RESEARCH OF GEOTHERMAL REINJECTION IN XI'AN GEOTHERMAL SYSTEM, WEST CHINA

Guiling WANG
Institute of Hydrogeology & Environmental Geology, Chinese Academy of Geological Sciences,
406 Shigang Street, Shijiazhuang, 050061 Hebei, P.R.China
E-mail: wguiling@heinfo.net

ABSTRACT

Geothermal resources are widely distributed in China. Recent years, a lot of research work has been carried out on the distribution, utilization, drilling, and exploration of geothermal resources. However, for geothermal reinjection, there is almost no record in China. In this paper, based on the geological characteristic, geophysical and geochemical features of Xi'an low-temperature geothermal field, a 3-D numerical model is established to model the change of temperature and pressure after reinjection. The results show that making reinjection at depth 1450m to 2300m will benefit the reservoir pressure and will not change the temperature a lot.

Key words: Reinjection Numerical simulation Xi'an

1. INTRODUCTION

The geothermal energy belongs to regenerative energy, together with nuclear energy, wind energy, solar energy and tide energy, it is classified as five kinds of new energy. The geothermal energy is mainly characteristic of regeneration (not complete regeneration), cleanness, and minor investment for exploitation and utilization. The geothermal specialists think it as the energy of the twenty-first century.

The geothermal resources are widely distributed in Xi'an with a great amount of reserve and it has a long history of exploitation and utilization. The scientific and rational exploitation and utilization of geothermal resources will play a promoting role in the development of local economy. However, owing to the shortage of rational planning, the geothermal resources are suffering the serious destruction and the geothermal reservoir pressure is decreasing. In order to rationally develop and utilize the geothermal water resources in Xi'an, prolong the life of geothermal fields and reduce the environmental pollution in urban area, Xi'an geothermal field has been chosen to carry out the re-injection test of geothermal tailed water. Based on the actual work such as field exploration, data collecting and water table observation, the researchers have studied the geological structure, geothermal reservoir and geothermal geochemistry and geophysics of Xi'an geothermal field and have put forward re-injection strata and re-injection quantity of geothermal tailed water, effect of re-injection on geothermal reservoir seepage field and temperature field as well as chemical field change of geothermal reservoir after the re-injection.

2. GEOLOGICAL ENVIRONMENT OF RE-INJECTION AREA

The re-injection pilot area is located in the first fault block southeast of Xi'an geothermal field-- Dayanta fault block, close to the second fault block--Xiaoyanta fault block. There are two main tectonic faults in the area:
Shuangshuimo-Dengjiapo fault: fault stride NEE, direction of dip SE and dip angle about 80°, belonging to the hidden fault, underlying 1,000 m beneath, the top reaching the upper part of Zhangjiapo formation of Pliocene series of Tertiary system.
Zaohe fault: its stride extends along the Zaohe River, in the direction of NW, and direction of dip SW. According to the profile interpretation of artificial shallow earthquake in Yuhuazhai geothermal well, the fault dip angle is 85°, this fault has strong activity and can exert the effect on the middle and lower parts of Quaternary system. Geothermal anomaly evidently occurs around Weiqu in the aspects of SiO_2, and F ions and geotemperature. In the re-injection area develops six sets of strata from top to bottom and the details are shown in Table 1.

3. DETERMINATION OF RE-INJECTION STRATUM AND DEPTH

In the study area, there are mainly five strata containing geothermal reservoirs, e.g., Sanmen formation (Q_{1s}), of Quaternary

Table 1 Strata in re-injection area.

