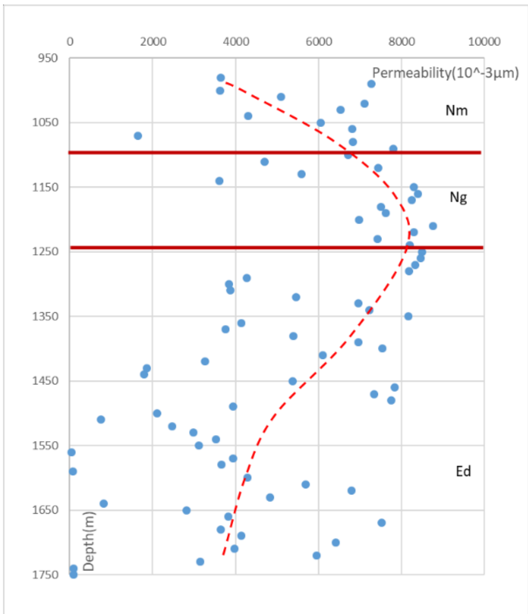

Figure 2: Permeability in well HR 2.

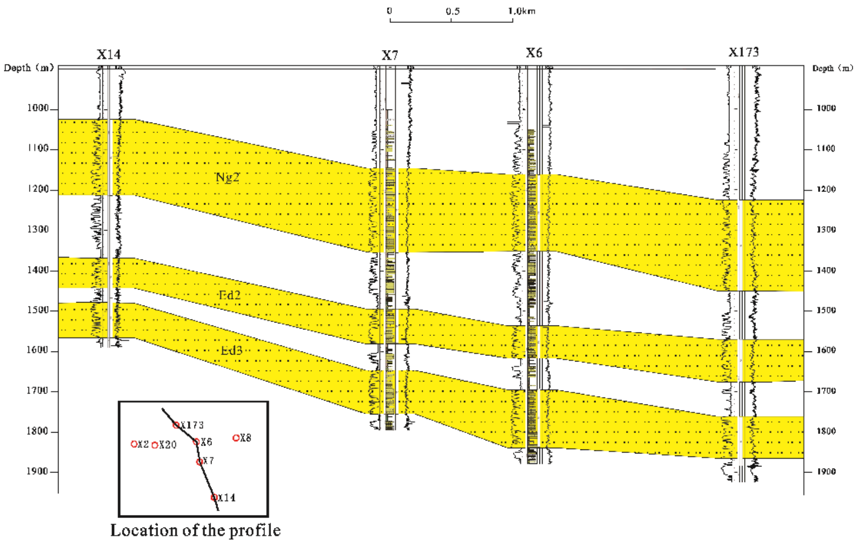

Figure 3: A connected wells profile of geothermal reservoir.

The reservoirs of Ng and Ed Formation have good water storage space. Two groups of the reservoir formations are distributed continuously and widely, and the circulation conditions of groundwater are good. The Ng2 geothermal reservoir, which is mainly formed with coarse clastic sandstone or glutenite of braided channel microfacies, is 320~ 440 m thick. The sand-to-ground ratio of 40%~50%. The porosity reaches 30%~36%. The Ed geothermal reservoir is 350~500m thick. Its lithology is dominated by fine sandstone-pebbly sandstone. The sand-to-ground ratio is 40%~50% while the porosity is 28%~30%. According to the pumping test results, the permeability of Ng2 reservoir reaches 800×10^{-3}μm^2～1400×10^{-3}μm^2, and the permeability coefficient is 0.59～2.0m/d; The permeability of Ed reservoir is 900×10^{-3} μm^2～1200×10^{-3} μm^2, and the permeability coefficient reaches 0.79～1.36 m/d (Wang, 2012).

2.2 Vertical Distribution of Thermal Conductivity

The thermal conductivity is the basic data for the heat flow calculation and the geotemperature field simulation. The thermal conductivity data of 20 core samples are measured in this study. In addition, other 117 thermal conductivity data of difference formation in Dongying Sag, Jiyang Depression is collected from the references (Xiong, et al., 1999), listed in Table 1 classified by lithology.

