AN ESTIMATING METHOD OF FRACTION OF REINJECTED WATER TO PRODUCED FLUID ON THE BASIS OF A LUMPED PARAMETER MODEL

Ryuichi ITOI, Kentaro IMURA, Toshiaki TANAKA and Michihiro FUKUDA

Geothermal Research Center, Kyushu University, 6-1, Kasuga Koen, Kasuga, JAPAN 816

Abstract

We proposed a method for estimating mixing ratio(or fraction) of reinjected water to produced fluid on the basis of a reservoir model developed by Malate and O'Sullivan(1991). A lumped parameter model for the masses of fluid and chloride(Cl) was used for a reservoir system consisting reinjection and production zones. The method employs on-line analysis algorithm and estimates an optimum value of the fraction at each moment of Cl concentration measurement of the produced fluid. Field data from Palinpinon in the literature were analyzed with the present method. The results showed good estimates of the fraction were obtained during the early period of Cl concentration measurement.

1. INTRODUCTION

Reinjecting separated water from produced fluids has become common strategies for reservoir management at many geothermal fields of water dominated type. This operation has advantages of moderating reservoir pressure decrease due to exploitation as well as avoiding environmental contamination caused by discharging the separated water into nearby rivers or lakes. Care should be taken, however, for designing reinjection scheme such as a location for drilling reinjection wells, depth of reinjection, and reinjection water temperature. This is mainly because that an excessive mixing of heat depleted water into production zones may lead to cooling of reservoir temperature, which results in a decrease in steam output of production wells.

Detecting mixing of reinjected water and estimating its magnitude into produced fluids can be realized through tracer tests. Tracer tests are generally conducted for a newly drilled well to evaluate connectivity between reinjection and production wells prior to initiating operation of reinjection. Alternative methods for detecting effects of mixing reinjected water are chemical monitoring of fluids for both reinjection and production wells. Koga et al.(1988) emphasized advantages of chemical monitoring of these fluids for estimating changes in reservoir conditions upon exploration. They discussed the relationship between Cl concentration increase and enthalpy decrease of produced fluids at the Hatchobaru geothermal field, implying reservoir temperature decrease due to mixing of reinjected water. They also pointed out higher concentration front of Cl gradually extends to production zones with time after commencing reinjection operation. Temperature decrease of produced fluid and chloride(Cl) concentration increase was also reported at Palinpinon, Philippine(Malate and O'Sullivan, 1991).

However, estimating magnitude of the fraction of reinjected water to produced fluids requires mathematical modeling of reservoir systems. Malate and O'Sullivan(1991) developed a model for evaluating a fraction of reinjected water to produced fluids, using a simple lumped parameter model in terms of Cl mass, and applied it to analyze the field data from Palinpinon. Analytical solutions were used for estimating the fraction in a manner of forward analysis, and an optimum value was estimated for the fraction using the data of well PN-26 at Palinpinon for the period of 4 years. As pointed out, an excessive return of heat depleted water into production area would cause a serious temperature decrease and eventually resulting in a decrease in steam out put of production wells.

Thus, estimating a magnitude of the fraction after the initiating reinjection operation is an urgent task for reservoir engineer for improving and modifying a reinjection scheme for a desirable reservoir management in case of accepting serious mixing effects.

We have applied an on -line analysis method using the Kalman filtering(Brown, 1983) to their model and developed a method for estimating fraction of reinjected water to produced fluids. This method has been used to analyze the data from well PN-26 (Malate and O'Sullivan, 1991) and can successfully make good estimates during the early period of Cl concentration measurement.

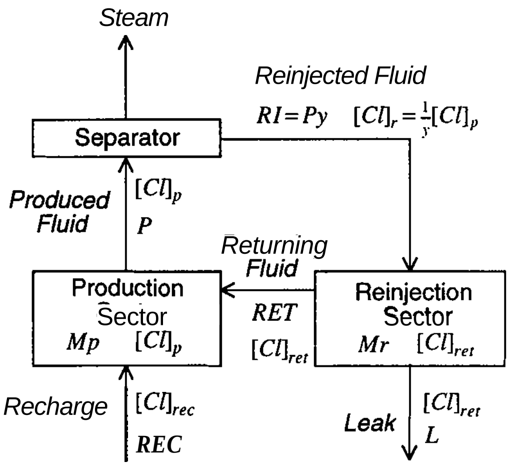

Fig. 1 Reservoir model consists of production and reinjection sectors (Malate and O'Sullivan, 1991).

2.MATHEMATICAL FORMULATION

A reservoir model developed by Malate and O'Sullivan(1991) is shown in Fig.1. The model consists of production, reinjection, and recharge sectors. **A** mathematical model was developed using following assumptions. They are, 1)no change in the mass of fluid stored in each of the production and reinjection sectors, 2)chloride concentration of recharge fluid is constant during the period of exploitation, 3)the fraction of reinjected fluid returning production area is constant, 4)the time delay of the chloride concentration return is assumed to be small. Then, chloride mass balances for both production and reinjection sectors are introduced in combination with fluid mass balances and yield a set of ordinary equations.

$$\frac{d[Cl]_p}{dt}=\frac{P}{M_p}\left\{(1-F)[Cl]_{rec}+F[Cl]_{ret}-[Cl]_p\right\} \qquad (1)$$

$$\frac{d[Cl]_{ret}}{dt}=\frac{P}{M_r}\left\{[Cl]_p-y[Cl]_{ret}\right\} \qquad (2)$$

where F is the fraction of reinjected fluid in the produced fluid(=RET/P) (-), [Cl] is the chloride concentration (mg/kg), P is the flow of production fluid(kg/s), RET is the flow of fluid returning from the reinjection area to'the production area(kg/s), y is the water fraction from the separator(-), M_p is the mass of fluid in the production area(kg), M_r is the mass of fluid in the reinjection area(kg), t is the time(sec). Subscripts *p*, *rec* represent the production and recharge sectors, and ***ret*** the returning fluid from the reinjection area to the production area.