Stratum era	Depth of bottom(m)	Depth (m)	Rock formation
Qinchuan Group $Q_{2\text{-}4}qc$	500	500	Greyish yellow silty clay sandwiched with sand layer in the upper part; variegated sand, sandy conglomerate interbedded with greyish yellow, brownish yellow silty clay at various thickness in middle and lower parts; sand layer loose and thick, clay soft
Sanmen Formation $N\text{-}Q_1s$	720	220	Grey silty clay, clay interbedded with light grey sand, sand containing gravels at various thickness, sand layers with various thickness and loose, clay soft
Zhangjiapo Formation N_2z	1,450	730	A set of fluvial, lacustrine deposits. greyish green, light brown mudstone, sandy mudstone interbedded with thin grey silty sandstone at various thickness, sandstone comparatively loose
Liantian Bahe Formation N_2L+b	2,307	857	A set of fluvial, lacustrine deposits. mainly light brown, brownish purple mudstone, sandy mudstone interbedded with light grey fine sandstone, sandy gravel. Sandstone semi-consolidated, mudstone comparatively soft
Gaoling Group N_1gl	3,700	1,493	A set of fluvial, lacustrine deposits. brownish red, brownish purple mudstone, sandy mudstone interbedded with flaggy grey silty fine sandstone. Mudstone containing calcareous concretions, comparatively hard, sandstone comparatively loose. totally 77 layers of sand with a thickness of 233 m. main section for getting water, totally fifteen screen pipes installed with a thickness of 204 m, mainly distributed between 2,423-2,708 m, 2,992-3,096 m and 3,293-3,438 m
Bailuyuan Formation E_3b	4,006	306	Purple, brown mudstone interbedded with grit stone containing gravels of various thickness, totally 23 layers of sand with a thickness of 98 m main section for getting water, the length of screen pipes installed 148 m

Table 2 Characteristics of geothermal reservoirs.

Geothermal reservoir	Thickness of reservoir (m)	Thickness of sandstone (m)	Ratio of sandstone /mudstone (%)	Permeability(md)
LantianbaheGroup	857	286.5	33.3	125-330
Gaolingqun Group	1495	233	15.6	<30

Table 3 Temperature correction of geothermal reservoirs

Well No.	Temperature before rectifying			Temperature after rectifying		
	II	III	IV	II	III	IV
XR41	56.9	71.85	93.6	67.2852	78.1554	93.6
2	55	65.3	76.3	61.596	76.512	86.1315
XR31		70.55	87.55	58.758	70.55	88.5405
XR24	49.5	66.8	77.3	56.5635	66.645	78.9375
XR13	51.9	60.3	83.52	62.2395	71.6775	83.52
1	56.75	76	86.02	61.233	76	86.02
11	65	79.5	91.5	69.1365	81.726	95.4375

system, Zhangjiapo formation (N_{2z}), Liantianbahe formation (N_{2L+b}), Gaoling group (N_{1gL}) and Bailuyuan formation (E_{3b}) of Tertiary system.

The drilling data reveal that the Liantianbahe formation (N_{2L+b}) from 1,450 to 2,307 m with a total thickness of 857 m is a set of fluvial, lacustrine deposits, mainly consisting of fine sandstone, interbedded with sandy conglomerate. The general characteristics show that grain of sandstone is coarse, semi-consolidated, comparatively loose and poorly-sorted, in subangular shape and occurring argillaceous cementation. The thickness of single layer is 1.5-10 m, the thickness of sandstone and sand thickness ratio is comparatively large. According to the logging data, there are fifty-six layers of aquifers in this section with a total thickness of 286.5 m, accounting for 33.3% of the total strata; The change of average value of total porosity is within 14.4-27.8%; The average permeability of aquifer within the range of 1,662.4-1,854 m is comparatively large; From 125 to 330 m the maximum permeability is 742 md, and in this section the single layer of the aquifer is bigger; Except for a few layers of aquifers with the average value of permeability more than 110 md, all others are less than 70 md; Based on the calculation of adjacent geothermal wells pumping test the K value is 0.38 m/d-0.47 m/d.

The thickness of geothermal reservoir in Gaoling group is 1,493 m ranging from 2,307 m to 3,700 m. In this section it mainly consists of mudstone and sandy mudstone, interbedded with flaggy powder, fine sandstone. There are totally 77 layers of sand with a total thickness of 233 m, and sand thickness ratio is 15.6%. According to the logging data, the aquifer porosity is low, most less than 10%. From 3,028.3 m to 3,451.9 m, the porosity is within the range of 11-18%; the permeability of geothermal reservoir is also low, usually less than 30 md, only two aquifers are more than 100 md. According to the regional data, the filtration coefficient of geothermal reservoir is 0.07-0.24 m/d.

From above data, the sand thickness ratio of geothermal reservoir of Liantianbahe formation is big, and porosity and permeability are high, but the sand thickness ratio of Gaoling group is comparatively small and the porosity and permeability are low. In addition, the Liantianbahe formation geothermal reservoirs are main exploitation formations with the large exploitation quantity and the pressure decreases more rapidly, so the Liantianbahe formation is chosen as the re-injection stratum, from 1,450 to 23,00 m.