According to the ratio of mudstone and sandstone, the average thermal conductivity of each formation Jiyang Depression was calculated with the dispersion model of thermal conductivity (Table 2).

Table 1: Measured thermal conductivity data

Lithology	Sample number	Thermal conductivity (W/ m·K)
Mudstone	12	1.091～1.558
Sandstone and shaly sandstone	74	0.580～2.282
Limestone	18	2.400～2 . 979
Granitic gneiss	13	3.089～3.269

Table 2: Average thermal conductivity of each formation in Jiyang Depression

Stratum name	Stratum Code	Average Thermal conductivity （W/ m·K）
Minghuazhen Formation	Nm	2.04
Guantao Formation	Ng	1.97
Dongying Formation	Ed	2.09
Shahejie Formation	Es	1.85
Kongdian Formation	Ek	2.23
Mesozoic	Mz	2.22
Paleozoic	0-	2.87
Proterozoic era	Pre	2.83

2.3 Distribution of Temperature and Pressure

According to the temperature-depth chart of Dongying Sag (Figure 4), there is mainly linear correlation relation between the formation temperature and the depth, which reflects the characteristics of conductive geotemperature field. The depth (H_0) and the temperature (T_0) of the constant geotemperature zone in Jiyang Depression is 14 m and 14.7 ℃, respectively. The temperature data from oil test shows that the temperature at the bottom of the Ng Formation is 65-70 ℃ and the temperature at the bottom of the Ed Formation is 70-90 ℃. The heat flow in Jiyang Depression is high, which is 65.8±5.4 mW/m^2. It is 66.0±6.1 mW/m^2 in Dongying Sag.

According to the Pressure-depth Chart of Dongying Sag (Figure 5), it is normal pressure system above the Member 2 of Shahejie Formation, including the geothermal reservoir while there is overpressured in the Member 3 and Member 4 of Shahejie Formation due to the displacement of oil and gas, and the initial depth of the overpressure zone is 2,100m.

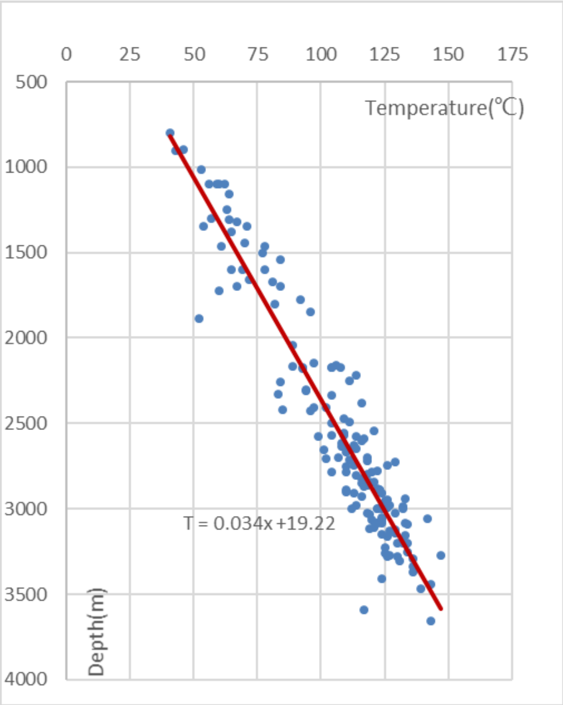

Figure 4: Temperature-depth chart of Dongying Sag.

