Analysis of Reinjection Tests in a Bedrock Geothermal Reservoir, Tianjin, China

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By the end of 2008 there were about 245 production wells and 12 reinjection wells operating in Tianjin. The annual production rate is 25 million m^3 and the reinjection rate is 4.2 million m^3. Reinjection is expected to gradually cool the reservoir and so it is important to carefully design and manage the well fields and this involves estimating the thermal breakthrough time for different well separation distances. This paper describes the 2-D mass and heat transfer in the heterogeneous fractured rocks. Equations that arise for each grid block were linearised and anumerical model of the geothermal system was developed with TOUGH2. This model was then used to analyse the reservoir pressures and temperatures with special emphasis on simulating break-through of cooling at the production well. The tracer test is shown to be important for improving our understanding of the tracer and heat transport processes and reservoir (channel/fractured/karst) porosity, and for enabling the estimation of future reservoir cooling caused by fluid reinjection.

Keywords: Geothermal reservoir, Simulation, Heat break-through, Doublet system

Introduction

Tianjin is located at the north-east of the Hua-Bei plane in China, with the Yanshan Mountains at its north and Bohai Bay at its east. The total region area is 11305 km^2. The bedrock outcrop is limited to the mountain area of the north JI County[1].

In Tianjin, the main productive reservoirs are porous reservoir in the sandstone (two productive zones) and karst/fractured reservoir in bedrock (three productive zones). The top depth of the karst /fractured reservoir in bedrock is over 950 m. The discharge rate of the single well is more than 100 m^3/h, the wellhead temperature is 55-100 °C. The waters are mainly used in space heating, physical therapy, bathing, fish farming etc.

Since 1996, the reinjection test started in the basement reservoir in Tianjin. Till now there are 27 doublet (reinjection/production) geothermal wells, and 10 of them are located in Tianjin urban area. These doublet wells are significant for the protection of the geothermal resource in Tianjin.

By the end of 2008, there were about 245 production wells (including 27 reinjection wells). The annual production rate is 25 million m^3 and the reinjection rate is 4.2 million m^3. The static water level is between –35m and –90m, the annual draw down rate is 6-9m.

Analysis of the Tests in the Basement Geothermal Reservoir

Geological modelling of the doublet system

The system of WR45 is the second production-reinjection doublet well in the basement reservoir of Tianjin, which was drilled in 1995. Production and reinjection wells were drilled into the Wumishan formation of the Jixian series of the Proterozoic group.

Analysis of the reinjection tests in WR45

The productive zone of the doublet WR45 is Wumishan formation of the Jixian series in Proterozoic group. The main lithologic characteristic is the dolomite and limestone. The karst fissure is well developed in this area.

The first reinjection test was carried out with the pressurization pump in Oct. 1996. Figure 1 shows the monitoring data for the test. Removing the abnormal data that may cause by some equipment problems, the reinjection flow-rate was inverse proportional to the re-injective pressure during the test. When the pump pressure was 0.02 MPa, the reinjection rate was 100m^3/h. But the re-injective rate decreased to 86 m^3/h when the pump pressure increased to 0.05 MPa. During the last stage, the pump pressure was 0.09MPa, the re-injective rate settled at 50m^3/h more or less.

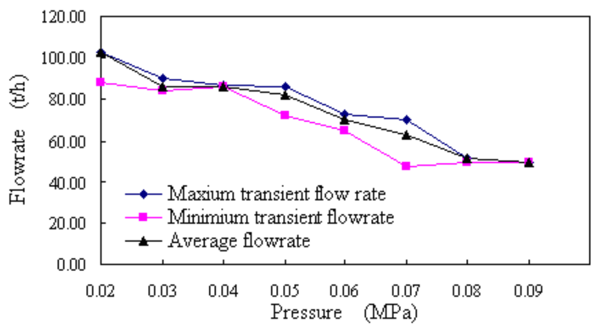

Figure1 Relationship between re-injection pressure and flow rate.

The doublet well of the WR45 is located at the well-developed karst fissure area in Wumishan reservoir, which is the porous-fracture medium of doubling porosity. At the beginning of the reinjection test, the flow along the fissure takes the leading effects. The pump pressure influences a little on the reinjection rate. The reinjection fluid transfers the aquifer quickly because of the increasing of the pressure gradient between the reinjection and production well. As the reinjection time extended, the seepage flow in porous medium took more and more effects. The velocity of reinjection fluids in the reservoir became slowly, and the re-injective was decreased. As a whole, the pump pressure increased and the injection rate decreased gradually as the reinjection test continued.

During the space-heating period from Nov. 1999 till March 2001, the doublet WR45 has been run under the natural state without pressure pump. All the released geothermal water was reinjected into the reservoir quickly after the heating cycling. Because several geothermal production wells were used for space heating simultaneously around WR45, the reservoir pressure decreased fast. It would be of influence to the water level of the reinjection well. For the case, it may be easier to reinject. However, the temperature changes of the production zone should be monitored so that the rate of reinjection can be adjusted. By the 2002, the temperature changes have not observed in surrounding the production geothermal wells.