4. NUMERICAL SIMULATION OF GEOTHERMAL WELL RE-INJECTION

The re-injection simulation area of geothermal wells are chosen in I, and II tectonic fault blocks--most part of Dayanta block and Xiaoyanta block, with an area of 98 km^2, and the ground average elevation of some 410 m. The re-injection target formation--Liantianbahe formation N_{21+b} of the third geothermal reservoir is mainly simulated by the model.

4.1 Correction of Geothermal Reservoir Temperature and Determination of Initial Pressure Field and Temperature Field

The temperature data of geothermal wells in Xi'an are obtained under the unstable conditions and need to be corrected before use. The correction of geothermal reservoir temperature is gained by adopting the following equations:

The corrected results of temperature are shown in Table 3.

The initial temperature field of each geothermal reservoir is shown in Fig.1.

$T_i = 3.30 H_i + 24.90$ ----------(1)

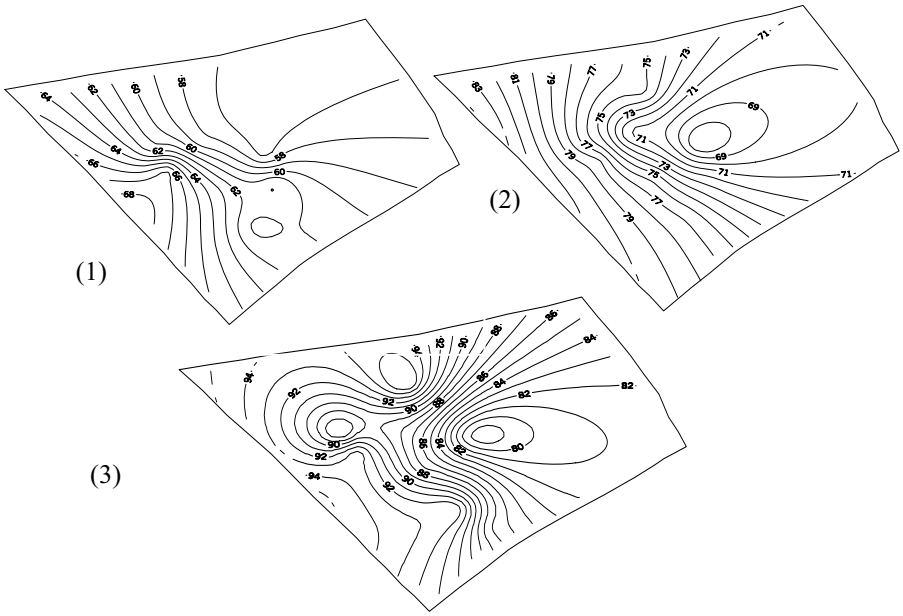
Where,
Ti----geotemperature
Hi----depth (10^2 m)

There is no much measurement data of geothermal reservoir pressure available in the study area, usually the pressure change of geothermal reservoir is observed by the method used for measuring the static water table of geothermal well. So the following equation is used to calculate the pressure value:

$P = (H-h) \times \rho \times g$ ---------- (2)

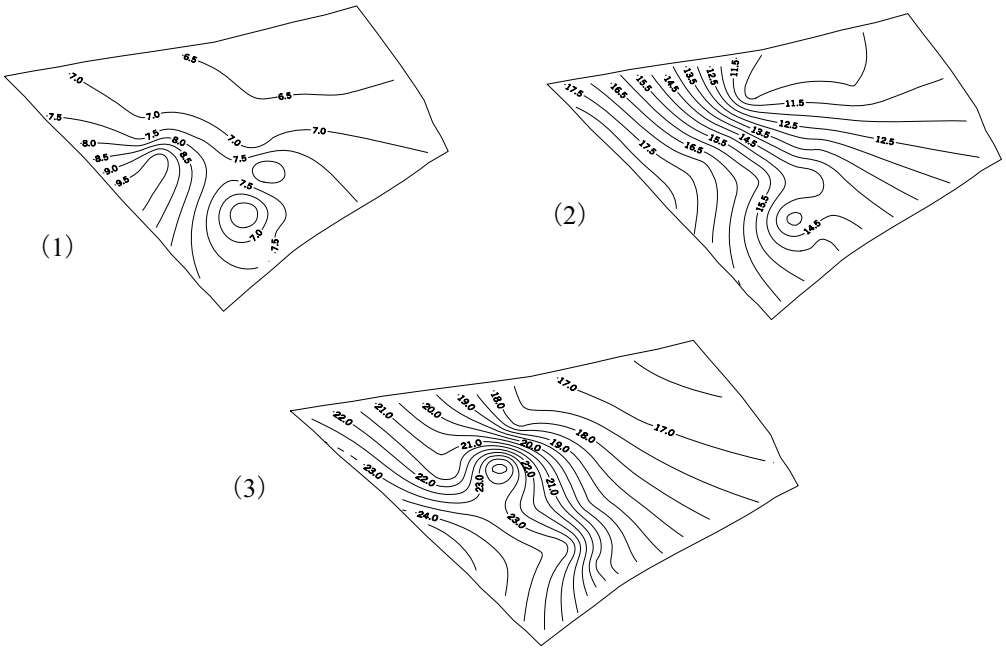
Where,
H = piezometric head (m)
H = topwall elevation of geothermal reservoir (m)
ρ = fluid density, 998.28 kg/m^3 adopted
g = acceleration of gravity, 9.80665 N/kg adopted