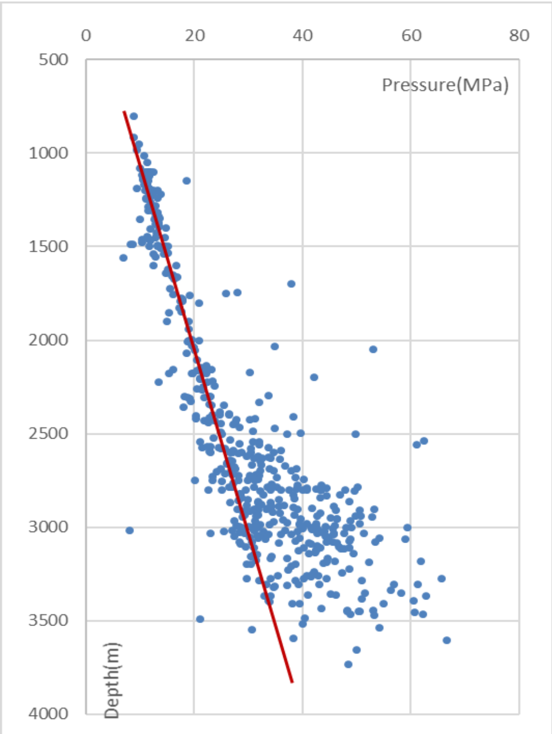

Figure 5: Pressure-depth Chart of Dongying Sag.

3. SETTING OF HYDROTHERMAL COUPLING MODEL

Based on the geological characteristics of the central uplift geothermal field, the numerical simulation method is used to study the geothermal well spacing parameters.

3.1 Model Structure and Mesh Generation

The Quaternary, Neogene Minghuazhen Formation and the upper Guantao Formation are set as caprock, which is divided into 6 layers. The lower Guantao formation and Dongying Formation are geothermal reservoir, which are the main simulation target, with finer subdivision of 8 layers. The bottom depth of the model is 2500m. The distribution of each layer is set according to the seismic interpretation data (Figure 6). In the horizontal direction, the Polygon Triangulation method is adopted and it is refined at the area with high calculation accuracy requirements, like the area around the geothermal wells.

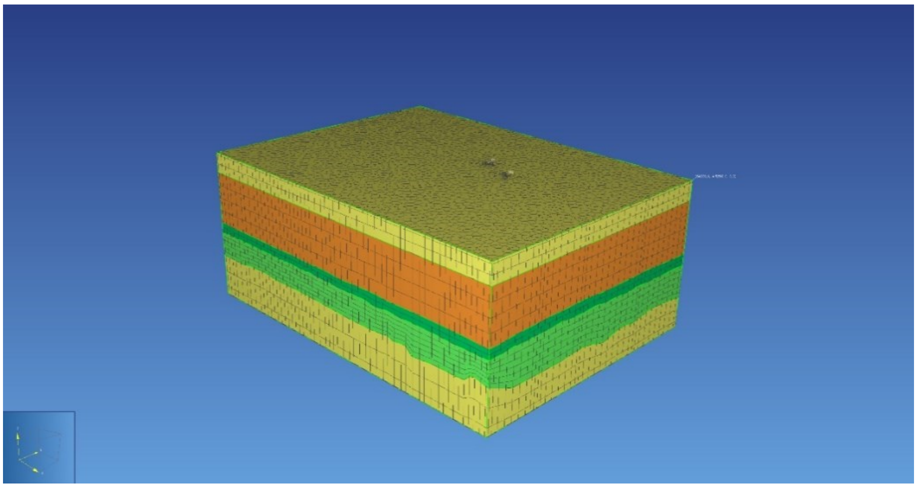

Figure 6: Meshes of the model.

3.2 Setting of Boundary Condition

1. Top Boundary: Set as a constant temperature and pressure boundary. The temperature is 14.5°C, and the pressure is set as atmospheric pressure, 1.013E5 Pa.

2. Bottom Boundary: Set as a constant heat flux boundary. The heat flow value is 65-70 mW/m^2.

3. Lateral boundary: Set as constant pressure boundary. At present, the pressure basically maintains normal hydrostatic pressure because the quantity of geothermal water exploitation is still small.

