# A GEOTHERMAL RESERVOIR SIMULATION FOR A COMPLEX MODEL

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## ABSTRACT

Using a complex model consisting of lumped-parameter reservoirs and a fault zone, all connected by aquifers, a geothermal reservoir simulation was carried out by changing the permeability of the aquifer. The results indicate that the permeability has a considerable effect on mutual interferences among reservoirs.

### Symbols

A thermal equivalent of work, $kJ/m^3MPa$
C specific heat, kJ/kg °C
c compressibility, 1/MPa
F seepage area, $m^2$
G mass change, kg
h enthalpy, kJ/kg
L aquifer length, m
P pressure, MPa
S saturation
t time, hr
u internal energy, kJ/kg
V reservoir volume, $m^3$
v specific volume, $m^3/kg$
W mass of fluid, kg
x distance, m
density, $kg/m^3$
θ temperature, °C
ø porosity

Subscripts

w water
s steam

Superscripts

m' state just after end of outflow
m mth step

## INTRODUCTION

In the planning stages of development of a new reservoir within, or adjacent to, already developing fields, one of the most important tasks is to estimate the effects of the new development on the existing production wells. In order to obtain basic data on mutual interferences among reservoirs, the changes in pressure and temperature of each reservoir with time are predicted for a complex model consisting of the reservoirs and the fault zone, changing only two permeabilities of the aquifer.

## BASIC MODEL

The basic model for the simulation of geothermal reservoirs is shown in figure 1. The model consists of three lumped-parameter reservoirs, and a fault zone, where compressed water is supplied. The reservoirs and the fault zone are connected in series by aquifers having the same scale and parameters. In addition, the followin assumptions are made:

1. Surface discharge is negligible.
2. Combined production rate (water and steam) from one reservoir is constant.
3. Pressure and temperature at the fault zone are equal to the initial condition and are kept constant.
4. After the extraction of steam, water is reinjected into the original reservoir.

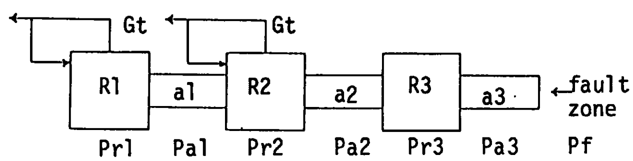


Figure 1 Basic model

## THEORY

When production from a reservoir, for example, R1, starts, due to the substantial pressure drop, the compressed water in the adjacent aquifer, a1, begins to flow into R1 at a rate proportional to the pressure gradient at the boundary between R1 and a1, increasing the pressure of R1. Then, due to the water outflow, the pressure distribution of a1 changes and the water flows out of the reservoir R2 into a1, at a rate proportional to the pressure gradient at the boundary between a1 and R2, as decreasing the pressure of R2. Similar phenomena occur in the other reservoirs and aquifers. That is, an outflow from a reservoir and an inflow from an aquifer adjacent to the reservoir occur simultaneously. However, it is impossible to solve the differential equation considering both outflow and inflow at the same time. Therefore, to deal with this problem, the outflow and the inflow are considered as a series of short time outflows and inflows occuring alternately.

Basic equation

1. Aquifer pressure

The basic equation for linear flow is

$$\frac{\partial Pa}{\partial t}=\alpha\frac{\partial^2 Pa}{\partial \chi^2} \quad (1)$$

where

$$\alpha=\frac{k}{\phi\mu C}$$

At the first step $\Delta t$, when the geothermal fluid is discharged from R1 and R2, for example, and the pressures drop to $P'_{r1}$ and $P'_{r2}$ respectively, the pressure distribution $P'_{a1}$ in a1 will be

$$P'_{a1}=Pr_1'+(Pr_2'-Pr_1')\frac{\chi}{L}+\frac{2}{\pi}\sum_{n=1}^{\infty}\frac{1}{n}\{(Pr_2'-Pf)\cos n\pi+(Pf-Pr_1')\}\times\sin\frac{n\pi}{L}\chi\cdot e^{-\frac{n^2\pi^2}{L^2}at} \quad (2)$$