The calculated initial pressure fields of each geothermal reservoir are shown in Fig.2.



(1)-geothermal reservoir II； (2) -geothermal reservoir III； (3) -geothermal reservoir IV

Fig.1 Initial temperature map of geothermal reservoirs (℃).



(1) -geothermal reservoir II； (2) -geothermal reservoir III； (3) geothermal reservoir IV

Fig.2 Pressure map of geothermal reservoirs on January 1998 (Mpa).

4.2 Conceptual Model

According to the structure of geothermal reservoir in the simulation area, the model is controlled by the N_{2z} Zhangjiapo formation of the second geothermal reservoir and N_{1g1} Gaoling group of the fourth geothermal reservoir. According to the initial temperature field and pressure field, the northern, western, eastern and southern boundaries of the model can be determined as the impermeable boundaries, which are corrected in the course of recognance.

Table 4 Structural parameters of geothermal reservoirs.

Reservoir No.	Stratum	Fractured area	Depth of the top (m)	Depth of the bottom (m)	Average thickness (m)	Ratio of sandstoe and clay (%)
II	N_2^zZhangjiapo group	I	660.33	1368.75	708.42	14.91
		II	641.16	1244.27	603.11	8.98
III	N_2^{l+b}Lantianbahe group	I	1368.75	2082	713.25	32.98
		II	1244.7	1886.5	642.23	35.08
IV	N_1^{gl}Gaolingqun group	I	2082	2500	418	10.00
		II	1886.5	2500	613.5	11.71

4.3 Mathematical Model

By the law of fluid conservation of energy, the three-dimensional flow pressure equation of fluid movement is the following partial differential equation:

Where,
Kxx, Kyy, Kzz----filtration coefficient along the main flow direction (m/s)

$$\frac{\partial}{\partial x}(K_{xx}\frac{1}{\rho g}\frac{\partial p}{\partial x})+\frac{\partial}{\partial y}(K_{yy}\frac{1}{\rho g}\frac{\partial p}{\partial y})+\frac{\partial}{\partial z}(K_{zz}\frac{1}{\rho g}\frac{\partial p}{\partial z})$$
$$=S_s\frac{1}{\rho g}\frac{\partial p}{\partial t}-Q\quad\quad(3)$$

p----geothermal reservoir pressure (MPa,1MPa=10^6N/m^2)
ρ ----fluid density (kg/m^3)
g----acceleration of gravity (N/kg)
Q----fluid flow of unit geothermal reservoir thickness (m^3/s m)
Ss---- water storage coefficient of unit geothermal reservoir thickness (1/m)
t----time (s)

By the law of conservation of energy, the geothermal migration equation of fluid three-dimensional flow is represented by the following partial differential equation:

$$\frac{\partial}{\partial x}(\lambda M\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(\lambda M\frac{\partial T}{\partial y})+\frac{\partial}{\partial z}(\lambda M\frac{\partial T}{\partial z})+Q_E-$$
$$(\rho Cv_x M\frac{\partial T}{\partial x}+\rho Cv_y M\frac{\partial T}{\partial y}+\rho Cv_z M\frac{\partial T}{\partial z})$$
$$=[\varphi\rho C+(1-\varphi)\rho_R C_R]\frac{\partial T}{\partial t}\quad\quad(4)$$

Where,
T----temperature (℃)
Vx,Vy,Vz----fluid seepage velocity vectors (m/s)
λ ----specific thermal conductivity of geothermal reservoir (J/m.s.℃)
ρ R----rock density of geothermal reservoir (kg/m^3)
C,C_R----specific heat of fluid and rock (J/kg.℃)
M----thickness of geothermal reservoir (m)
Q_E----vertical heat flux (J/m^2 s)
ϕ ----porosity

After dispersion to the above two equations, the triangular finite element method is used to make them coupled and then get the solution. The study area is divided into 192 nodes by the triangular units.