Tracer Test in Fractured Medium Reservoir

The tracer test is very important to understand the transport state and channel/space in the production/reinjection zone. And it is a very important stage to simulated heat transfer in the reservoir. To investigate the connective channel between the reinjection and production well of doublet WR45, the tracer tests have been done in the winter of 1998-1999. 10kg of iodide of potassium (KI) is selected for the first stage as the tracer. A series of instruments are installed surrounding wells to monitor the water quality for a long period. The detailed data is listed in Figure 2.

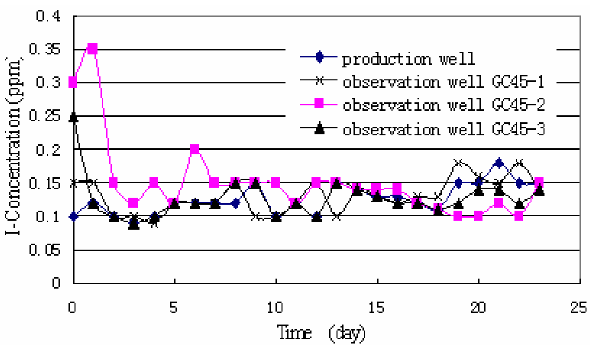

Figure 2 Observed concentration breakthrough curves of the tracer test.

The monitoring data shows that the tracer concentration is almost constant in production wells, in the other hand the observation well GC45-2 is more sensitive to the iodine. It means that the hydro-geological connection between the production and reinjection well of doublet WR45 is indirect, and maybe there is a direct or fast migration channel between the reinjection well and the other geothermal production well, like the production well GC45-1, which is about 2.5 km away from reinjection well. The test results in the well of GC45-2 were simulated by the mathematics model in order to understand the geometry structure of the fracture passage between GC45-2 and reinjection well (See Figure 3 and Table 1).

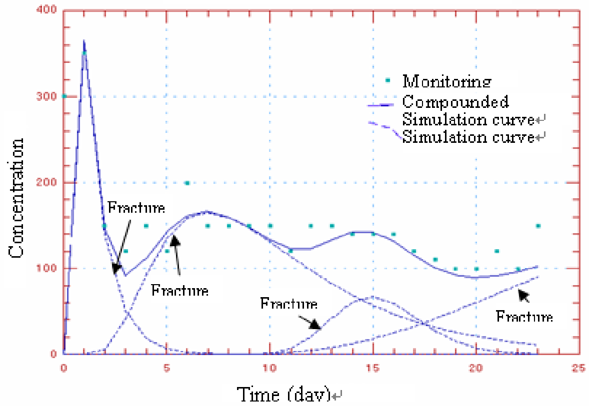

Figure 3 Simulated breakthrough curves compared with the results of the tracer test.

Table 1 Calculated parameter of the tracer test

	Cross section area $A\varphi$	Dispersion α_L	Recovery mass (%)
Fissure 1	1.50	355.50	20.35
Fissure 2	15.74	142.25	38.90
Fissure 3	29.51	10.06	10.27
Fissure 4	54.68	161.38	21.90

Table 1 shows a comparison of the simulation curves and calculation data. One simulation curve compounded by 4 pulse curves is derived from the modelling. When the tracer was injected into the aquifer, it would quickly travel along the most direct/fast pathway, which has the smallest cross section and biggest disparity. Then the tracer would move to the production well quickly and its concentration will reach the maximum value in a very short time. If the reinjection water diffuses into a large space, only a small fraction of the tracer will be detected and the time reach the peak value will be longer. The heat breakthrough time will not be a problem in doublet system if the distance is more available between the production and reinjection well.

Model and Constitutive Equations

The main side effect anticipated from reinjection is a cooling of the reservoir [2]. It is necessary to estimate the thermal breakthrough time for different injection-production well spacing, i.e. the time from initial injection until a significant cooling is observed in a production well [3].

The mass conservation equation

$$\frac{\partial \phi \rho}{\partial t} = \frac{-\partial \phi S \rho_v}{\partial t} + \frac{\partial \phi (1-S)\rho_l}{\partial t} = -\nabla F + q_\rho \quad (1)$$

l = liquid phase; v = vapour phase; F = vector of mass matrix; q_ρ = external energy; ρ = density; ϕ = porosity; S = vapour saturation.

The energy conservation equation (conductivity and convection):

$$\frac{\partial (\frac{Q}{V})}{\partial t} = \frac{\partial (u\rho\phi + u_s \rho_s (1-\phi))}{\partial t} \quad (2)$$

$$= -\nabla G + (\frac{F_v}{\rho_v} + \frac{F_l}{\rho_l})\nabla P + Q_u$$

S = solid phase; u = internal energy; G = energy matrix; Q = energy; V = volume of reservoir; Q_u = external energy.

