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Effect of Cycling Reinjection on Geothermal Resource Recovery

**Yu M. Parrisky, Saint Petersburg State Mining Insitute,
St. Petersburg, Russia**

ABSTRACT

Under complicated geological conditions typical for high temperature water dominated geothermal reservoirs reinjection can cause premature cooling of the production area because of the injected water breakthrough. To mitigate this problem we have investigated the theoretical possibilities of the temperature field restoration in the cooled part of the productive zone due to the inflow of hot water into it caused by permanent production while injection is stopped. Developed methods of numerical simulations take into account different conditions of thermal interaction between the productive zone and surrounding formations at each phase of the exploitation cycle including injection and temperature restoration ones. Simulation results show that under definite conditions the duration of the restoration phase can become close to that of the injection what makes the cycling regime of reservoir exploitation with different production rate at each phase of the cycle possible. It was confirmed by the results of numerical simulation carried out for a doublet well system exploiting subvertical fractured zone sited into water dominated high temperature background reservoir.

Introduction

Production of geothermal energy is associated in many cases with the problem of waste water utilization capable to avoid any environmental impact. Underground fluid injection or injection into the same reservoir from which fluid is produced called reinjection has become most widely used practice to solve this problem in many countries. Beside environmentally clean waste disposal reinjection provides full or partial artificial recharge of the fluid reserves and more effective utilization of the reservoir energy resources including heat from the rock matrix. Since that the injection is considered as an important element of the geothermal reservoir development and management. However under complicated geological conditions that are typical for high temperature geothermal reservoirs injection can cause cooling of the production area much earlier than it is planned because of the injected water breakthrough. In this case the temperature or enthalpy of the produced fluid decline, and further production can become ineffective. Cooling due to injection is considered as the most common problem actually experienced or feared in the geothermal industry of the USA (Sanyal, et al, 1995). Most preferable solution of this problem is undoubtedly such that does not require any additional expenditures caused by re-drilling the wells, well spacing change or other serious modifications of the exploitation system. In this connection the investigation of possible ways to restore the temperature field of the productive zone damaged due to injection seems promising.

Model Description

In order to investigate these possibilities the numerical simulation of a hypothetical geothermal reservoir was carried out reflecting some characteristic features of high temperature water- dominated reservoirs. It was assumed that the reservoir (Figure 1) includes two hydrogeological complexes 2 and 4 the upper one of which is characterised by fluid circulation within

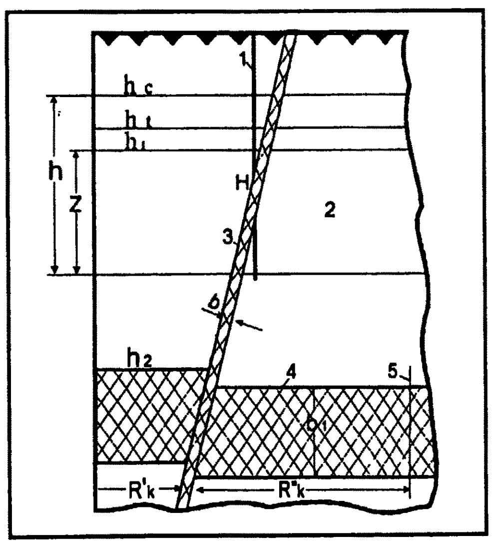

Figure 1. Scheme of hypothetical reservoir model used in numerical simulation.

subvertical fractured zone 3 of relatively small thickness and rather high permeability.

The underlying complex 4 is located at the depth from 3 to 4 km and consists of fractured-porous formations representing the background aquifer. The pressure is controlled by the position of hydrostatic level at the depth *hc (hc =300-600 m)* which depletes to ht when fluid is produced from the production well 1intersecting the fractured zone 3 at the depth H (H=1,500-2,000 m). Temperature is distributed with depth according to hyperbolic relation and ranges from 90°C at the depth hc to about 300°C at the depth of the main aquifer. Fluid withdrawal is accompanied by pressure decline in the aquifer, propagating at the distance R'k and R"k in both directions from the fractured zone 3 up to the line 5 of constant pressure. The upper border of the calculational area is located at the depth h1 which is considered as the reference line to determine relative initial pressure at any point z beneath it

$$Pz=(h - z)\,\rho g = (\eta_1 - h_c)\,\rho g \quad (1)$$

were h is the hydrostatic head at the point z, ρ is the average fluid density. When injection was simulated, it was assumed that the injection well intersects the productive zone 500 m below the production one and 500 m apart from it in horizontal direction. Two- dimensional fluid flow equation was used in the set of basic equations describing the process of exploitation

