MODELLING STUDIES OF INJECTION CAPACITY DECLINE CAUSED BY SILICA DEPOSITION IN SOME REINJECTION WELLS IN TONGONAN, PHILIPPINES AND OTAKE, JAPAN

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ABSTRACT. Mathematical models of silica deposition are derived using the method of characteristics for the problem of constant and variable rate injection into a well producing radially symmetric flow. Solutions are developed using the first order rate equation of silica precipitation suggested by Rimstidt and Barnes (1980). The changes in porosity and permeability resulting from deposition are included in the models. The models developed are successfully applied in simulating the changes in injection capacity of some of the reinjection wells in Tongonan geothermal field, Philippines and Otake, Japan.

1. INTRODUCTION

The transport of chemicals in hot water reservoir has received considerable attention because of its importance in the development of the geothermal resource. One of the problems associated in using hot water from the reservoir is the inevitable deposition of chemicals as exploitation proceeds. Deposition or scaling occurs not only in the bores and surface equipment but also in the immediate vicinity of the wellbore. These scales composed of silica, calcite or anhydrite are encountered in exploited reservoirs throughout the world. Silica in its amorphous form heads the list of the problem precipitates associated with the reinjection of waste water. Deposition of silica around the wellbore causes reduction in formation permeability and subsequently the injectivity of the well (Hauksson and Gudmundsson, 1986; Sarmiento, 1986; Itoi et al., 1987a; Itoi et al., 1989).

Malate and O'Sullivan (1988) presented mathematical models to describe silica transport and deposition in geothermal reservoirs. In particular, they derived analytic solutions for the idealised problem of isothermal constant rate injection into a one-dimensional channel or into a uniform layer from a well, producing radially symmetric flow. They used several forms of kinetic models of silica deposition and solved the problem using the method of characteristics. The changes in porosity and permeability resulting from deposition were included in their models.

Here, the radial flow model is extended to analyse the non-isothermal problem of injection of a silica-rich fluid into reservoir of a different temperature. This process is of great significance to the problem of reinjection into geothermal reservoirs, because the reinjected water is usually at a different temperature to the receiving reservoir. The thermal processes significantly change the rate of precipitation or dissolution of silica which affect the permeability and porosity of the reservoir rock.

The governing equation used is the same as for isothermal flow namely a standard chemical transport equation that includes a reaction term describing the deposition of silica. The first order rate equation of Rimstidt and Barnes (1980) is used to represent silica precipitation. For non-isothermal flow, this equation is coupled to an energy equation. Analytic solutions are also derived using the method of characteristics and the models are validated to some reinjection field experiments in Otake geothermal field Japan.

In general, field experiments are conducted at constant pressure and not constant flow rate. The experiments have often produced significant decline in injection capacity of reinjection wells in geothermal reservoirs. Unfortunately, no analytic solution is available for the variable flow rate problem. In this paper, a quasi-analytic solution is also presented for the isothermal variable flow rate case. The first order rate equation is also used to represent silica deposition. The model derived is applied to simulate the changes in injectivity of some reinjection wells in Tongonan geothermal field in the Philippines.

2. CONSTANT FLOW RATE MODEL

For the constant radial flow model, the governing equation used also represent conservation of mass, momentum, chemicals and energy (Malate and O'Sullivan, 1988). The same basic assumptions used in the isothermal case of injection have also been employed. For single phase flow, mass conservation gives

$$\frac{\partial (\rho \phi)}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r}(rQ_m) = 0 \tag{1}$$

where \(r\) is the radius, \(Q_m\) is the radial mass flux, \(\phi\) is the porosity and \(\rho\) is the density of the fluid.

Then Darcy's law gives for horizontal flow,
where $v_l$ is the kinematic viscosity of the fluid and $k$ is the permeability of the rock matrix.

The equation for conservation of energy is

$$\left(\phi \rho c_p + (1-\phi) \rho_r c_r\right) \frac{\partial T}{\partial t} + Q_{\text{mv}} \frac{\partial T}{\partial r} = K \frac{\partial^2 T}{\partial r^2} \tag{3}$$

where $T$ is the temperature of the fluid; $\rho_r$, $c_r$ are the density and specific heat of the rock matrix respectively and $K$ is the thermal conductivity.