Then, at the mth step

$$\begin{aligned}Pa=&P_1^{m'}+(P_2^{m'}-P_1^{m'})\frac{\chi}{L}\\&+\frac{2}{\pi}\sum_1^{\infty}\frac{1}{n}[(P_2^{m'}-P_2^{m-1})\cos n\pi+(P_1^{m-1}-P_1^{m'})\\&\times\sin\frac{n\pi}{L}\chi\cdot e^{-\frac{n^2\pi^2}{L^2}\alpha\{t-(m-1)\Delta t\}}\\&+\frac{2}{\pi}\sum_1^{\infty}\frac{1}{n}[(P_2^{m-1}-P_2^{m-2})\cos n\pi+(P^{m-2}-P_1^{m-1})\\&\times\sin\frac{n\pi}{L}\chi\cdot e^{-\frac{n^2\pi^2}{L^2}\alpha\{t-(m-2)\Delta t\}}]\\&\vdots\\&+\frac{2}{\pi}\sum_1^{\infty}\frac{1}{n}[(P_2^{1}-Pf)\cos n\pi+(Pf-P_1^{1})\\&\times\sin\frac{n\pi}{L}\chi\cdot e^{-\frac{n^2\pi^2}{L^2}\alpha t\}}]\end{aligned} \quad (3)$$

where the primed variables, $P'_{r1}$ and $P'_{r2}$, and the unprimed variables, $P_{r1}$ and $P_{r2}$, refer to the states just after the end of the outflow and the inflow, respectively. The outflow and inflow for $m\Delta t-(m-1)\Delta t$ can be given by

$$G_1^m-G_1^{m-1}=F\cdot\gamma\frac{k}{\mu}\int_{(m-1)\Delta t}^{m\Delta t}\frac{\partial Pa}{\partial\chi}\Big|_{x=0}dt$$

$$G_2^m-G_2^{m-1}=F\cdot\gamma\frac{k}{\mu}\int_{(m-1)\Delta t}^{m\Delta t}\frac{\partial Pa}{\partial\chi}\Big|_{x=L}dt$$

where $\gamma$ is the fluid density.

For the two phase flow, the diffusivity can be expressed as

$$a=\frac{k}{\phi\mu tc}$$

where

$$\frac{1}{\mu_t}=\frac{k_{rs}}{\mu_s}+\frac{k_{rw}}{\mu_w}$$

$$\phi c=[(1-\phi)\gamma rCr+\phi S\gamma wCw]\times(1.92\times10^{-2.66}\times P^{-1.66})$$

where $\gamma_r$ and $C_r$ are the density and the specific heat of rock[ Grant et al, 1979 ], and

$$S=\frac{\gamma s(hs-h)}{\gamma s(hs-h)+\gamma w(h-hw)}$$

krw and krs are calculated using Corey's equation.

2. Reservoir pressure

Mass and energy balance equations for any of the reservoirs can be written as

$$\frac{d}{dt}\{G_1(t)+G_2(t)\}=\frac{dW}{dt} \quad (5)$$

and

$$\frac{d}{dt}\{h_1G_1(t)+h_2G_2(t)\}=\frac{dWu}{dt}+(1-\phi)Vo\gamma r\cdot Cr\frac{d\theta}{dt} \quad (6)$$

The temperature $\theta$ for the compressed condition is derived from the above equations(see Appendix):

$$\theta=[C_{m-1}+\frac{B_{m-1}+C_{m-1}A_{m-1}N_{m-1}}{N_{m-1}\{G+N_{m-1}-A_{m-1}\}}]G+[1-\frac{A_{m-1}G}{N_{m-1}\{G+N_{m-1}-A_{m-1}\}}]\theta_{m-1} \quad (7)$$

where $G=(G_1-G_1^{m-1})+(G_2-G_2^{m-1})$.

and the pressure P can be calculated by

$$\begin{aligned}P=&(9.638698\times10^{-3}\underline{\theta}^5-1.219126563\underline{\theta}^4\\&+61.33767183\underline{\theta}^3-1536.270868\underline{\theta}^2\\&+19254.35436\underline{\theta}-98062.26)\times10^3v\\&-(1.1746563\times10^{-2}\underline{\theta}^5-1.485916992\underline{\theta}^4\\&+74.77054795\underline{\theta}^3-1871.898574\underline{\theta}^2)\\&+23412.66535\underline{\theta}-118656.8748)\end{aligned} \quad (8)$$

where $\underline{\theta}=\theta/10$[ Fukuda et al. 1985 ].