$$\frac{\partial}{\partial x}\left(\frac{K\rho}{\mu}\frac{\partial p}{\partial x}\right)+\frac{\partial}{\partial y}\left[\frac{K\rho}{\mu}\left(\frac{\partial p}{\partial y}\right)-\alpha_t\rho_0 g(t-t_0)\sin\gamma\right]+ +\frac{Gi}{b}\delta(x_i,y_i)=\frac{Gp}{b}\delta(x_p,y_p) \quad (2)$$

where temperature effect on the fluid density r is accounted by the coefficient of the fluid thermal expansion ατ. This effect can cause thermal convection of the fluid in the fractured zone with the angle of inclination γ=900. G_i and G_p are injection and production mass rates of the fluid respectively related to the effective thickness of the fractured zone b. At each time step of the calculations pressure p and fluid mobility Kρ/μ are considered to be constant that allows to use stationary flow equation. The equation of energy describes the conductive and convective heat transfer in the productive zone as well as the effect of the cooled water injection and thermal interaction of the zone with the surrounding rocks:

$$C_0\frac{\partial t}{\partial \tau}=\lambda_0\left(\frac{\partial^2 t}{\partial x^2}+\frac{\partial^2 t}{\partial y^2}\right)-\rho_w C_w\left(V_x\frac{\partial t}{\partial x}+V_y\frac{\partial t}{\partial y}\right)+ +q_c+q_v\delta(x_i,y_i) \quad (3)$$

where c_0 and λ_0 are heat capacity and heat conductivity coefficients of the productive zone, ρ_w c_w is the specific heat capacity of water per unit volume, v_x and v_y are flow velocities in the direction of the productive zone spreading and dipping respectively, $qv=\rho_w c_w{}^w t_i$ is the heat delivered by the injected water and qc is the amount of heat per unit volume of the productive zone resulted from its thermal interaction with the surrounding rocks. The value of qc is a function of the heat flow between the productive zone and the surrounding rocks and can be expressed as follows

$$q_c=\frac{2\lambda}{b}\frac{\partial T}{\partial z}, \qquad z=0 \quad (4)$$

where λ is the thermal conductivity and ∂T/ ∂z is the rock temperature gradient at the rock-productive zone interface. It must be found from the solution of the heat conduction equation

$$\frac{\partial T}{\partial \tau}=a\frac{\partial^2 T}{\partial z^2} \quad (5)$$

with the following initial and border conditions

$$\tau=0, \qquad T(z,o)=To(H) \quad (6)$$

$$\tau>0,\ z=0, \quad T(0,\tau)=t(x,y,\tau), \qquad z\to 4\sqrt{a\tau} \quad T(z,\tau)=To(H) \quad (7)$$

accounting that the initial temperature of the rock T depends on the depth H and the temperature at the rock-productive zone interface being equal to the local temperature of the fluid t (x, y, t) is changing in time according to cycling regime of reinjection. It seems reasonable to assume that the local temperature in any net block of the calculational area goes through three phases in the process of reservoir exploitation with cycling injection:

- phase of the temperature decline starting at the moment when the local temperature drops below its initial value T_o (H) due to the cooling effect of the injected water and lasting till the injection shut down τ_1;
- phase of relatively stable temperature corresponding to its minimum value attained at the previous phase and lasting till the moment of time τ2;
- phase of the temperature rising (restoration) from the time τ2, when hot water from the main aquifer enters the block till the moment τ3; when the temperature reaches its initial value T_o (H) or becomes even higher.

Taking into account rather limited duration of each phase compared with the whole exploitation period it seems possible to assume linear temperature-time dependence for the phases 1 and 3 that greatly simplifies the solution of the problem (5)-(7). The solution of this problem obtained on the base of these assumptions for the first cycle of exploitation allows to determine the value of q_c as a function of time and local fluid temperature t(x,y,t) as follows:

for the phase 1 ($0 \le \tau \le \tau_1$)

$$q_c=\frac{4}{b}\sqrt{\frac{\lambda\rho c}{\pi\tau}}\left[T_o(H)-t(x,y,\tau)\right] \quad (8)$$

for the phase 2 ($\tau_1 \le \tau \le \tau_2$)

$$q_c=\frac{4}{b}\sqrt{\frac{\lambda\rho c}{\pi\tau}}\left[\left(\tau-\frac{\tau-\tau_1}{\sqrt{1-\tau_1/\tau}}\right)\frac{T_o(H)-t(x,y,\tau_1)}{\tau_1}\right] \quad (9)$$

