INJECTION RETURNS IN WELL SK-2D
MINDANAO GEOTHERMAL PRODUCTION FIELD, PHILIPPINES

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ABSTRACT
Since the start of large-scale exploitation of the Mindanao Geothermal Production Field in 1997, changes in temperature and chloride concentration in some production wells are observed. Well SK-2D is one of the wells that have exhibited a remarkable increase in chloride and a noticeable decline in temperature. The cause was assumed to be the invasion of injectate fluids from the injection wells.

Reservoir chloride changes in SK-2D were modeled by using a time-dependent production-injection lumped-parameter model. By matching the calculated chloride values with the observed values the fraction of injectate returning in well SK-2D is obtained. The total mass in place in SK-2D production sector is approximately 15.8x10^9 kg. The rapid increase of injectate fraction returning to SK-2D in the early months of exploitation clearly indicates good connection between SK-2D and injection wells MT-1RD and MT-2RD.

The fraction of injectate returning to the production sector varies depending on the injection load of Pad RA wells. The returning injectate peak to 70-75% from April 1998 to March 2000 when injection load was increased from 200 kg/s to 350 kg/s. In the succeeding months the injectate fraction declined to around 45-50% equivalent to around 145 kg/s of injectate returning to the production sector. Around 35% of the fluids produced by well SK-2D are injection returns.

The decline in reservoir temperature based on quartz geothermometer is then modeled by coupling the lumped parameter model to a one-dimensional fracture flow model. The final model that reasonably matches the thermal decline suggests a fractured zone and production zone porosity of 8-10%.

INTRODUCTION
The Mindanao Geothermal Field (MGPF) is located on the northwest flanks of Mt. Apo situated in the southeastern part of the island of Mindanao, Philippines (Figure 1). Commercial operation of the field commenced in March 1997 with the commissioning of the first 52-MWe Mindanao 1 Geothermal Plant (M1GP). The second 52-MWe double flash turbine unit, the Mindanao 2 Geothermal Plant (M2GP) started its commercial operation last June 1999.

Figure 1. Map of the Mindanao geothermal production field.

The scenario of injected fluids returning to the M1GP production sector was already recognized as a potential problem to the sustainability of the field even before the start of exploitation. Such concern was raised because of: (1) the proximity of Pad RA injection wells, particularly MT-2RD, to the production sector, (2) the similarity of the baseline reservoir pressures of the production and injection sectors and (3) the presence of structural and lithologic flow paths connecting the two sectors.
A year after the start of exploitation telltale signs of injected fluid returning to some production wells (APO-1D, APO-3D and SK-2D) was observed. Chemical changes persistently noticed on these well are increasing chloride and decreasing gas concentrations. Well SK-2D have exhibited a remarkable changes on its chemistry as well as noticeable decline on its temperature. These changes are mainly attributed to the invasion of injected fluids into the production sector. In this paper, a lumped parameter model was used to estimate the fraction of injectate returning to SK-2D. The temperature decline is modeled by coupling the chloride mass balance model to a one-dimensional fracture flow model. In the absence of a thorough downhole temperature measurement in the well, the thermal decline is modeled by matching the calculated $T_{QTZ}$ in the well.

**SK-2D RESPONSE TO EXPLOITATION AND CHEMICAL MONITORING**

Well SK-2D was drilled directionally to a total depth of 1838 m MD (1500 m VD) in year 1992. The well’s production casing was perforated in 1995 to tap steam and two phase horizon of the production field. Flowing surveys indicated a major feed zone at 1050–1073 m MD (955–972 m VD). Well SK-2D is proximate to Pad RA injection wells, particularly MT-2RD where bottomhole separation between the two wells is approximately only 1.1 km (Pioquinto, 1997).

Well SK-2D has been continuously utilized since exploitation that begun in 1997 (Figure 2). It is one of the biggest producers in the field. With an average mass flow of 80 kg/s and a corresponding output of ~8 MWe, the well discharges neutral to slightly alkaline sodium-chloride fluid like other M1GP wells.

Well SK-2D exhibits an increasing reservoir chloride concentration as shown in Figure 3. Chloride concentration increased from the baseline value 4089 mg/kg to 5073 mg/kg in June 2000. Figure 3 also shows decreasing trends of CO$_2$ and H$_2$S. This suggests that the well is producing fluids rich in chloride but depleted in noncondesible gas, a chemical signature for wells affected by injection returns (Sambrano, B.G. and Nogara, J.B., 2000).

![Figure 2](image2.png)

**Figure 2.** Average mass flow and enthalpy trends of SK-2D. Filled symbols in enthalpy trend represent measurements using chemical tracers. Open symbols represent James-lip pressure measurements.