3.3 Model Calibration

The natural state of the reservoir is simulated. The model runs for 1,000,000 years (1 Ma) to stabilize the temperature and pressure field. The temperature and pressure field at the end time is the distribution under natural state. The temperature at the Ng bottom is 64-67°C, and the temperature at the Ed bottom is 76-86 °C, which agrees well with the actual situation (Figure 7).

Figure 8 shows measured and simulated pressure values in Well HR 1. They also agree well.

Hence the model can basically reflect the corresponding changes of pressure in the geothermal field.

Table 2 shows the model parameters after calibration .

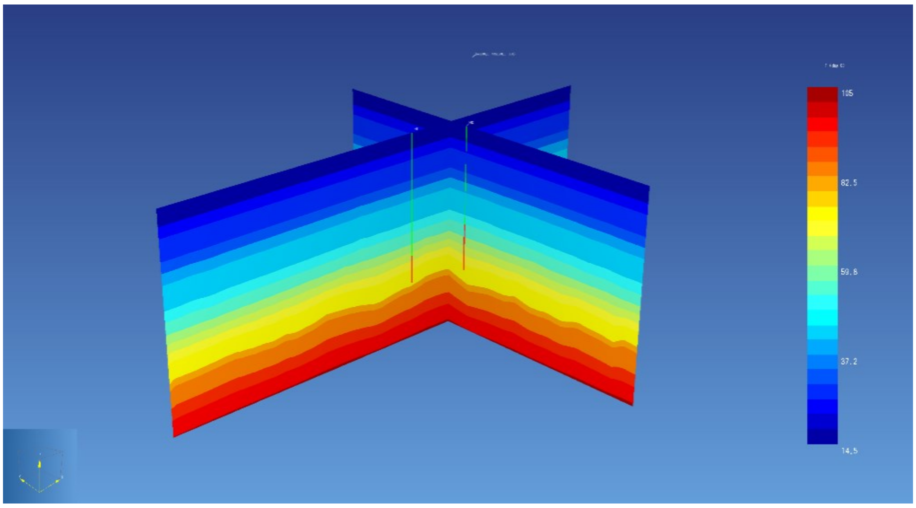

Figure 7: Temperature Distribution after 1 Ma.

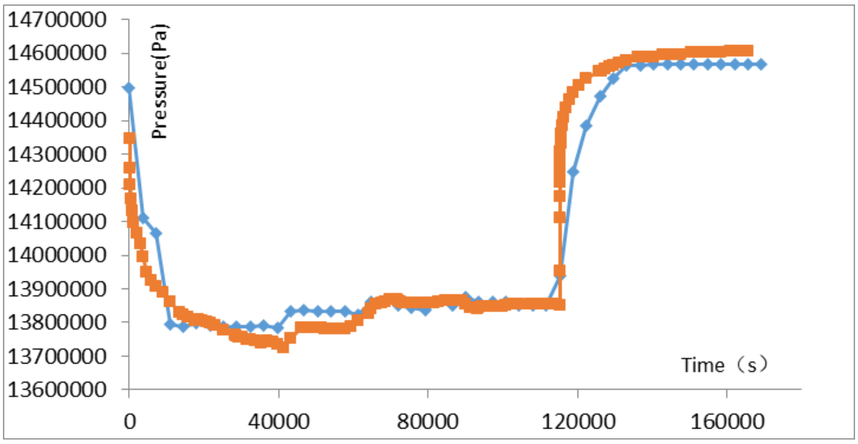

Figure 8: Measured and Simulated Values of Pressure in Well HR 1 .

Table 3: Parameters values after calibration

Value	Horizontal permeability ($10^{-3}\mu m^2$)	Vertical permeability ($10^{-3}\mu m^2$)	Porosity	Saturated thermal conductivity (W/m·℃)	Heat capacity (J/kg·℃)
Maximum	28	2.8	0.3	2.04	2100
Minimum	0.2	0.02	0.2	1.8	1600

4. DESIGN OF WELL SPACING PATTERN

The pumping test data of Well HR1 shows that the water yield is 60.23 m^3/h and the wellhead temperature reaches 64 ℃. We set the water yield to be 60 m^3/h. The period of heating season in the north of China is from Nov. 15 to Mar. 15 next year , recorded as 120 days. The parameters of well spacing pattern in the central uplift geothermal field are simulated and identified base on these data above.