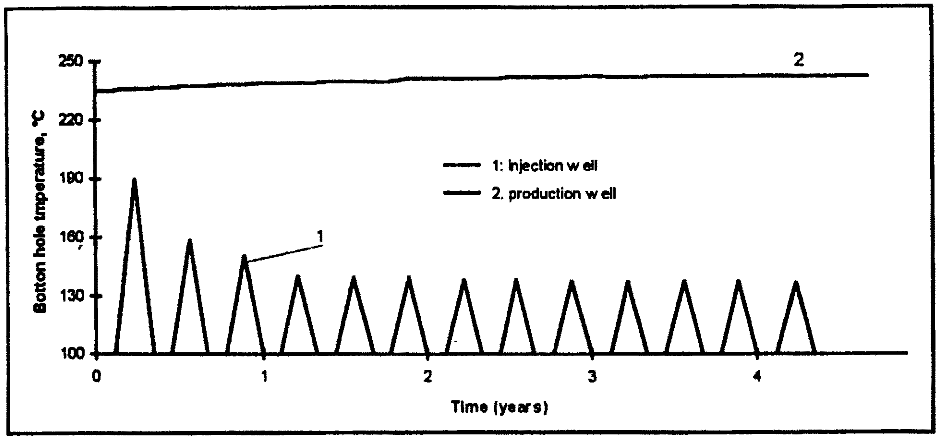

Figure 2. Bottom hole temperature versus time.

for the phase 3 ($\tau_2 \le \tau \le \tau_3$)

$$q_c = \frac{4}{b}\sqrt{\frac{\lambda\rho c}{\pi\tau}}\left[\left(\tau - \frac{\tau-\tau_1}{\sqrt{1-\tau_1/\tau}}\right)\frac{T_0(H)-t(x,y,\tau_1)}{\tau_1} - \frac{t(x,y,\tau)-t(x,y,\tau_1)}{\sqrt{1-\tau_2/\tau}}\right] \qquad (10)$$

Expressions (8)-(10) can be easily implemented into the energy equation (3) according to the particular phase of the simulated cycle. Some difficulties in simulating all the following cycles arise from the fact that the temperature field in the surrounding rocks may not regain its initial state during the phase 3 inspite of almost full restoration of the local fluid temperature. An approximate solution of this problem was found in the use of an average rock temperature of the net block accounting the values of the restored temperatures in it at the previous cycle of exploitation as follows

$$T^{n+1}_{(x,y)} = \frac{T_0(H) + t^{n-1}_{(x,y)} + t^{n}_{(x,y)}}{3} \quad \text{(n=1,2...)} \qquad (11)$$

where n is the number of a cycle $t^{n-1}_{(x,y)}$, $t^{n}_{(x,y)}$, are local temperature values of the fluid at the beginning and at the and of the previous cycle.

Simulation Results

As the results of numerical simulation show the fluid flow to the production well intersecting the fractured zone at the depth H=1,500m when injection is not operated changes from 15 kg/s at the beginning to about 17 kg/s at the stabilised stage of the production with bottom temperature from 230°C to 250°C. Injection of 20 kg/s of 100°C water results in increasing the fluid inflow to 22 kg/s for the first 10 years of production with slow decrease in the following time. Increase the injection rate up to 40 kg/s leads to the increase of production up to about 27 kg/s at the initial stage and then to 22 kg/s after 25 years when bottom temperature still remains higher than 200°C. It should be noted that under simulated conditions the temperature field of the productive zone changes very significantly due to interaction of the reinforced and free thermal convection of the fluid especially when injection is used. But if production is continued after injection shut down the inflow of hot water from the main aquifer results in rather fast temperature increase in the productive zone that leads to the restoration of its energy resource. The result of simulation showed that 60 days after the injection with the rate of 40 kg/s that lasted also 60 days, the cooled area in the productive zone marked by the temperature drop in relation to its initial value not less then 1°C represents not more than 50% of its size at the time of the injection shut down whereas the maximum temperature drop near the injection well restricts from 80 to only 10°C. Based on these results the duration of a cycle in simulating the cycling regime of injection was assumed to be equal to 120 days with the rate of injections 40 kg/s. The result of the simulations have shown that the periodic oscillations of the temperature in the net blocks have the tendency to self-stabilisation which is most clearly demonstrated at the vicinity of the injection well (Figure 2). After several cycles the amplitude of the temperature oscillations stabilizes at constant value and does not anymore depend on time. The same phenomena can be observed in any other net block with the only difference that the temperature amplitude and the duration of its stabilisation are changing from one block to another. It is obvious that the establishment of such a temperature regime gives an evidence of the balanced character of heat exchange between the productive zone and the surrounding formations that results in practically stable average temperature for the cycle. The main difference between cycling and permanent regime of the injection is presented by this possibility to exclude typical for permanent injection temperature decline at the production area. Moreover, sycling injection