![Figure 3](image3.png)

**Figure 3.** Reservoir chloride and gas trends in well SK-2D. Increasing chloride and decreasing gas concentrations suggest invasion of injection fluids into the well.
After a year of production, a gradual decrease in temperature was measured at the major feed zone (1050 mMD) and at the deepest feed zone (1750 mMD) of the well with an average temperature drop of 8–9 °C (Figure 4). Temperatures based on quartz and Na-K-Ca geothermometers likewise declined gradually after two years of production (Figure 4). The wells discharge enthalpy, however, remains relatively stable (Figure 2). This may be due to the contribution of the upper two-phase feed zone of the well.

Thus, massive injection in MT-1RD and MT-2RD has clearly affected well SK-2D due to their proximity. The changes in the chemical and physical discharge characteristics of well SK-2D are attributed to injection fluids returning into the production sector.

**MGPF INJECTION HISTORY**

Injection of separated brine in the Mindanao Geothermal Production Field began as early as 1994. Large-scale injection, however, started only in January 1997 during M1GP’s testing and commissioning activities. Injection wells in the Matingao sector have their permeable zones located in the Lower sequence of the Older Apo Volcanics (oAVl) intersected from sea level down to ~600 m to ~700 m ASL. The most permeable horizons in this injection sector occur at 0 to ~200 m RSL.

Since the start of commercial exploitation of the field, brine injection rate has averaged about 300 kg/s. Injection rates gradually increased from 200 kg/s in 1997 to 450 kg/s in 1999. The increase in brine load was due to the increase in plant load. Around 60 – 70 % of the spent brine were injected in MT-1RD and MT-2RD located in Pad RA (Figure 5). The biggest injection well, MT-1RD, accepts around 45% of the total separated brine produced by the production wells. Pad RA wells are closest to the production sector.

During the first two years of operation, well KL-3RD was utilized as cold injection well. However, cold injection was shifted to well KL-2RD in the later part of 1999 due to increasing amount of separated brine in the later part of 1998. During the first two years of operation, the condensed steam injected amounts to an average of 70 tons per hour. With the commissioning of the second power plant by mid-1999, condensed steam injected increased to 140 tons per hour.

**Figure 4.** Declining trends in temperature (measured and calculated based of geothermometers) are observed in well SK-2D.

**Figure 5.** Brine loads of Pads RA and RI hot injection wells.
LUMPED PARAMETER MODEL

To model the chemical changes in SK-2D a simple time-dependent production-injection model developed by Kato (2000) was used (Figure 6). Hot fluid recharge and a fraction of injected are flowing into the production box. The outflow to the surface is represented by the well. The separated water is injected into the injection boxes that represent the injection wells of Pads RA. The model was developed using the following basic assumptions:

1. The fluid in the production sector is single liquid phase.
2. The fluid mass in the production and injection sector remains constant during exploitation.
3. The fluid flow and chloride concentration of the recharge are constant during the exploitation period.
4. The time delay of the chloride concentration in the returning fluid is assumed to be small.

A chloride mass balance in the production box gives;

\[
\frac{d}{dt} M_T [Cl]_P = M_{REC} [Cl]_{REC} + I_{RT} [Cl]_{RA} - P [Cl]_P
\]  

where, \([Cl]_P, [Cl]_{REC}, \) and \([Cl]_{RA}\) are the concentrations of chloride in production, recharge and injectates from pad RA, respectively. \(P, M_{REC},\) and \(I_{RT}\), are the flow rates of production, recharge, and injection from Pad RA, respectively, \(M_T\) is the mass of fluid in the production sector.

From assumption (2), which means that \(M_T\) is constant, a mass balance of fluids in the production sector gives:

\[
M_{REC} + I_{RT} - P = 0
\]  

The fraction of mass of hot water returning to the reservoir is \(f_{RA}\), thus

\[
I_{RT} = f_{RA} I_{RA}
\]  

where \(I_{RA}\) is the total injection flow rate of Pad RA wells. Substituting equations (2) and (3) into equation (1) will gives:

\[
\frac{d}{dt} M_T [Cl]_P = f_{RA} I_{RA} [Cl]_{RA} - f_{RA} I_{RA} [Cl]_{REC}
\]

Differentiating (4) would give a time-dependent equation as follows;

\[
[Cl]_{P, N + 1} = [Cl]_P, N + \left(\frac{1}{M_T} \right) \left\{ (f_{RA} I_{RA}) [Cl]_{RA} - [Cl]_{REC} I_{RA} - ([Cl]_P - [Cl]_{REC}) P \right\}
\]

The unknown parameters are \(f_{RA}\) and \(M_T\).