4.1 Influence Range of Single Well Pumping

During the heating season, the pressure around the wellbore decreased due to pumping, but the geothermal water replenishes quickly and the pressure recovers rapidly when the pumping stops, and the pressure quickly recovers. At the end of the heating season (Mar. 15 next year), the cumulative pumping volume reaches the maximum and the influence range of pressure is also maximized. Figure 9 shows the pressure distribution in Well HR1 (-1490) at the end of the heating season. A cone of depression appears around the geothermal well, and its radius R is about 910m.

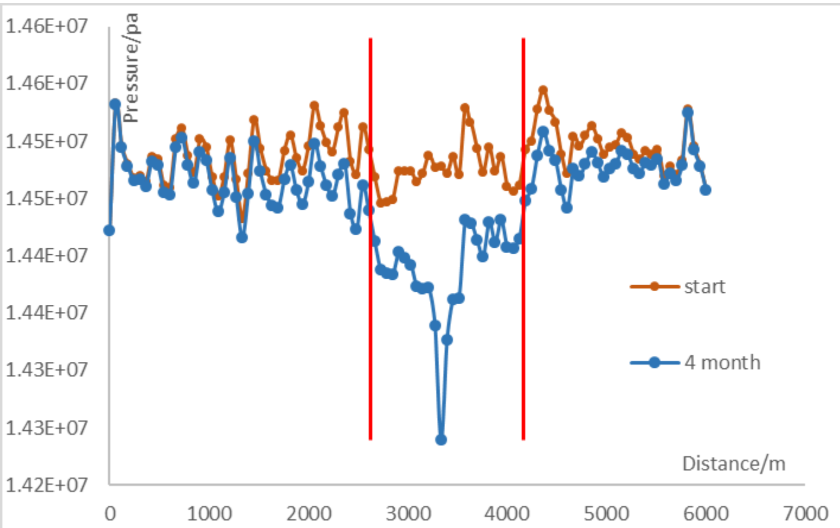

Figure 9: Pressure Distribution at the Top of Dongying Formation in Well HR 1 After Heating Season.

4.2 Ratio of Production Well and Reinjection Well

For the sake of economy, the natural pressure reinjection method is adopted currently. At present, the water level of Ed geothermal reservoir is about 40 m. It means that the maximum reinjection pressure or maximum water level rising space is 40 m. The reinjection water temperature is 35 °C. The simulation results show that when the reinjection rate is 40 m^3/h, the reinjection pressure reaches about 0.38 MPa and the water level reaches the ground (Figure 10).

Several reinjection tests have been carried out in Dongying area (Gao, et al., 2009). It can be inferred that when the maximum reinjection pressure is 40 m, the maximum reinjection rate is estimated 34.02 m^3/h. This is smaller than the simulation result. It may be the result of the reduce of reservoir permeability caused by the pore plug when reinjection. Therefore, it is recommended that the reinjection rate is 30 m^3/h, and the ratio of production well and reinjection well is 1:2. Namely, the well placing pattern is one production well with two reinjection wells.