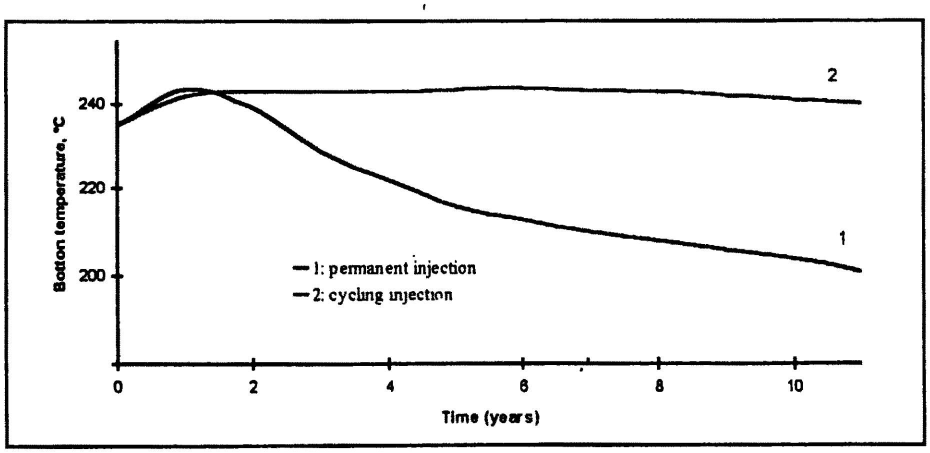

Figure 3. Temperature ar bottom of production well at permanent and cycling injection.

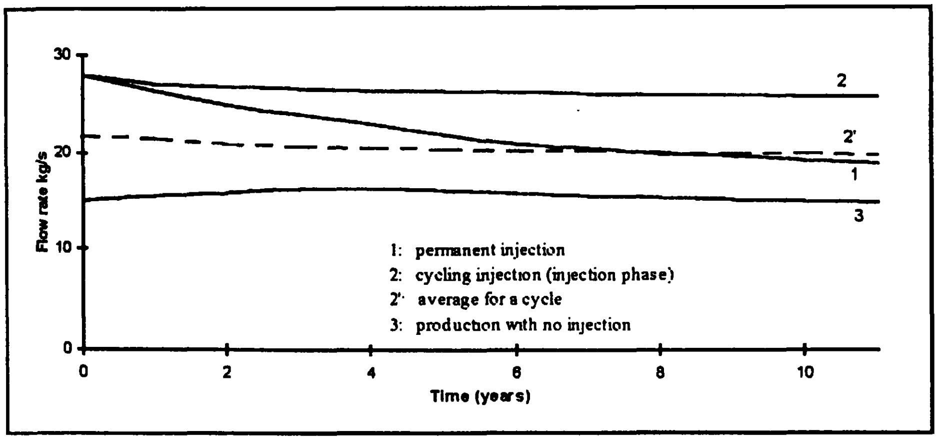

Figure 4. Fluid flow rate to production well depending on method of operation.

leads to the temperature rising at the upper part of the productive zone due to thermal convection effect and pressing out some portion of the hot water from the bottom part of the zone by the injected cooled water at each cycle of the injection. As the result the temperature at the production area not only does not decline but exceeds to some extent its initial value (Figure 3). It is followed by some favourable alterations in the hydraulic resistance to flow in the productive zone that leads to significant increase in the average for the cycle rate of production (Figure 4). At cycling injection the rate of production changes according to the particular phase of the exploitation cycle. At the injection phase it is much higher than at the permanent injection especially at the late period of exploitation. At the temperature restoration phase when injection is terminated the fluid to the production well decreases compared to its value obtainable in the case of permanent production (15 kg/s) because of higher resistance in the most cooled bottom part of the productive zone beneath the injection well. Since that the average for the cycle rate of production is lower than in the permanent injection case at the earlier stage of exploitation, but later becomes higher than that. Never the less the average for the cycle rate of production at any stage is significantly higher than in no injection case (Figure 4).

Discussion and Conclusion

Obtained results show that using both artificial and natural sources of the fluid reserves recharge it is possible under certain conditions to stabilise the fluid parameters at the production area and prevent their decline that is often considered as the main risk of injection. It should be stressed that it does not require any additional operations concerned with the well dislocation, redrilling or other cost increasing works.

There are some field observations confirming the possibility of recovering or even over-recovering the production rate following the injection shut in (Pruess, 1995, Sta et al.,1995). They were considered as unique manifestations of the injection-production interference but as it is seen now they actually reflect very fundamental processes of geothermal resource recovery.

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