4.4 Model Correction

For the model correction, time span between January, 1998 to January, 1999 is taken as the correction period, the parameters are corrected with a time period of a month. The pressure data in January, 1998 are taken as the initial

values, because the temperature change is small, so the temperature data reported of each accomplished well is taken as the initial values.

4.4.1 Determination of Initial Parameter

There are rich pumping test data available in this area. Based on the past pumping test and study results, and at same time in consideration of geological structure and lithology, the filtration coefficient and elastic specific yield parameters of the area can be classified into four subareas. The zonation and value adoption are shown in Fig.3.

The rock thermophysical parameters and the initial values of geodetic heat flow values of the second, third, and fourth geothermal reservoirs in the simulation area can be seen in Table 5.

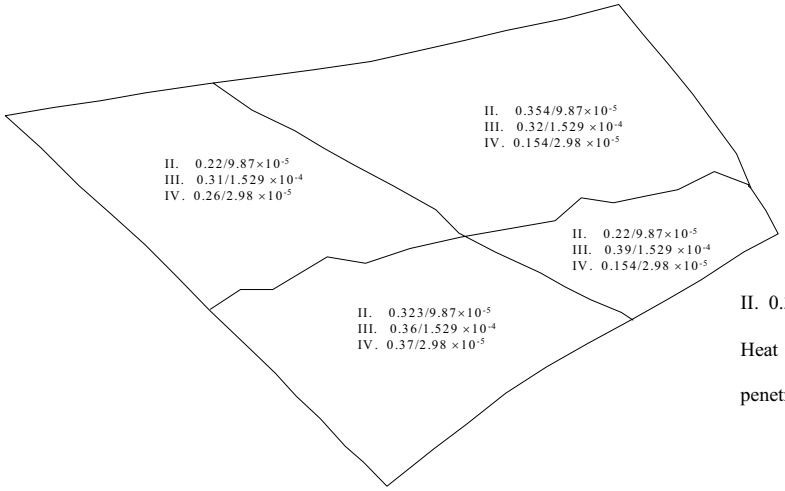


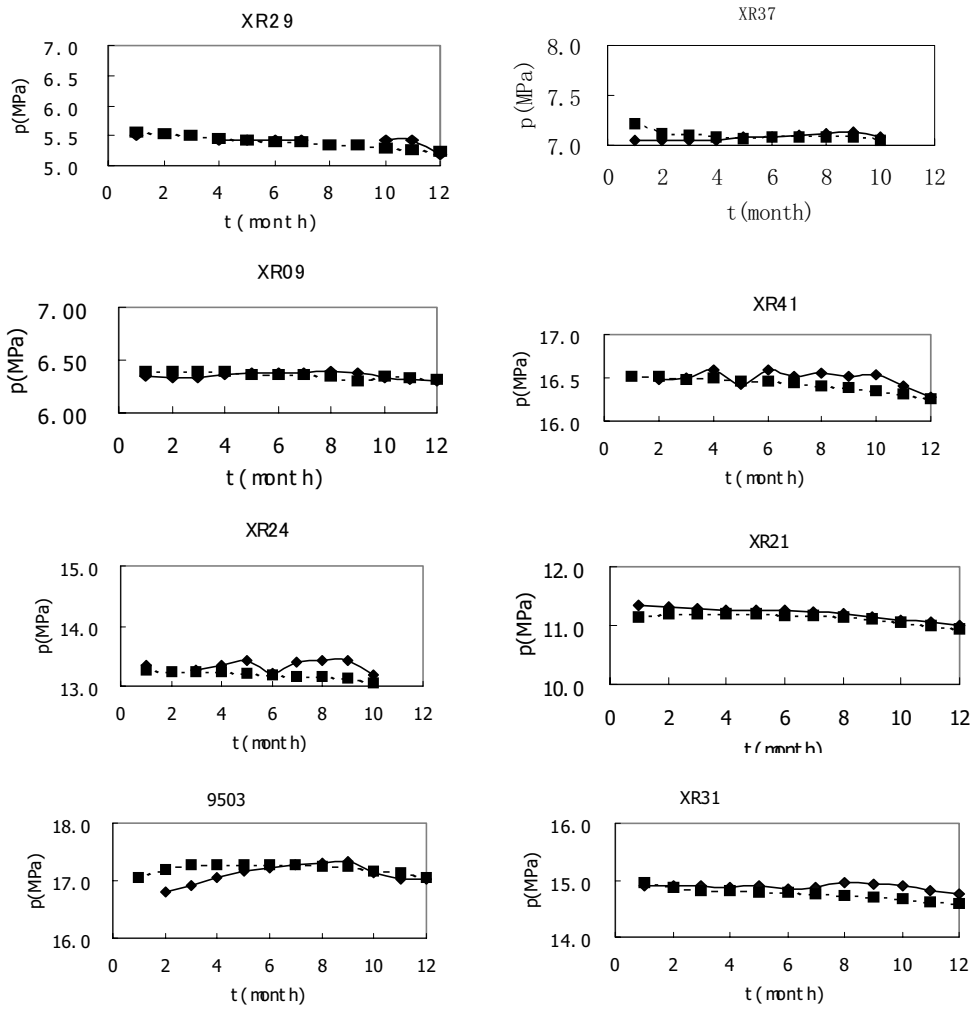
Fig.3 The coefficient of penetrability and the special yield zoning map of geothermal reservoirs.