The silica mass balance equation is given by

$$\frac{\partial (\phi \rho \phi' C)}{\partial t} + \frac{1}{r} \frac{\partial}{\partial r} \left( r Q_{\text{mv}} C \right) = D \left( \frac{1}{r} \frac{\partial}{\partial r} \left( r \frac{\partial C}{\partial r} \right) \right) - \text{Re} \phi \phi_l \tag{4}$$

where $C$ is the mass fraction of silica in the fluid, $D$ is the diffusion coefficient and the reaction term $\text{Re} \phi$ represents the net loss of dissolved silica per unit mass of fluid.

The rock mass balance equation is

$$\frac{\partial (1-\phi) \rho_r Q_r}{\partial t} = \text{Re} \phi \phi_l \tag{5}$$

where $Q_r$ is the mass fraction of silica in the rock.

By neglecting the diffusion term in (4), the radial flow model reduces to a hyperbolic equation

$$\frac{\partial C}{\partial t} + V_r \frac{\partial C}{\partial r} = -\text{Re}$$

where $V_r$ is the radial flow in $\text{m}^2/\text{s}$ defined by $V_r = \frac{r Q_{\text{mv}}}{\phi \phi_l}$.

Using the first order rate equation (Rimstidt and Barnes, 1980) the silica transport equation is given by

$$\frac{\partial C}{\partial t} + V_r \frac{\partial C}{\partial r} = -k(C-C_r) \tag{7}$$

where $k = k^* \left( \frac{A}{M} \right)$.

Here $A/M$ is the ratio of the surface area to the mass of water available and $k^*$ is the precipitation rate constant given by

$$\log k^* = -0.707 - \frac{2508}{T_K} \tag{8}$$

where $T_K$ is in $^\circ \text{K}$.

The problem considered here involves the injection of water, supersaturated with silica into a confined layer initially in chemical equilibrium with silica previously deposited in the porous medium. Thus the relevant initial and boundary conditions are

$$C(r,0) = C_s \quad \text{and} \quad C(0,t) = C_1$$

where $C_1$ is the mass fraction of silica in the water injected and $C_s$ is the silica saturation concentration.

For the case of isothermal constant flow rate injection, analytic solutions to the silica transport equation have been obtained by Malate and O'Sullivan (1988) using the method of characteristics. The silica concentration is given by

$$C(r,t) = C_s + (C_1-C_s) \exp \frac{-kr^2}{2V_r t} \quad \text{for} \quad \frac{r^2}{2} < V_r t \tag{9}$$

and

$$C(r,t) = C_s \quad \text{for} \quad \frac{r^2}{2} \geq V_r t \tag{10}$$

Assuming the thermal conductivity $K$ to be negligible, the energy equation (3) also reduces to a hyperbolic equation

$$\frac{\partial T}{\partial t} + U_r \frac{\partial T}{\partial r} = 0 \tag{11}$$

where $U_r$ is the thermal front velocity given by

$$U_r = \frac{Q_{\text{mv}} t}{\phi \rho \phi_l} \tag{12}$$

The pertinent initial and boundary conditions are

$$T(r,0) = T_0 \quad \text{and} \quad T(0,t) = T$$

where $T_0$ is the initial fluid (reservoir) temperature and $T_1$ is the temperature of the fluid injected.

An exact solution of (10) can also be obtained by the method of characteristics, Here it is assumed that $U_0 = U_1$. The solution for the temperature of the injected fluid is

$$T(r,t) = T, \quad \text{for} \quad \frac{r^2}{2} < U_1 t \tag{13}$$

and

$$T(r,t) = T_0 \quad \text{for} \quad \frac{r^2}{2} \geq U_1 t \tag{14}$$
The temperature solution must now be coupled with the solution for the silica concentration. Malate and OSullivan (1990) solved a similar problem in one-dimensional case. Following their procedure, it was found that the solutions for C and Q$_s$ of the one-dimensional model can be converted to the radial flow model by simply using the variable transformation $x = \frac{r^2}{2}$ and replacing $V$ by $V_r$.

The solution for the silica concentration is now expressed as follows:

For Region I ($\frac{r_1^2}{2} < U = T_1$)

The silica concentration is given by

$$C(r,t) = C_{s1} + (C_{s1} - C_{s0}) \exp \left( -\frac{k_1 r^2}{2 V_{r1}} \right) \tag{15}$$

where $V_{r1}$ is the radial flow and $C_{s1}$ is the silica saturation at temperature $T_1$. The symbol $U_1$ refers to the radial thermal flow given by (12).