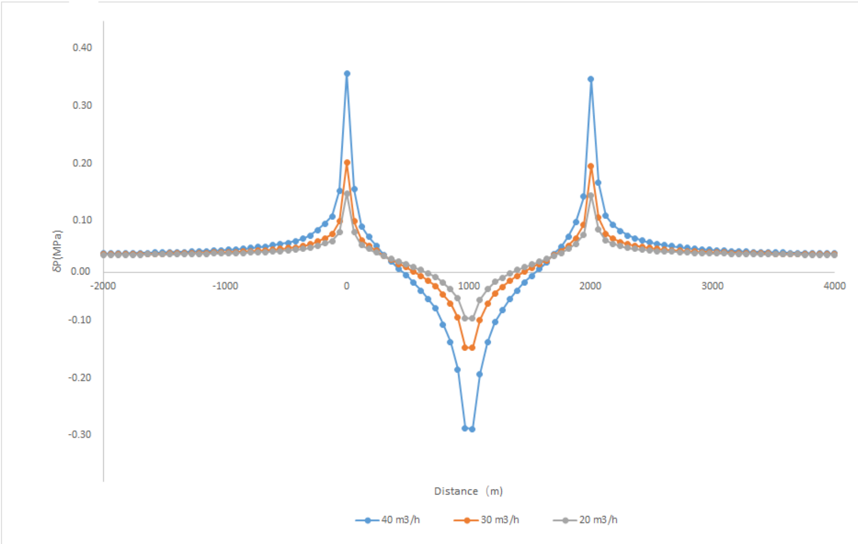

Figure 10: Pressure distribution between production well and reinjection well under different injection rates.

4.3 Inter-well Space

During the production with reinjection, it must be ensured that the water temperature in production well doesn't decrease during the project period. Therefore, it is necessary to predict the temperature influence of the cold reinjection water in the geothermal reservoir. Different reinjection rate and reinjection temperatures will affect the migration speed and the migration range of the cold front will change slightly.

The reinjection rate is set as 30 m^3/h, the reinjection temperature as 35 °C, the range of $\Delta t > 0.1$°C is 282.5 m after 30 years operation (Figure 11). Taking the reservoir anisotropy and the influence of wells around into consideration, it is recommended that the inter-well space between production well and reinjection is 350 m to ensure there is no thermal breakthrough in the production well.

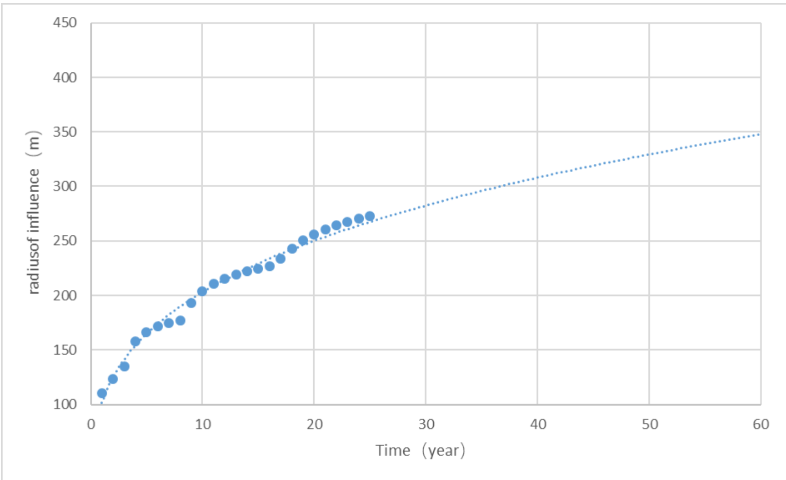

Figure 11 Change of the radius of temperature influence

5. CONCLUSION

Well spacing pattern must be designed when reinjection while exploitation to avoid temperature decrease in the production wells while maintain the geothermal reservoir pressure. A calibrated hydrothermal model is useful to predict the change of pressure and temperature in the geothermal reservoir under difference exploitation scenes and obtain necessary well spacing parameters.

The concept model and the parameters about geological condition and exploitation situation is derived from the Central Uplift geothermal field of Dongying Sag, Jiyang Depression, Bohai Bay Basin(BBB), China. The simulation result shows that the inter-well space between production well and reinjection is 350 m when the reinjection rate is 30 m^3/h and the reinjection temperature is 35 ℃ and the ratio of production well and reinjection well is 1:2.

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