Table 5 Physical parameters of geothermal reservoirs.

Reservoir No.	Thermal physical parameters of rock				Heat flow ($\times 10^{-2}$w/m^2)
	ϕ (%)	λ (w/m ℃)	ρ (g/cm^3)	C(cal/g· ℃)	
II	0.262	1.64	1.97	0.21	7.16
III	0.232	1.73	2.07	0.21	7.16
IV	0.22	1.9	2.26	0.21	7.16

4.4.2 Model Correction

Through the model correction for twelve time periods from January, 1998 to January, 1999, the pressure curve fitting of each observation well is comparatively good, with the maximum error 0.5Mpa and minimum error only 0.02Mpa, such errors are considered to be acceptable (Fig.4). The temperature field basically remains unchanged (Fig.5), indicating that the model reflects the actual conditions. Thus, the parameters, boundaries and other terms adopted for the model are reasonable.



Dash line: calculated data solid line: observed data

Fig.4 Comparison of calculated and observed pressure at observation wells from February 1998 to January 1999.

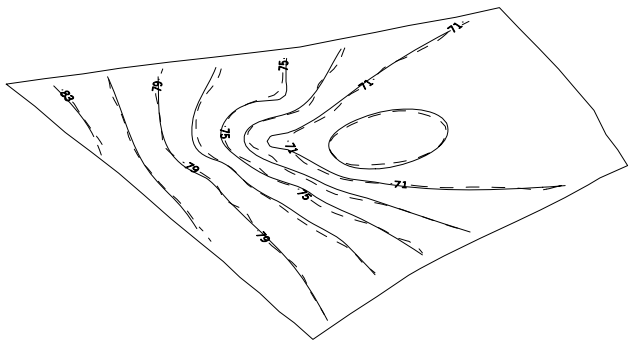


Fig.5 Comparison of calculated and observed temperature of the III heat reservoir.