For Region II ($\frac{r_2^2}{2} < U = T_0$)

$$C(r,t) = C_{s0} + (C_{s1} - C_{s0}) \exp \left( \frac{\sigma r^2}{2} \right) \tag{16}$$

Here

$$\tau = \frac{k_0}{(U_1 - V_{r0})}; \quad \sigma = [k_0 V_{r1} - k_1 U_1]$$

$$\omega = U_1 k_1 V_{r0} - k_0 V_{r1} \quad \text{and} \quad \delta = V_{r1}(U_1 - V_{r0}).$$

The subscripts (1) and (0) refers to conditions at temperatures $T_1$ and $T_0$, respectively.

For Region III ($\frac{r_2^2}{2} < U = T_0$)

$$C(r,t) = C_{s0} \tag{17}$$

The rate of silica deposition can now be evaluated from the rock mass balance equation. Assuming $\rho_r$ and $\phi$ are constant, the rate of deposition becomes

$$\frac{\partial Q_s}{\partial t} = \frac{\rho_r}{(1-\phi)\rho_r} k(C - C_s) \tag{18}$$

The porosity is given in terms of the amount of silica deposition (Itoi et al., 1987b)

$$\phi = \phi_0 - \frac{(1-\phi_0)\rho_r(Q_s - Q_{s0})}{(1-\phi)\rho_s} \tag{19}$$

where $\phi_0$ and $\rho_s$ are the density of the deposited silica and $Q_{s0}$ is the initial mass fraction of deposited silica in the rock. Equation (19) is used to eliminate $\phi$ from (18). After substituting the solution for the concentration (15), (16) and (17), equation (18) can now be easily integrated.

The solution for the silica deposit $Q_s$ is obtained as follows:

For Region III ($\frac{r_2^2}{2} < U = T_0$)

$$Q_s = Q_{s0} \tag{20}$$

For Region II ($\frac{r_1^2}{2} < U = T_0$)

$$Q_s = Q_{s0} + \frac{\phi_0}{\alpha} [1 - \exp(f(r,t))] \tag{21}$$

where

$$f(r,t) = \beta \alpha \left\{ \frac{\sigma r^2}{2} + \omega \right\} + M_2 \exp \left( \frac{\delta}{2 V_{r0}} \right) \right\} .$$

Here

$$\alpha = \frac{(1-\phi_0)\rho_r}{(1-\phi)\rho_s} \quad \text{and} \quad \beta = \frac{\rho_r k_0}{(1-\phi_0)\rho_s}.$$
After calculating the changes in porosity from (19), the corresponding permeability changes can be determined using the Kozeny-Stein equation (Itoi et al., 1987b)

\[
\frac{\kappa}{\kappa_0} = \left( \frac{\phi_0 - (1-\phi_0)\gamma}{\phi_0^3(1+\gamma)^2} \right) \left\{ \frac{1}{3} + \frac{1}{2} + \left[ \frac{1}{4} + \frac{1}{3}\gamma \right]^{1/2} \right\}.
\]  

Here \(\kappa_0\) is the initial permeability of the reservoir and

\[
\gamma = \frac{\rho_s(1-\phi_0)}{\rho_0(1-\phi_0)} = \frac{\phi_0 - \phi}{1 - \phi_0}
\]

### 21 Application to Otake wells

Itoi et al. (1987a, 1987b) conducted non-isothermal field experiments of reinjection in the Otake geothermal field in Japan. A total of 9.9 x 10^5 tonnes of geothermal wastewater were injected into two reinjection wells (R-1 and R-2) for a period of 650 days. Fall-off tests and maximum injectivity tests were carried out during the injection tests to monitor the decrease in injectivity. After the experiments, the permeability-thickness (\(kh\)) of well R-2 had declined from 91 darcy meter to 5 darcy meter while well R-1 had almost lost its injection capacity when the \(kh\) decreased from 224 darcy meter to 0.79 darcy meter. This decline in permeability thickness was mainly caused by silica depositing in the wellbore and the formation. Caliper logs and borehole televiewer surveys conducted after the injection tests further verified the silica deposits encountered in the wells.

Itoi et al. (1987b) also numerically modelled the changes in permeability thickness of the wells. They assumed isothermal injection in their model. They were only able to match the permeability and injection capacity changes by using a very small inlet concentration and reservoir porosity. The results for the two wells are used here to test the applicability of the non-isothermal radial flow model in simulating the decrease in permeability thickness due to silica deposition.

The reinjection water was injected into well R-1 at three stages with different injection temperatures. The wastewater was also injected into well R-2 at four stages with different injection temperatures. Since the radial flow model is only applicable for a constant injection temperature only, the result of the first stage of injection (227 days) for well R-1 is used here. This stage also gave the largest reduction in permeability. Similarly, only the result of the first stage of injection (53 days) for well R-2 is used in testing the radial flow model. It also produced the largest permeability reduction.

