MUTUAL INTERFERENCES AMONG RESERVOIRS FOR A COMPLEX MODEL

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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 lumped-parameter reservoirs and a fault zone, with and without reinjection, and changing only two permeabilities of the aquifers.

Symbols used in this paper are as follows:
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), γ density (kg/m^3), θ temperature (°C), ϕ porosity (-)
Subscripts: w water, s steam, Superscripts: m' state just after end of outflow, m mth step.

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 following assumptions are made:
1. Surface discharge is negligible.
2. Combined production rate (water and steam), Gt, from one reservoir is constant.
3. Pressure and temperature at the fault zone are equal to the initial condition and are kept constant.
4. In the case of considering reinjection, separated water is reinjected into the original reservoir.

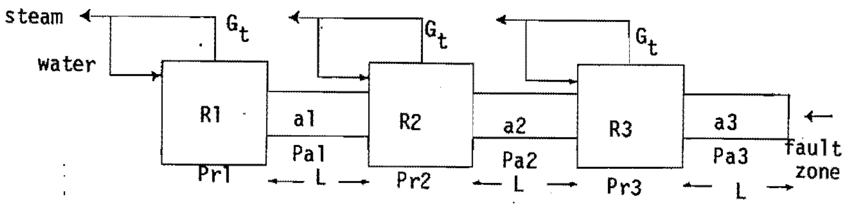

Figure 1. Basic model

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, thus decreasing 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 altenately.

i) Aquifer pressure

The basic equation for a linear flow is

$$\frac{\partial P_a}{\partial t}=\alpha\frac{\partial^2 P_a}{\partial \chi^2} \qquad (1)$$

where

$$\alpha=\frac{k}{\phi\mu c} \qquad (2)$$

for one phase (water) flow. Introducing a time step Δt, eq.(1) can be solved, and flow rates at the boundaries x=0 and x=L can be given by

$$G_1-G_1^{m-1}=F\cdot\gamma\frac{k}{\mu}\int_{(m-1)\Delta t}^{t}\left.\frac{\partial P_a}{\partial \chi}\right|_{x=0}dt \quad \text{and} \quad G_2-G_2^{m-1}=F\cdot\gamma\frac{k}{\mu}\int_{(m-1)\Delta t}^{t}\left.\frac{\partial P_a}{\partial \chi}\right|_{x=L}dt \qquad (3)$$

respectively.

For two phase flow, the diffusivity can be expressed as

$$a = \frac{k}{\phi \mu_t c} \qquad (4)$$

where

$$\frac{1}{\mu_t} = \frac{krs}{\mu_s} + \frac{krw}{\mu_w} \qquad (5)$$

and

$$\phi c = [(1-\phi)\gamma_r C_r + \phi S \gamma_w C_w] \times (1.92\times10^{-2.66} \times P^{-1.66}) \qquad (6)$$

where γ_r and C_r are the density and the specific heat of rock [Grant et al., 1979], and

$$S = \frac{\gamma_s(h_s - h)}{\gamma_s(h_s - h) + \gamma_w(h - h_w)} \qquad (7)$$

krw and krs are calculated using Corey's equation.

ii) <u>Reservoir pressure</u>

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

$$\frac{d}{dt}\{G_1(t) + G_2(t)\} = \frac{dW}{dt} \qquad (8)$$

and

$$\frac{d}{dt}\{h_1 G_1(t) + h_2 G_2(t)\} = \frac{dW_u}{dt} + (1-\phi)V \cdot \gamma_r \cdot C_r \frac{d\theta}{dt} \qquad (9)$$

where G_1 and G_2 are fluid discharge and recharge respectively. The temperature θ for the compressed condition is derived from the above equations [Fukuda et al., 1985]:

$$\theta = \left[C_{m-1} + \frac{B_{m-1} + C_{m-1} A_{m-1} N_{m-1}}{N_{m-1}\{G + N_{m-1} - A_{m-1}\}} \right] G + \left[1 - \frac{A_{m-1} G}{N_{m-1}\{G + N_{m-1} - A_{m-1}\}} \right] \theta^{m-1} \qquad (10)$$

where $G=(G_1-G_1^{m-1})+(G_2-G_2^{m-1})$ is a mass change for t-(m-1)Δt, and the pressure, P, at the temperature, θ, can be calculated by

$$P = (9.638698\times10^{-3}\underline{\theta}^5 - 1.219126563\underline{\theta}^4 + 61.33767183\underline{\theta}^3 - 1536.270868\underline{\theta}^2 + 19254.35436\underline{\theta} - 98062.26)\times10^3 v$$
$$-(1.1746563\times10^{-2}\underline{\theta}^5 - 1.485916992\underline{\theta}^4 + 74.77054795\underline{\theta}^3 - 1871.898574\underline{\theta}^2 + 23412.66535\underline{\theta} - 118656.8748) \qquad (11)$$