The mass change G(t) for the saturated condition is also derived from the same equations(see Appendix):

$$G=\frac{1}{(1+p)^{0.236}-L_{m-1}}[\frac{H_{m-1}\{(1+p)^{0.866}-1\}}{0.866}+\frac{I_{m-1}\{(1+p)^{0.236}-1\}}{0.236}+\frac{J_{m-1}\{(1+p)^{0.238}-1\}}{0.238}\} \quad (9)$$

where $(p+1)=P/P_{m-1}$.

The temperature $\theta$ at the pressure P is given by

$$\theta=179.8890\,P^{0.238} \quad (10)$$

## CALCULATIONS

The following is an example of the calculation procedures and variables to be calculated:

1. The first step
   i. Pressure of R1, $P_{r1}^{1}$, a short time $\Delta t$ after the beginning of production.
   ii. Pressure distribution change, $P_{a1}^{1}$, in a1.
   iii. Water inflow, $G_{a1}^{+1}$, from a1 to R1 at the boundary between a1 and R1, and water inflow, $G_{a2}^{-1}$, from R2 to a1 at the boundary between R2 and a1.
   iv. $P_{r1}^{1}$ after inflow, $G_{a1}^{+1}$, with $P_{r1}^{1}$ being the initial pressure, and $P_{r2}^{1}$ after the outflow, $G_{a2}^{-1}$.
   v. $P_{r2}^{1}$ and $P_{r3}^{1}$ by similar calculation.
   vi. $P_{a1}^{1}$, $P_{a2}^{1}$ and $P_{a3}^{1}$, with $P_{r1}^{1}$, $P_{r2}^{1}$, $P_{r3}^{1}$ and $P_f$ being the boundary pressures.
2. The second step
   $P_{r1}^{2}$, $P_{r2}^{2}$, $P_{r3}^{2}$, $P_{a1}^{2}$, $P_{a2}^{2}$ and $P_{a3}^{2}$ for next $\Delta t$ by following similar procedures as with the first step, starting with $P_{r1}^{1}$, $P_{r2}^{1}$, $P_{r3}^{1}$, $P_{a1}^{1}$, $P_{a2}^{1}$ and $P_{a3}^{1}$ as the initial conditions.

For further steps, repeat the above calculations by shifting the intial conditions.

Calculations were made with the following parameters and conditions

Reservoir
volume of each reservoir $1x10^8$ $m^3$
porosity 0.1

Aquifer
length of each aquifer 500 m
porosity 0.05
permeability $3.77x10^{-14}$ and $3.77x10^{-13}$ $m^2$
seepage area $1x10^4$ $m^2$

Others
combined flow rate (water and steam) $5x10^5$ kg/hr
initial temperature 280 °C
initial pressure 8 MPa
reinjection temperature 90 °C
time interval 10 hrs

For one simulation, production from two reservoirs was considered as starting simultaneously, and for the another, with a time lag of $5x10^3$ hours between the two.

## RESULTS AND CONSIDERATIONS

Some examples of the results of the calculations are shown in figures 2 ~ 5.

The pressures of the producing reservoirs show steep drops in the compressed water condition, and comparatively gentle drops in the saturated codition. While, the temperatures show smooth-curved drops in the both conditions. The compressibility of the water is so small that even a small mass decrease in the reservoir, i.e. density decrease, causes a steep pressure drop, and the pressure in the saturated condition does not drop so steeply, due to the volumetric expansion, as that in the compressed water condition. The heat extraction due to the production from a reservoir does not have so large effect on the temperature drop because of the heat supply from the reservoir rock, but the low temperature reinjection ( 90 °C ) lowers the temperature ( compare with figure 4 or 5 ).