---- Calculated data

– – observed data

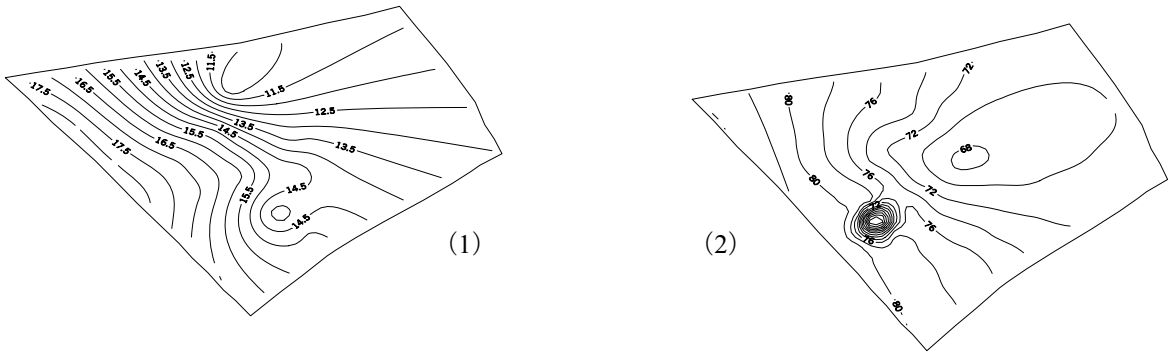
4.5 Re-injection Simulation Calculation

The re-injection simulation is conducted under the exploitation condition, the average exploitation quantity of twelve months in 1998 is taken as the monthly exploitation quantity of each well, namely, 0.993 million m3, to simulate the re-injection condition with the re-injection tailed water temperature 45℃ and re-injection quantity of 100 m3/h. Through

the simulation calculation, the model predicts the temperature field and pressure field of the sixth year. Under present exploitation intensity, after six years, the temperature of the third geothermal reservoir will maintain unchanged basically, but the pressure will decreases by 1.8 Mpa on average, 0.3 Mpa each year.

On condition of the re-injection, the model predicts the temperature field and pressure field of the fifth year shown in Fig. 6.

From the simulation results of the fifth year, it is found that the effect of geothermal water re-injection on the target reservoir is limited within 1 km. After five years' re-injection, the pressure field change of re-injection target stratum is remarkable. Compared with the prediction results of the sixth year on condition of no re-injection, the pressure increases by 2.0 Mpa with the re-injection quantity of 100 m3/h. The exploitation wells of same stratum, closest o the re-injection well, are No.XR41 and No.XR27, which are only 1.5 km away from the re-injection well. The re-injection has no effect on the temperature of these two exploitation wells. It is can be seen from Fig.10 the re-injection has no effect on the fourth geothermal reservoir.



（1）-reservoir pressure；（2）-reservoir temperature

Fig.6 The fifth year's pressure (Mpa) and temperature in geothermal reservoir III after reinjection by 100 m^3/h

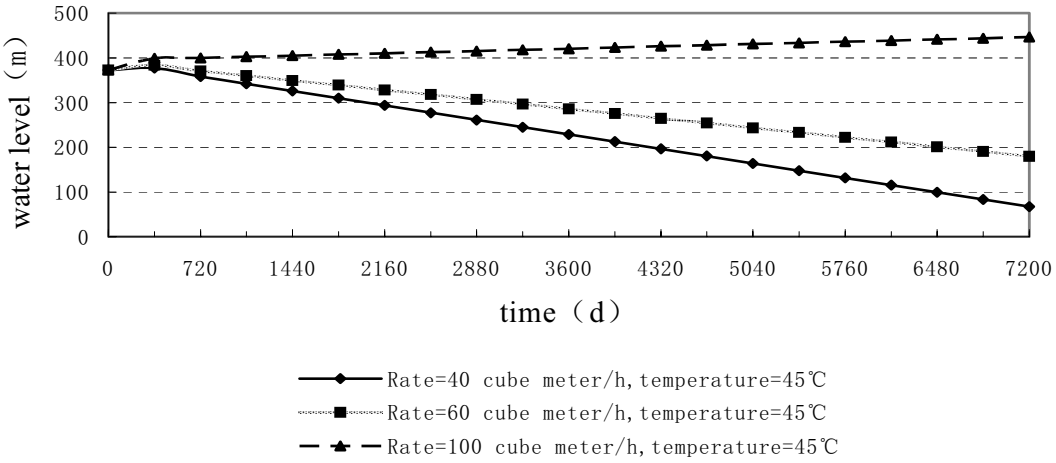


Fig.7 Prediction of reservoir pressure at well XR41 under different re-injection rates