The parameters used in the model are listed in Table 1. The radial flow rate, \(V_{r1}\) and \(V_{r0}\) are calculated by dividing the flow rate by porosity and relevant fluid density. The radial thermal velocity parameter \(U_r\) is calculated from (12). An average reservoir temperature of 141°C is used in the model. Equilibrium concentrations of amorphous silica are derived from Fournier and Rowe (1977). An average porosity of 0.10 is assumed in the model.

### Table 1. Model parameters for wells R-1 and R-2

<table>
<thead>
<tr>
<th>Parameter</th>
<th>R-1</th>
<th>R-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vol, flow rate (m³/hr)</td>
<td>30</td>
<td>90</td>
</tr>
<tr>
<td>Injection temp. (°C) Tᵢ</td>
<td>50</td>
<td>80</td>
</tr>
<tr>
<td>Injection fluid pH</td>
<td>8.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Reservoir temp. (°C) T₀</td>
<td>141</td>
<td>141</td>
</tr>
<tr>
<td>Injected silica conc. (mg/kg) Cᵢ</td>
<td>587.0</td>
<td>565.0</td>
</tr>
<tr>
<td>Silica satn. at 141°C, (mg/kg) Cᵢ</td>
<td>568.8</td>
<td>568.8</td>
</tr>
<tr>
<td>Silica satn. at Tᵢ, (mg/kg) Cᵢ</td>
<td>181.1</td>
<td>281.9</td>
</tr>
<tr>
<td>Silica radial flow, (dsec) Vᵢ₁</td>
<td>4.06 x 10⁻⁴</td>
<td>1.02 x 10⁻³</td>
</tr>
<tr>
<td>Silica radial flow, (dsec) Vᵢ₀</td>
<td>4.34 x 10⁻⁴</td>
<td>1.07 x 10⁻³</td>
</tr>
<tr>
<td>Radial thermal flow, (dsec) Uᵢ</td>
<td>5.86 x 10⁻⁵</td>
<td>1.46 x 10⁻⁴</td>
</tr>
<tr>
<td>Surface Area, (m²/kg) A/M</td>
<td>54.69</td>
<td>95.18</td>
</tr>
<tr>
<td>Rate constant, (sec⁻¹) kᵢ</td>
<td>7.11 x 10⁻⁶</td>
<td>9.23 x 10⁻⁶</td>
</tr>
<tr>
<td>Rate constant, (sec⁻¹) kᵢ</td>
<td>5.72 x 10⁻⁶</td>
<td>9.96 x 10⁻⁶</td>
</tr>
<tr>
<td>Initial permeability-thick. (m²) kh</td>
<td>224 x 10⁻¹²</td>
<td>9.1 x 10⁻¹²</td>
</tr>
<tr>
<td>Average thickness, (m) h</td>
<td>32.7</td>
<td>38.92</td>
</tr>
<tr>
<td>Initial porosity ϕ₀</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Porosity of silica ϕₛ</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>Density of rock, (kg/m³) ρᵣ</td>
<td>2720.0</td>
<td>2720.0</td>
</tr>
<tr>
<td>Density of deposited silica ρₛ</td>
<td>2040.0</td>
<td>2040.0</td>
</tr>
</tbody>
</table>

The evaluation of the effective surface area \(A/M\) for the reservoir matrix is more difficult than the relative surface area of porous materials used in laboratory experiments. Argon and BET measurements are commonly used with accuracy as a standard technique in laboratory experiments (Rimstidt and Barnes, 1980). Other values of the surface area are obtained from idealised geometries like the closely packed uniform spheres used by Malate and O'Sullivan (1988). There is scarcity of data available for real reservoir materials and the best approximation available is the Kozeny equation (Itoi et al., 1987b) which is represented by

\[
\frac{A}{M} = \frac{(1-\phi_0)S_y}{\phi_0γ} \quad \text{(24)}
\]

and

\[
S_y = \left[ \frac{\phi_0^3}{\xi k_c (1-\phi_0)^2} \right]^{0.5}
\]

Here, \(S_y\) is the surface to a unit volume of rocks and \(k_c=5.0\), Kozeny constant.