The fraction of injected fluid in the produced fluid is:

\[
F = \frac{I_{RT}}{P}
\]

Since

\[
f_{RA} = \frac{I_{RT}}{I_{RA}} \text{ and } I_{RA} = y P, \text{ where } y \text{ is the water fraction from the separator, then}
\]

\[
f_{RA} = \frac{F}{y}
\]

MODELING THERMAL DECLINE

Since permeability in the Mindanao Geothermal Field is primarily structurally controlled, well siting is based on structures. The main flow path for the return of injection fluid to the production sector is
provided by structural faults. For this type of geothermal system, a one-dimensional fracture zone model could provide a good prediction of temperature decline (Malate and O’Sullivan, 1991). A simple heat advection model was used in modeling the thermal decline. This model, developed by Malate and O’Sullivan (1991), assumes that the reservoir is a highly fractured zone consisting of many flow paths that allows good contact between water and the fractured rock.

The thermal decline of the well was modeled by coupling the chloride mass balance to the one-dimensional fractured zone model. The model was derived from an energy balance for the production block (Figure 4) and from the conservation of energy equation for a one-dimensional flow in a fractured zone (porous medium). The equation for conservation of energy for flow in a porous medium is:

\[
(1 - \phi \rho c_f + \phi \rho c_l) \frac{\partial T_f}{\partial t} + \rho c_l V \frac{\partial T_f}{\partial x} = K \frac{\partial^2 T_f}{\partial x^2} \quad (7)
\]

where \( T_f \) is the temperature of the fractured zone, \( V \) is the Darcy velocity, \( \phi \) is the porosity of the fractured zone and \( K \) is the thermal conductivity of the rock matrix. It is assumed that \( \rho_l \), the density, and \( c_i \), the specific heat of the fluid moving in the fracture, are independent of temperature. The effect of heat conduction is also assumed negligible.

From equation (6) the model derived by Malate and O’Sullivan (1991) to calculate the thermal decline in the production block is given by:

\[
T_p = T_o \quad \text{for } t \leq t_T \quad (8)
\]

and

\[
T_p = T_o + W \{1 - \exp[-\beta (t - t_T)]\} \quad \text{for } t > t_T \quad (9)
\]

where

\[
W = \frac{\phi}{\kappa} (T_i - T_o) \quad (10)
\]

where, \( T_i \) is the injection temperature.

The term \( t_T \) is the time it takes for the thermal front to travel the distance \( L \), and is expressed by

\[
t_T = \frac{L}{U}
\]

The thermal front velocity, \( U \), is from equation (7) and is given by

\[
U = \frac{V \phi \rho c_l}{[(1 - \phi) \rho c_f + \phi \rho c_l]}. \quad (11)
\]

where, \( V \) is the chemical (chloride) front velocity and \( \phi \) is the effective porosity for the fractured zone.

The energy balance in the production block is given as follows:

\[
V \tau (1 - \phi) \rho c_f + \phi \rho c_P \frac{d}{dt} T_p = -P c_r T_p + (M c)_{REC} + (M c)_{RA}(1)
\]

where \( T_P, T_{REC}, \) and \( T_{RA} \) are the temperatures of the production, recharge and returning fluid respectively; \( V_P \) is the total volume of the production sector; \( \phi \) is the effective porosity of the production block; \( \rho_r \) and \( c_r \) are the density and specific heat of the rock matrix in the production sector.

In addition, \( c_P, c_{REC} \) and \( c_{RET} \) are the heat capacities of production, recharge and returning fluids, and are assumed identical in the model. The recharge temperature, \( T_{REC} \), is assumed constant and equal to the initial reservoir temperature, \( T_0 \). The temperature of the returning injectate, \( T_{RA} \) is a function of time determined by the mathematical model of the fractured zone connecting the injection and production sectors.

From equation (11), the terms \( \kappa \) and \( \phi \) in equations (8) and (9) are respectively expressed as follows:

\[
\kappa = \frac{P}{M \tau (1 + \beta)} \quad (13)
\]

\[
\phi = \frac{P}{M \tau (1 + \beta)} \quad (14)
\]
And, solving for \( \beta \) using equation 12

\[
\beta = \frac{(1-\phi)p_{rC}}{\phi p_{cC}}
\]  

(15)

**CHLORIDE MODELING RESULTS**

To model the chloride increase in well SK-2D an initial production chloride of 4089 mg/kg was assumed. The recharge chloride used was 4089 mg/kg. The initial injection chloride concentration used was 5641 mg/kg, which was the pre-commissioning chloride concentration of separated brine of M1GP production wells (Nogara, J.B., et.al., 1999).