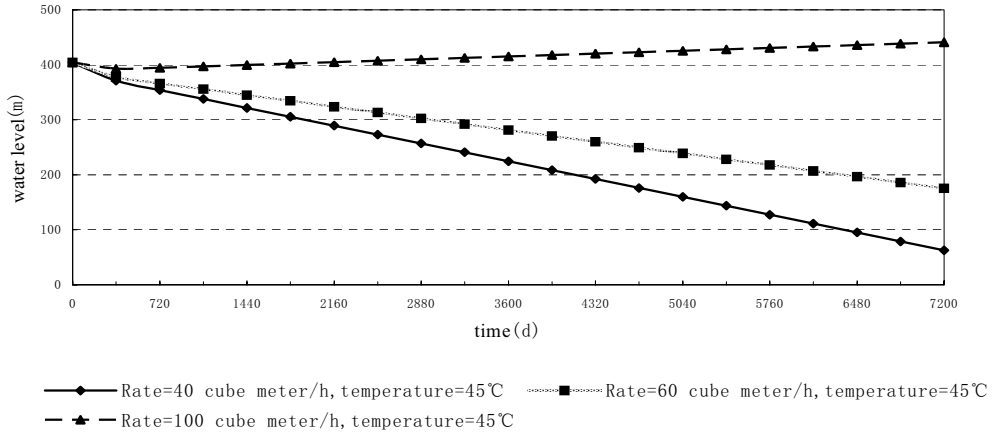


Fig.8 Prediction of reservoir pressure at well XR27 under different re-injection rates

In order to instruct the re-injection, the pressure change of geothermal reservoir after twenty years' re-injection has been simulated and calculated based on the effect assessment of re-injection for five years. The simulation results can be seen in Fig.7 and Fig.8. It can be seen that the re-injection with water quantity of 40-100 m^3/h has remarkable effect on No. XR41 Well and No. XR47 Well in pressure, when the re-injection is conducted with water quantity of 60 m^3/h, the water table of these two wells are higher by 40 m on average. When the re-injection is conducted with water quantity of 100 m^3/h, the water tables are higher by 80 m than that with water quantity of 60 m^3/h. Besides, when the re-injection is conducted with water quantity of 100 m^3/h, the water tables rise year by year.

5.CONCLUSIONS AND SUGGESTIONS

1) The proper stratum for re-injection of geothermal tailed water is the geothermal reservoir of Liantianbahe formation, within the depth range of 1,450-2,300 m.

2) After five years' re-injection, the effect of geothermal water re-injection on the target stratum is limited within 1 km. The exploitation wells closest to the re-injection well are No.XR41 and No.XR27, only 1.5 km away. The re-injection has no effect on the temperature of two exploitation wells and the temperature field of No.IV geothermal reservoir is basically unchanged.

3) After five years' re-injection, the pressure field change of re-injection target stratum is remarkable. Compared with the prediction results of the sixth year on condition of no re-injection, the pressure increases by 2.0 Mpa with the re-injection quantity of 100 m^3/h.

4) After twenty years' re-injection, with re-injection quantity of 40-100 m^3/h, the effect of temperature of the re-injection target stratum is less than 1.1 km. With the re-injection quantity of 100 m^3/h, the water table will slightly rise under present exploitation intensity. Therefore, it is feasible to carry out the re-injection so as to maintain the geothermal reservoir pressure.

ACKNOWLEDGEMENT

This work is a special project funded by Xijing Company and is also supported by the Geological Bureau. The authors are gratefully to professor Shijiansheng for many useful discussions and for the hospitality and support of Shanxi Geological Bureau where some of this work was conducted. I thank Mrs. Zhang Junpai for his contribution to this work, and Liu Huatai for preparing most of the drawings. Special thanks go to Dr. Zhang Fawang for his suggestions and guidance of this work.

REFERENCES

Bureau of Geology and Mineral Resources of Tianjin City and Institute of hydrogeology and Engineering Geology, Chinese Academy of Geological Sciences (1998) Study on Re-injection of Geothermal Fluid in Tanggu District of Tianjin City.

Institute of Engineering Exploration, Shaanxi Province (1998) The Preliminary Planning of Development and Utilization of Geothermal Resources in Xi'an.

Wang Guiling et al. (1992) Industrial uses of geothermal energy in China. *International Conference on Industrial Uses of Geothermal Energy*.

Wang Guiling et al. (1993) Modeling of Yangbajing High-temperature Geothermal System. *Proceedings of the second Geothermal coference*.

Wang Guiling and Gudni Axelsson (1992) Simulation of small fractured low-temperature geothermal system by lumped parameter models. *International Conference on Groundwater and Environment*.

Wang Runsan, Xue Huafeng, Wang Fenglin et al. (2000) The Preliminary Study on Abnormal Stratum Pressure of Geothermal Field in Xi'an---Xianyang. *Geothermal Energy*, No. 2, P1-5

Xi'an, No.1 Hydrogeological Team, Bureau of Geology and Mineral Resources of Shaanxi Province (1996) Survey Report of Geothermal Resources in Xi'an geothermal field.