The apparent rate constants \(kᵢ\) and \(kᵢ₀\) obtained from Rimstidt and Barnes formula (equation (8)) did not give a good match of the observed permeability-thickness decline.
of the wells. The $k_1^-$ value was first varied while $k_0^-$ was kept fixed at the value given by Rimstidt’s formula. Later $k_0^-$ was varied but the good match already obtained using the calculated $k_0^-$ from Rimstidt’s equation was not improved. The dimensionless permeability-thickness versus time for wells R-1 and R-2 are presented in Figures 1 and 2 respectively. The best fit to the observed data was obtained with $k_1^-=7.11\times10^{-6}$ and $k_0^-=5.72\times10^{-6}$ for well R-1 and $k_1^-=9.23\times10^{-6}$ and $k_0^-=9.96\times10^{-6}$ for well R-2. A comparison of the apparent rate constants $k_1^-$ and $k_0^-$ obtained from the best fit and the ones calculated from Rimstidt’s formula is shown in Table 2. The values of $k_1^-$ derived from the best fit are larger than the calculated rate constants.

The results of the model gave a good match to the significant decline in permeability-thickness for wells R-1 and R-2 despite the uncertainties of some reservoir parameters ($\phi$ and $A/M$ for example). The results were also obtained without using an artificially small inlet supersaturation which Itoi et al. employed in their numerical modelling study. The results indicate that the first order model for amorphous silica deposition suggested by Rimstidt and Barnes (1980) can be confidently applied to field data in simulating the decline in injection capacity and permeability-thickness of the wells provided the rate constants are chosen correctly. Unfortunately the rate constants given by the theoretical formulae of Rimstidt and Barnes (1980) did not give good results.

### Table 2. Comparison of $k_1^-$ and $k_0^-$ from the best fit and Rimstidt’s formulae.

<table>
<thead>
<tr>
<th>Well</th>
<th>Calculated</th>
<th>Best fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>R-1</td>
<td>$k_1^-(T=50^\circ\text{C})$</td>
<td>$1.80\times10^{-9}$</td>
</tr>
<tr>
<td></td>
<td>$k_0^-(T=14^\circ\text{C})$</td>
<td>$1.05\times10^{-7}$</td>
</tr>
<tr>
<td>R-2</td>
<td>$k_1^-(T=80^\circ\text{C})$</td>
<td>$8.60\times10^{-7}$</td>
</tr>
<tr>
<td></td>
<td>$k_0^-(T=141^\circ\text{C})$</td>
<td>$1.05\times10^{-7}$</td>
</tr>
</tbody>
</table>

3. **VARIABLE FLOW RATE MODEL**

In this section, a quasi-analytical solution is presented for the variable flow rate case. Here the first order rate equation of Rimstidt and Barnes (1980) is also used to represent silica deposition. It is assumed that over a short time interval, $(t_{n+1}^r-t_n^r)$, the fluid particle velocity can be approximated by a constant value $V_{n+1}^r$, determined at the beginning of the interval. Then the analytical methods used in the previous section apply for $t_n^r \leq t \leq t_{n+1}^r$. The details of the calculation method for evaluating $C$ and porosity $\phi$ at $t_{n+1}^r$, that is for proceeding from $C(x,t_n^r)$, $\phi(x,t_n^r)$ to $C(x,t_{n+1}^r)$, $\phi(x,t_{n+1}^r)$, are discussed in Malate (1991). Once $\phi(x,t_{n+1}^r)$ is known, a new particle velocity $V_{n+1}^r$ can be calculated by following the procedure below.

The changes in density of the water are insignificant and therefore the mass balance equation (1) reduces to

$$\frac{1}{r} \frac{\partial}{\partial r} (rQ_{nu}) = 0$$

(25)

Thus $Q$ must be a function of time only and Darcy’s law (2) can be integrated to give

$$q_{nu}(t) = \frac{(p_0-p_f)2r_n}{v_l} \left[ \int_{R}^{R} \frac{1}{r} \, dr \right]$$

(26)

(26)
where \( q_{mr} \) is the total mass flow rate, \( h \) is the thickness of the permeable layer, \( R \) is the radius of the outer boundary, \( r_1 \) is the well radius, and \( p_0 \) and \( p_1 \) are the inlet and outlet pressure respectively.

From the porosity \( \phi(x,t_{n+1}) \) the corresponding permeability can then be calculated using the Kozeny-Stein equation (Ito et al., 1987b) from (23). The integral in (26) cannot be evaluated analytically and was evaluated here using the trapezoidal rule:

\[
I_{n+1} = \sum_{j=1}^{j-1} \frac{1}{2} [f_j + f_{j-1}] \Delta t
\]

where \( f_j = [\kappa(j \Delta r, r_{n+1}) \eta_j]^{-1} \) and \( j = 1, j-1 \).