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

The mass change, G, for the saturated condition is also derived from the same equations as:

$$G = \frac{1}{(1+p)^{0.236} - L_{m-1}} \left[\frac{H_{m-1}\{(1+p)^{0.866} - 1\}}{0.866} + \frac{I_{m-1}\{(1+p)^{0.236} - 1\}}{0.236} + \frac{J_{m-1}\{(1+p)^{0.238} - 1\}}{0.238} \right] \qquad (12)$$

where $(p+1)=P/P_{m-1}$. The temperature, θ, at the pressure, P, is given by

$$\theta = 179.8890\, P^{0.238} \qquad (13)$$

Taking a case of production from R1 only, calculation procedures and variables to be calculated are as follows:

1. <u>The first step</u>
   - i. Pressure of R1, $P_{r1}^{1'}$, a short time Δt after the beginning of production.
   - ii. Pressure distribution change, P_{a1}^{1}, in a1.
   - iii. Water inflow, G_{a1}^{+1}, fromal to R1 at the boundary between a1 and R1, and water inflow, G_{a2}^{-1}, from R2 to aq 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_{a3}^{1} and P_f being the boundary pressures.
2. <u>The second step</u>

   P_{r1}^{2}, P_{r2}^{2}, P_{r3}^{2}, P_{a1}^{2}, P_{a2}^{2} and P_{a3}^{2} for next Δt by the similar procedures 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 initial conditions.

Calculations were carried out with following parameters and conditions:

<u>Reservoir</u>

volume of each reservoir 1×10^8 m^3, porosity 0.1

<u>Aquifer</u>

length of each aquifer 500 m, porosity 0.05, permeabilities 3.77×10^{-13} and 3.77×10^{-14} m^2, seepage area 1×10^4 m^2

Other conditions

combines flow rate (water + steam) 5×10^5 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 5×10^3 hours between the two.

Some examples of the results of the calculations are shown in figures 2~5. The pressure of the producing reservoirs show steep drops in the compressed water condition, and comparatively gentle drops in the saturated condition. 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 lowers the temperature (compare with figure 4 or 5).

Figures 2 and 3 show the results when productions from R1 and R3 were considered as starting ing simultaneously, changing permeability of the aquifer, 3.77×10^{-14} and 3.77×10^{-13} m^2. As seen in figure 2, the pressure drop of R3 is a little gentler than that of 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 fluid 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 the 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 5×10^3 hours after the start of production of R1, and R2 starts the same hours after R1 respectively. 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 which is not producing, begins to drop. The pressure of R2 in figure 4 drops steeper than that of R3 in figure 5, because the fluid flows out of R2 to R1 and R3 in figure 4, and the fluid flows of R3 to R2 only in figure 5, with the inflow from the fault zone.

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

Grant, M. A. and Sorey, M. L. 1979
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, pp 503-506

Coefficients in eqs.(10) and (12).

$$A_{m-1} = \phi V \frac{2582.5715\times10^3}{(1-\phi)\gamma_r C_r + 5776.9661}$$

$$B_{m-1} = \phi V \frac{508053.5620\times10^3}{(1-\phi)\gamma_r C_r + 5776.9661}$$