The two parameters \( M_T \) and \( f_{RT} \) were then adjusted to match the measured data. After several trials, \( M_T = 1.58 \times 10^9 \) kg gave results that approximate the observed chloride trend. Figure 8 shows the best possible match between the measured and calculated chloride concentration of the production fluid and the fraction of injectate returning to the well. The returning injectate is mainly coming from Pad RA injection wells (MT-1RD and MT-2RD).

The very rapid rise of injectate returns particularly during the early months of field exploitation, suggests a high degree of connection between Pad RA injection wells and well SK-2D. Injection returns to SK-2D peaked to 70-75% from the second quarter of 1998 to the first quarter of 1999. It was during this period that the injection loads in Pad RA wells were increased. The reduction of injection load in the succeeding months also resulted to the decrease in fraction of injectate returning to SK-2D. By the second quarter of 2000, the fraction injectate fluids returning to the production sector is around 45-50%.

At an injection return rate of 50%, all of the brine injected in well MT-2RD is returning into the production sector of well SK-2D. With the water fraction from M1GP’s separator is around 65%, around 35% of fluids produced by SK-2D are injection returns.

In spite of a decreasing fraction of returning injectate by 1999 increasing production chloride was still observed. The increasing chloride concentration may result from an invasion of higher chloride indigenous fluid probably coming from Sandawa Collapse.

**THERMAL MODELING RESULTS**

From the start of exploitation in 1997 to mid-1999, the spent water from M1GP production wells was injected directly into the injection wells at an average temperature of 170°C. With the commissioning of the second power plant last June 17, 1999, which utilizes a dual-flash condensing turbine, the temperature of the spent brine injected into the injection wells was lowered to 150°C. To match the thermal decline in well SK-2D the parameters used are as follows; reservoir temperature \( T_0 = 249 \) °C; injection temperature from January 1997 to June 1999 is equal to 170°C; and the injection temperature in the succeeding months is equal to 150°C (Nogara, J.B., et.al., 1999).

From Figure 4, the thermal breakthrough based on \( T_{QZ} \) occurred about 24-30 months after the start of exploitation. Since the distance between the production area and Pad RA injection sector of about 1.1 km the thermal velocity was computed to be around 37 meters/month. And based on Figure 3, the
chloride front arrival is observed to have occurred three to five months after the start of production. The effective porosity, $\phi$, of the fractured zone was determined using equation (11). Assuming $\rho_r = 2500 \text{ kg/m}^3$, $c_r = 1.0 \text{ kJ/kg K}$, $\rho_l = 804 \text{ kg/m}^3$ and $c_l = 4.85 \text{ kJ/kg K}$, the effective porosity of the fractured zone was calculated to be around 8%.

The production temperature was derived from equations (8) and (9). The effective porosity of the production block, $\phi$, was then varied to match the temperature decline. Figure 9 presents the modeling results for different values of porosity. A better temperature match with the observed data was obtained when 8.0-10.0% effective porosity of the production block was used.

![Figure 9. SK-2D calculated $T_{QTZ}$ and simulated temperatures at various porosities.](image)

**SUMMARY AND CONCLUSION**

The chloride increases observed in well SK-2D, attributed to the return of injectate from the nearby injection wells MT-1RD and MT-2RD, were modeled using a time-dependent production-injection lumped parameter model. The rapid increase injectate fraction particularly in the early months of field exploitation suggests good connection between SK-2D production sector and the injection wells of Pad RA.

The fraction of injectate returning to the production sector varies depending on the injection load of Pad RA wells. Returns peak to around 70-75% from the second quarter of 1998 to the first quarter of 1999 when the injection load in Pad RA wells increased from 200 kg/s to 350 kg/s. The decrease in injection load in the succeeding months also resulted to a noticeable decline in injection returns to the production sector.

The injectate returning by April 2000 is around 45-50%. At this rate it suggests that around 145 kg/s of fluid out of the 285 kg/s injected in Pad RA wells are returning to SK-2D production sector. This further suggests that the all the 90 kg/s of fluid injected in well MT-2RD is returning to SK-2D production sector. Furthermore, around 35% of the fluids produced by well SK-2D are injection returns.

The decline in quartz geothermometer occurred in SK-2D after more than two years of exploitation. By coupling the lumped-parameter model to a simple fracture (porous medium) zone model the thermal decline on the well was modeled. In the absence of a thorough downhole temperature measurement in the well, the $T_{QTZ}$ geothermometer was used instead. At an effective porosity of 8.0–10.0% for both the production zone and fracture zone, the model obtained a reasonable temperature match of the thermal decline.

In spite of the substantial amount of injectate returning to well SK-2D there has been no significant degradation on the production output of the well. The relatively minimal decline in the well’s temperature decline based on quartz geothermometer suggests that injected fluid have undergone sufficient heating as it return to the production sector of well SK-2D.

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