The new mass flow and fluid particle velocity are then calculated using

\[
q_{mr}(t_{n+1}) = \frac{(p_0 - p_1) 2 \pi h l}{\eta_1 I_{n+1}}
\]

and

\[
v_r(t_{n+1}) = \frac{q_{mr}(t_{n+1})}{\rho_0}
\]

The changes to the initial porosity caused by deposition are ignored in (29). The approximation of constant porosity is not correct, but it was employed in the model in order to be able to proceed with the semi-analytic solution. A small reduction of porosity near the inlet \( r=0 \) would give a slightly faster velocity \( v_r \) there which produce a small extra spreading out of the silica deposit.

3.1 Application to Tongonan wells

The variable flow rate model was applied to calculate the injection capacity decrease of two reinjection wells in Tongonan geothermal field in the Philippines. The Tongonan geothermal field is situated in the island of Leyte in central Philippines. Twelve production wells distributed in the lower Mahiao and Sambaloran sectors support the 112.5 MWe Tongonan I power plant (See Figure 3). Estimated capacity of the production wells under the wellhead is 134 MWe (Sarmiento et al., 1985). The reject water from the power plant are reinjected back to four reinjection wells in the Southwestern part of the two production sectors. Reinjection wells 1R3 and 1R5D are designed for the Mahiao sector while wells 2R3D and 2R4D are intended for the Sambaloran waste water. The reinjection fluids being accepted by the wells are slightly supersaturated with amorphous silica and they are operated at approximately constant wellhead pressure. The wells were also closely monitored for capacity changes by conducting regular flowmeter logs, pressure measurements and go devil surveys (Sarmiento et al., 1985).

Fig. 3. Tongonan geothermal field. (After Sarmiento, 1986).

All the four reinjection wells have exhibited a decline in their injection capacities during the period of exploitation. The injection capacity of 1R5D is presented in Figure 4. This decline in injection capacity is believed to have been caused by chemical deposition. Well 1R5D is a deviated well drilled to a total depth of 2408m MD. The well has a minor permeable zone at 1200-1400m and a major one at 1800-2000m MD. Stable bottomhole temperatures recorded range from 250-260°C. A blockage was observed at the upper feed zone of the well during the first 24 months of reinjection (See Figure 4). This blockage is believed to have been caused by the accumulation of debris since a solids trap was installed after the blockage had been recognised. It was then postulated that silica deposition had taken place and damaged the well and the formation. It appears that silica had completely sealed off the blockage at the upper feed zone. This was confirmed by a sinker bar tagging the maximum cleared depth of the well at 1222m MD (Sarmiento, 1986). The further decline of injection capacity after 36 months is caused by silica deposition in the formation.

The blockage at the upper feed zone was successfully removed after a work-over was done at the beginning of 1988 (See Figure 4). The major feed zone was thus re-accessed which resulted to the recovery of the original injection capacity of the well. A scraper run conducted on the well showed deposited scales which consisted mainly of amorphous silica, iron oxide flakes and andesite stones.
covered with layers silica. It was also found that the scales were much thicker in the upper portion of the blockage compared with the scales deposited at the lower portion of the well. The injection capacity of the well also declined steadily after the work-over. This reduction in capacity is now believed to have been mainly caused by silica depositing in the formation near the major permeable zone (1700-1800m). Go devil surveys conducted also showed some blockage at 1600m. It is also of interest to note that the decreasing trends of injection capacity before and after the work-over are similar.

The parameters used in the model are listed in Table 3. Here an initial \( \Delta t \) of 0.1m was used which was then increased geometrically by a factor 1.2. A constant time step of 2 months was employed. The equilibrium concentration of amorphous silica was also calculated from Fournier and Rowe (1977). The average thickness of the reservoir was based on the permeable zone of the well. The initial permeability \( k_0 \) was obtained from permeability-thickness (kh) measurements measured in interference tests. A radius of the outer boundary of 200m was used in the model to ensure deposition effects did not occur near the outlet boundary. The Kozeny equation (24) was used to calculate the average surface area per unit mass of fluid (m²/kg) available for deposition in the reservoir matrix.