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

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

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

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

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

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

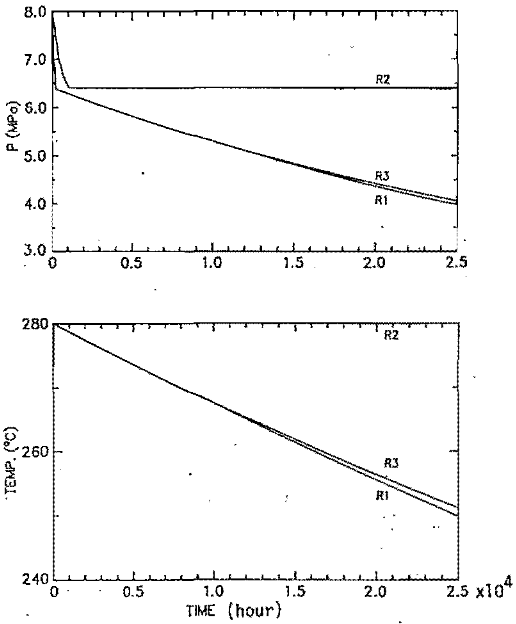

Figure 2 $k=3.77\times10^{-14}$ m^2

Production from R1 and R3 with reinjection

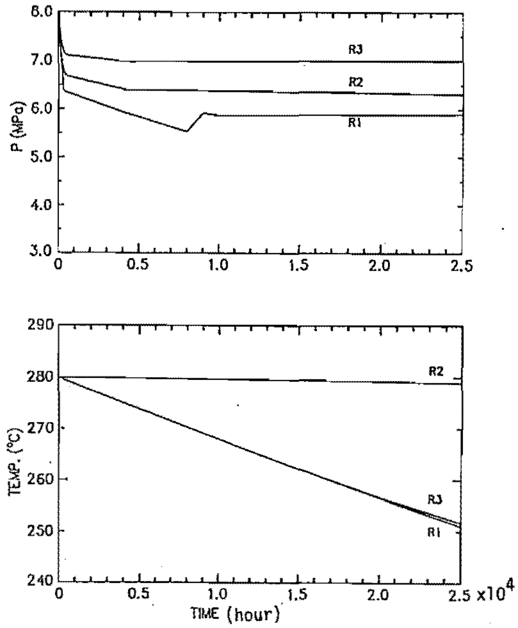

Figure 3 $k=3.77\times10^{-13}$ m^2

Production from R1 and R3 with reinjection

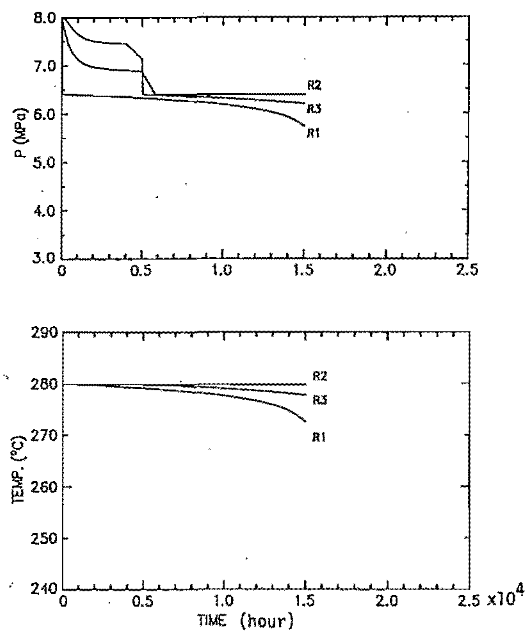

Figure 4 $k=3.77\times10^{-14}$ m^2

Production from R1 and R3 with a time lag and without reinjection

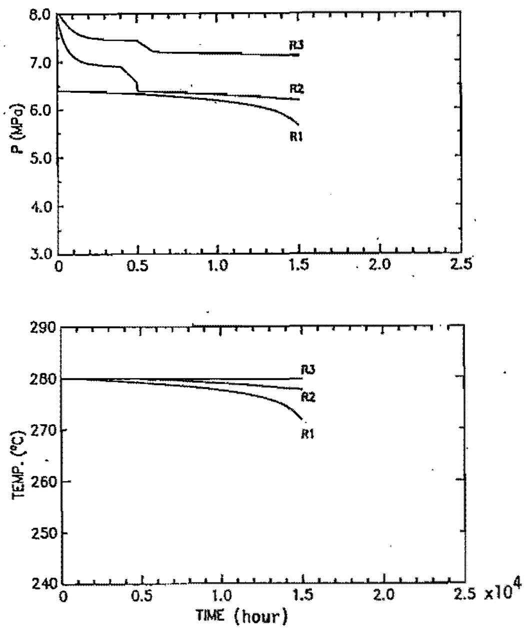

Figure 5 $k=3.77\times10^{-13}$ m^2

Production from R1 and R2 with a time lag and without reinjection