Set of equations (l) and (2) is related to one or two phase filtration in a porous or fractures medium where rock matrix and fluid are considered to be in local thermal equilibrium. For a block of micro volume Vn of the field, the transfer equation of mass and energy (5) call be interpreted by equations (3) and (4).

$$\frac{\partial \phi \rho}{\partial t} = \sum_{m=1}^{N} \frac{F_m A_m}{\tau} + q \quad (3)$$

$$\frac{\partial u_s}{\partial t} = (\frac{\partial u_s}{\partial t})_\rho \frac{\partial u}{\partial t} + (\frac{\partial u_s}{\partial \rho})_u \frac{\partial \rho}{\partial t} \quad (4)$$

$$\Delta U_n = \Delta t \frac{\frac{1}{V_n}\sum_{m=1}^{N} A_{nm}(G_{nm} - u_n F_{nm}) + (Q_n - Q_n^{'})}{\phi\rho + (1-\phi)\rho_s \{ (\frac{\partial u_s}{\partial u})_\rho + (\frac{\partial u_s}{\partial \rho})_u \frac{\alpha\rho / \partial t}{\partial u / \partial t} \}} \quad (5)$$

At present, the main reinjection math model in Tianjin has been simulated by a program called TOUGH2[4]. The results would be helpful to analyse changing of the temperature field and predict the pressure and temperature alteration later than 10 years in the Wumishan aquifer. Fig 4 is a sketch map of another doublet WR82/83. Considering the heat transfer between the reservoir and the other stratum at the top or bottom, a multi-aquifers model is set up to predict the temperature changes in reservoir during the reinjection test. The parameters used in modelling are listed in Table 2.

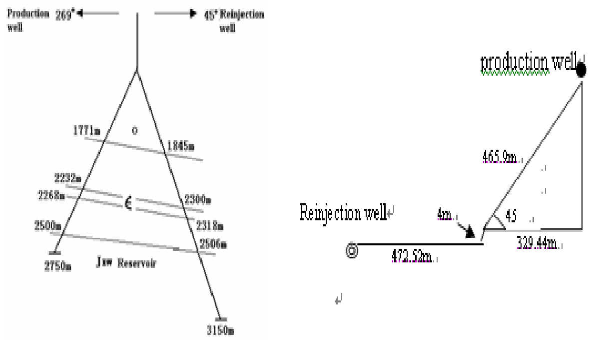

Fig. 4 The Conceptual Model of WR82/83.

Table 2 The parameters in the modelling

Reservoir temperature	87°C
Reservoir thickness	900m
Permeability of aquifer	0.2-200Darcy
Porosity of aquifer	0.03-0.5
Temperature of aquifer	85°C-90°C
Reinjection temperature	30°C
Reinjection/production rate	26.78kg/s
Rock density	2550-2770kg/m3
Heat capacity of reinjection fluid	4100J/kg°C
Density of reinjection fluid	995.62kg/m^3
Specific enthalpy of reinjection fluid	125.7kJ/kg
Specific enthalpy of production fluid	419.1kJ/kg
Reservoir's average heat capacity	1200J/kg°C
Rock specific heat	800-999J/kg°C
Rock heat conductivity	1.9-3.5W/m°C

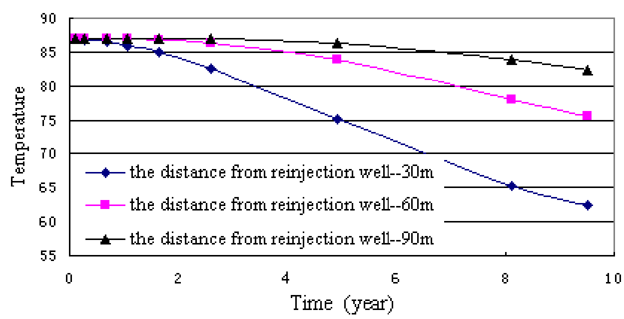

Figure 5 Temperature drawdown curves

The Figure 5 shows the simulation results. It appears that locating reinjection wells at a distance of about 100m from production well should not cause a thermal break-through in less than 10 years. It should be pointed out that the reinjection would only be carried out in wintertime here. The reinjected water will extract more thermal energy from the rock matrix when geothermal wells are shut down in summer, resulting in slower cooling rates. However, the result is highly uncertain because the flow channel dimensions are unknown. So, more tracer tests are recommended in future research.

Summary

An important process in geothermal energy extraction is the gradual cooling of the reservoir by the reinjection fluid when reinjection is involved. The thermal breakthrough time at the production well is related to the geologic structure, hydraulic and thermal properties of the reservoir, and the reinjection rate. If the reinjection water is diluted by a large volume of reservoir fluid then tracer return concentrations will be low and cooling breakthrough is expected to be less problematic.

The reinjected water will receive more thermal energy from the rock matrix when geothermal wells are shut down in summer. This will slow the reservoir cooling process somewhat. Interpretations and predictions regarding reservoir cooling are difficult to make because the geometry of the pore space and major flow channels is the most unknown. Tracer tests provide the best means of characterising reservoir advection and dispersion between injection and production wells and are recommended for estimating the future cooling trends. It is also recommended that long-term monitoring of the Tianjin geothermal field be carried out to detect and record temperature changes caused by reinjection.

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