Table 3. Model parameters for wells 1R5D and 1R3.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1R5D</th>
<th>1R3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Injected silica conc. (mg/kg) ( C_i )</td>
<td>782.0</td>
<td>782.0</td>
</tr>
<tr>
<td>Silica saturation, (mg/kg) ( C_s )</td>
<td>711.0</td>
<td>711.0</td>
</tr>
<tr>
<td>Injection temperature (°C) ( T_i )</td>
<td>165.0</td>
<td>165.0</td>
</tr>
<tr>
<td>Initial porosity ( \phi )</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Density of rock, (kg/m³) ( \rho_r )</td>
<td>2600.0</td>
<td>2600.0</td>
</tr>
<tr>
<td>Density of deposited silica ( \rho_d )</td>
<td>2040.0</td>
<td>2040.0</td>
</tr>
<tr>
<td>Porosity of silica ( \phi_s )</td>
<td>0.91</td>
<td>0.91</td>
</tr>
<tr>
<td>Surface Area (m²/kg) ( A/M )</td>
<td>668.0</td>
<td>554.0</td>
</tr>
<tr>
<td>Thickness of perm. layer (m) ( h )</td>
<td>2000.0</td>
<td>1500.0</td>
</tr>
<tr>
<td>Well radius (m) ( r_1 )</td>
<td>0.178</td>
<td>0.178</td>
</tr>
<tr>
<td>Radius of outer boundary (m) ( R )</td>
<td>200.0</td>
<td>200.0</td>
</tr>
<tr>
<td>Initial permeability-thick. (m²) kh</td>
<td>11.0×10⁻¹²</td>
<td>12.0×10⁻¹²</td>
</tr>
<tr>
<td>Rate coefficient (sec⁻¹) ( k )</td>
<td>1.40×10⁻⁵</td>
<td>8.32×10⁻⁶</td>
</tr>
</tbody>
</table>

The injection temperature of 165°C is used in the model. It is also assumed that injection is isothermal despite the fact that reservoir temperature over in the reinjection area is over 250°C. This approximation is justified by some of the results obtained by Malate (1991). The results obtained show that injection of a cool fluid into a hotter reservoir does not result in a significant amount of deposition outside the region affected by the injection temperature. The variable flow rate model derived here can only accommodate isothermal injection. More work is required to develop a semi-analytic solution of the variable flow rate non-isothermal problem. It is assumed that amorphous silica controls the solubility of the injection fluid.

Fig. 4. Injection capacity decline of wells 1R5D and 1R3 (1983-1988).

Well 1R3 is a vertical well drilled to a total depth of 1903m MD. The well is fed by two permeable zones, a major feed zone at 1000-1200m and a minor feed zone at 1700-1800m. The stabilised inflow temperature at 1200m is around 260-270°C while the bottomhole at 250-260°C. The injection capacity of the well is also displayed in Figure 4. The decline in capacity of 1R3 is also attributed to silica deposition mainly occurring in the major feed zone. Go devil surveys also showed a blockage at 1100m but silica deposition is believed to have occurred mainly in the formation. A scraper run conducted on the well also produced deposited scales of amorphous silica.

32 Modelling results

An injection temperature of 165°C is used in the model. It is also assumed that injection is isothermal despite the fact that reservoir temperature over in the reinjection area is over 250°C. This approximation is justified by some of the results obtained by Malate (1991). The results obtained show that injection of a cool fluid into a hotter reservoir does not result in a significant amount of deposition outside the region affected by the injection temperature. The variable flow rate model derived here can only accommodate isothermal injection. More work is required to develop a semi-analytic solution of the variable flow rate non-isothermal problem. It is assumed that amorphous silica controls the solubility of the injection fluid.

The rate constant \( k \) and porosity \( \phi_s \) were varied to match the observed changes in injection capacity. The results of the model are presented in Figure 5. The best fit to the data gave a constant \( k = 1.40 \times 10^{-5} \) and \( \phi_s = 0.91 \). The corresponding apparent rate constant is \( k^* = 2.1 \times 10^{-8} \) which...
was surprisingly smaller than the rate constant calculated from Rimstidt formulae \((k^* = 2.3 \times 10^{-7})\).

The corresponding distributions of specific deposit and permeability calculated are displayed in Figures 6 and 7 respectively. Silica deposition and associated permeability reduction occurs mainly near the well. The radius of the deposit is approximately 20 meters. Note the inside radius used in the model corresponds to the well radius hence the calculated maximum value of specific deposit and permeability decrease will occur at the slotted liner or sand face of the well.

The variable flow rate model was also applied in simulating the mass flow changes of well 1R3. Again it was assumed that injection is isothermal and amorphous silica controls the solubility of the injection fluid. The best fit to the measured data was achieved with \(k = 8.32 \times 10^{-6}\) and \(\phi_s = 0.91\).