Figures 2 and 3 show the results when prodution from R1 and R3 was considered as starting simultaneously, changing the permeability of the aquifer, $3.77x10^{-14}$ and $3.77x10^{-13}$ $m^2$. As seen in figure 2, the pressure drop of R3 is a little gentler than R1 because the inflow to R1 is only from R2, and to R3 is from R2 and the fault zone. In figure 3, because of more rich permeability of the aquifer and consequent larger supply, the pressure drops of R1 and R3 are much gentler than those in figure 2, and though R3 is producing, its pressure is higher than that of R2 which is not producing, and changes without dropping to the saturated pressure. The temperature of R1 in figure 3 shows a little gentler drop than figure 2, but R3 shows similar drop in both figures. The pressure of R2 keeps constant in figure 2 and drops a little in figure 3. Figures 4 and 5 show cases where the production of R3 starts $5x10^3$ hours after the start of production of R1, and R2 starts the same hours after R1. As seen in these figures, the pressures of R2 and R3 drop together with the pressure drop of R1, and after the production of the second reservoir starts, the pressure of the third reservoir which is not producing, begins to drop. The pressure of R2 in fugure 4 drops steeper than the pressure of R3 in figure 5, because the fluid flows out of R2 to R1 and R3 in figure 4, and the fluid flows out of R3 to R2 only in figure 5, with the inflow from the fault.

## CONCLUSIONS

The results of the above calculations made for a simple model, using only two permeabilities of the aquifer, indicate that the permeability has a considerable effect on mutual interferences among reservoirs. But the sensitivity studies of the mutual interferences on the other parameters, such as the porosity, the reservoir volume, the aquifer scale, the production rate and so on have to be made.

## REFERENCES


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The compressibility and hydraulic diffusivity of a water-steam flow, Water Resources Research, Vol. 15, No.3, pp 684-686

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A prediction method of geothermal reservoir temperature and pressure changes, Geothermal Resources Council Transactions, Vol.9, Part 11, pp503-506


## Appendix

Writing an outflow(or a mass decrease due to the production) of and an inflow (or a mass increase due to the reinjection) to a reservoir, as $G_1(t)$ and $G_2(t)$, respectively, and also writing

$$h_1G_1 + h_2G_2 = ( G_1 + G_2 )h_{mix}$$

in the equation 6, and a mass change, G, for t-(m-1) $\Delta t$ as

$$G = (G_1 - G_1^{m-1}) + (G_2 - G_2^{m-1})$$

equation 7 can be obtained from the equations 5 and 6 in the same way with that in a previous paper [Fukuda et al. 1985]. The constants in the equation 7 are as follows:

$$A_{m-1} = \phi V \frac{2582.5715 \times 10^3}{(1-\phi)\gamma_r C_r + 5776.9661}$$

$$B_{m-1} = \phi V \frac{508053.5620 \times 10^3}{(1-\phi)\gamma_r C_r + 5776.9661}$$

$$C_{m-1} = \phi V \frac{h_{mix}}{(1-\phi)\gamma_r C_r + 5776.9661}$$

$$N_{m-1} = \frac{\phi V}{v_{m-1}}$$

The equation 9 can be derived, also, from the equations 5 and 6 in the same manner with that in the previous paper. The constants in the equation are as follows:

$$H_{m-1} = \phi V \frac{-P_{m-1}\left\{\frac{d}{dp}\left(\frac{h_s - h_w}{v_s - v_w}\right) - A\right\}_{m-1}}{\left(\frac{h_w v_s - h_s v_w}{v_s - v_w}\right)_{m-1}}$$

$$I_{m-1} = \phi V \frac{1}{v_{m-1}} \frac{-P_{m-1}\left\{\frac{d}{dp}\left(\frac{h_w v_s - h_s v_w}{v_s - v_w}\right)\right\}_{m-1}}{\left(\frac{h_w v_s - h_s v_w}{v_s - v_w}\right)_{m-1}}$$

$$J_{m-1} = \phi V (1-\phi)\gamma_r C_r \frac{-P_{m-1}\left(\frac{d\theta}{dp}\right)_{m-1}}{\left(\frac{h_w v_s - h_s v_w}{v_s - v_w}\right)_{m-1}}$$

$$L_{m-1} = \frac{h_{mix}}{\left(\frac{h_w v_s - h_s v_w}{v_s - v_w}\right)_{m-1}}$$

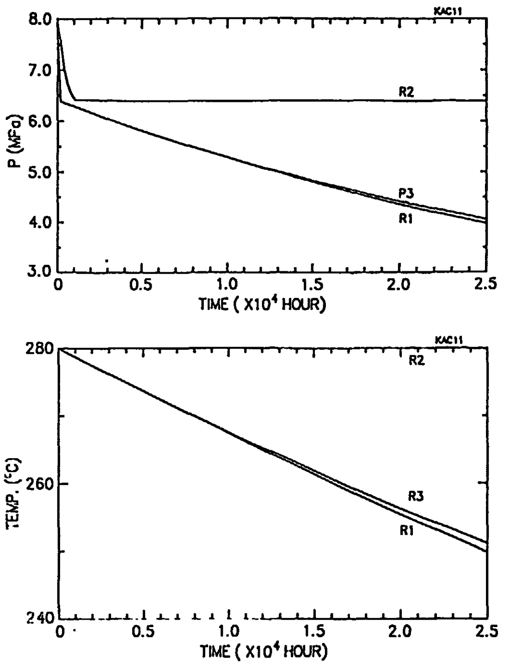


Figure 2 k=3.77x10$^{-14}$ m$^2$
production from R1 and R3 with reinjection

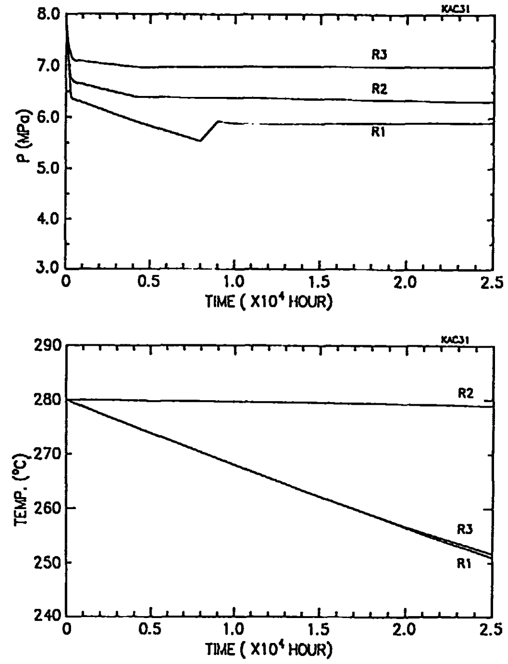


Figure 3 k=3.77x10$^{-13}$ m$^2$
production from R1 and R3 with reinjection

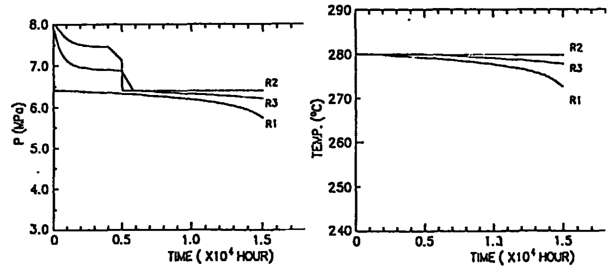


Figure 4 k=3.77x10$^{-14}$ m$^2$
production from R1 and R3 with a time lag and without reinjection

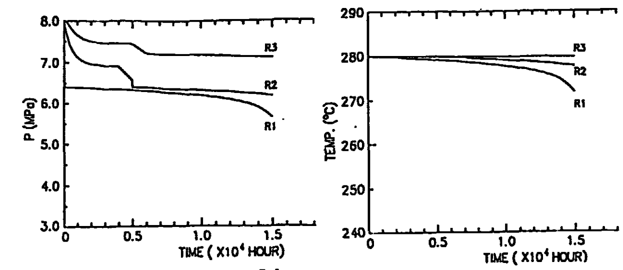


Figure 5 k=3.77x10$^{-14}$ m$^2$
porduction from R1 and R2 with a time lag and without reinjection