The apparent rate constant \(k^*\) obtained from the best fit is \(k^* = 1.3 \times 10^{-8}\) which is smaller than the rate constant derived from Rimstidt formulae \((k^* = 2.3 \times 10^{-7})\). The model parameters used are also listed in Table 3 and the calculated results for injection capacity is presented in Figure 8. The distributions of specific deposit and permeability are also shown in Figures 6 and 7 respectively. The results of the model gave good agreement with the observed data and deposition was also found to occur near the wellbore. The radius of specific deposit was approximately 30 meters.

4. CONCLUSIONS

The constant flow rate, radial flow model for non-isothermal injection was used to simulate some reinjection experiments of Itoi et al. (1987b, 1989). The model employed the first order rate equation (Rimstidt and Barnes, 1980) for silica deposition and gave a good match to the permeability-thickness decline measured in wells R-1 and R-2. These were obtained without using an artificially small inlet supersaturation which Itoi et al. employed in their numerical modelling study.

The problem of variable rate isothermal injection for radial flow was also studied. Quasi-analytic models of silica deposition incorporating the kinetic models of Rimstidt and Barnes (1980) were derived using the method of characteristics. This analysis is particularly important because most of the laboratory and field experiments are conducted at a variable flow rate. The radial flow models were successfully applied in simulating the changes in injectivity of some reinjection wells (1R5D and 1R3) in Tongonan geothermal field in the Philippines. The variable flow rate model using the first order rate equation gave a reasonable match to the measured injection capacities of reinjection wells 1R5D and 1R3. The values for the rate constant \(k\) obtained were found to be similar to those derived for wells R-1 and R-2.

The modelling results for wells R-1, R-2, 1R5D and 1R3, show that the first order model for amorphous silica deposition, proposed by Rimstidt and Barnes (1980) performs remarkably well in simulating the decline in injection capacity and permeability-thickness of the wells provided that the rate constants are selected correctly.
There was again a considerable difference between the apparent rate constant $k^*$ obtained from the model and the rate constant derived from Rimstidt's formulae. To illustrate these differences, the Arrhenius plot (log $k^*$ versus $1/T$) of experimentally determined precipitation rate constants for silica is reproduced from Rimstidt and Barnes (1980) and displayed in Figure 9. The values for apparent rate constant $k^*$ obtained here from the modelling of silica deposition are laboratory and field experiments are also shown in Figure 9. The values for the laboratory experiments are obtained from the modelling results of Malate (1991). These values were plotted as error bars which include the possible errors introduced by the evaluation of the surface area $A/M$ for deposition. The values with a small error bar correspond to the laboratory experiments while the values with large error bars represent field data. The error involved in determining the surface area for laboratory experiments is considered small, while there could be large uncertainty in the evaluation of $A/M$ for the reservoir matrix. A possible threefold increase or decrease in the surface area was used to quantify the possible error introduced by the Kozeny approximation. This level of uncertainty was selected by considering realistic limits of uncertainty in the choice of the parameters used in the calculation of $A/M$ (porosity $\phi$ for example).

The figure shows the rate constant $k^*$ derived here from matching laboratory experiments (Malate, 1991) are very different from the experimentally determined rate constant of Rimstidt and Barnes (1980). The rate constants derived from field experiments ($50^\circ C$ and $80^\circ C$) are also greater than the values calculated from the regression line. Jamieson (1984) in his thesis, noted the values of deposition rates given by Rimstidt equation were considerably lower than scaling rates commonly observed in surface equipment. The rate constant $k^*$ obtained by the model at high temperature ($165^\circ C$) was less than the values derived from the regression line. The result also shows that even if the surface area is increased or decreased by a factor of three, the calculated rate constant is still less than the value derived from Rimstidt's equation. In summary therefore, although the rate constants derived from field experiments plots closer to the empirical values of Rimstidt and Barnes than the rate constants derived from laboratory experiments, the three sets of data are not sufficiently close to support the application of Rimstidt's equation to the field situation. The reasons for this are not clear. Further work is required to resolve this situation. In most geothermal reinjection problems ($165^\circ C$), the fact that Rimstidt's formulae for $k^*$ gives a faster rate of silica deposition than the rate constant derived by the model means that the rate equation of Rimstidt and Barnes may usefully provide a conservative estimate of silica deposition during reinjection.

5. REFERENCES

Fournier, R.O. and JJ. Rowe, 1977, The solubility of amorphous silica in water at high temperatures and pressures, American Mineralogist, 62,1052-1056.