Eqs.(1) and (2) correspond to the system equation to form the Kalman filtering for on-line analysis. Thus, they can be expressed in a vector form as

$$\frac{d\mathbf{x}}{dt}=g(\mathbf{x})+\mathbf{v} \qquad (3)$$

where **x** is the state vector and expressed as

$$\mathbf{x}=[x_1,x_2,x_3,x_4,x_5,x_6]^T$$

where superscript **T** denote transposition.

Components of **x** are; $x_1=[Cl]_p$, $x_2=[Cl]_{ret}$, $x_3=[Cl]_{rec}$, $x_4=M_p$, $x_5=M_r$, $x_6=F$.

The function g(**x**) can be also expressed as

$$g(\mathbf{x})=[g_1,g_2,g_3,g_4,g_5,g_6]^{\mathrm{T}}$$

From the assumptions, $[\mathrm{Cl}]_{\mathrm{rec}}$, $\mathrm{M_p}$, $\mathrm{M_r}$, F are time invariant. Thus, the components of g(**x**) are expressed using the components of x as

$$g_1=\frac{P}{x_4}\left\{(1-x_6)x_5+x_2x_6-x_1\right\},\quad g_2=\frac{P}{x_5}(x_1-yx_5),\quad g_3=g_4=g_5=g_6=0$$

Eq.(3) is descretized in terms of time, then

$$\mathbf{x}_{k+1}=g(\mathbf{x}_k)\Delta t+\mathbf{x}_k+\mathbf{v}_k\Delta t \qquad (4)$$

where Δt is the time increment, subscript k denotes the time step.

The measurement equation is linearly correlated to the state vector and is expressed as

$$\mathbf{y}_k=\mathbf{H}_k\mathbf{x}_k+\mathbf{w}_k \qquad (5)$$

where y is the measurement vector, **H** is the measurement matrix, **w** is the measurement noise vector of zero-mean independent gaussian noise with known covariance **R**. **As** the chloride concentration of the produced fluid is the only measurement among components of the state vector, y and **H** are given as,

$$\mathrm{y}=[y_1],\quad \mathbf{H}=[1,0,0,0,0,0]$$

where $\mathrm{y}_1=[\mathrm{Cl}]_{\mathrm{p}}$.

A function in the state equation(Eq.(4)) is non-linear with respect to the state vector. Thus, it is linearized using Taylor's expansion(Brown, 1983) and expressed as

$$\mathbf{x}_{k+1}=\phi_k\mathbf{x}_k+\mathbf{D}_k+\mathbf{v}_k \qquad (6)$$

where

$$\phi_k=1+\mathbf{J}(\hat{\mathbf{x}}_{k/k})\Delta t$$

$$\mathbf{D}_k=\left\{g(\hat{\mathbf{x}}_{k/k})-\mathbf{J}(\hat{\mathbf{x}}_{k/k})\hat{\mathbf{x}}_{k/k}\right\}\Delta t$$

$$\mathbf{V}, =\mathbf{v}_k\Delta t$$

$$\mathbf{J}(\hat{\mathbf{x}}_{k/k})=\left.\frac{\partial g(\mathbf{x})}{\partial \mathbf{x}}\right|_{\hat{\mathbf{x}}_{k/k}}$$

The hat(^) denotes the estimate. ϕ_k is the state transition matrix and $\mathbf{v}_k\Delta t$ is written as $\mathbf{v}_k$ which is the system noise vector of zero-mean independent gaussian noise with known covariance **Q**. Eq.(6) indicates that the state vector at new time step, t_{k+1}, **is** correlated with that at time, t_k. Then, Kalman filtering algorithm, using Eqs.(5) and (6), provides estimate of x at the time t_k, $\hat{\mathbf{x}}_{k/k}$, using a following set of equations when a new measurement of chloride concentration is made.

$$\hat{\mathbf{x}}_{k/k}=\hat{\mathbf{x}}_{k/k-1}+\mathbf{K}_k(\mathbf{y}_k-\mathbf{H}_k\hat{\mathbf{x}}_{k/k-1})$$

$$\hat{\mathbf{x}}_{k+1/k}=\phi_k\hat{\mathbf{x}}_{k/k}$$

$$\mathbf{K}_k=\mathbf{P}_{k/k-1}\mathbf{H}_k^{\mathrm{T}}\left[\mathbf{H}_k\mathbf{P}_{k/k-1}\mathbf{H}_k^{\mathrm{T}}+\mathbf{R}_k\right]^{-1}$$

$$\mathbf{P}_{k/k}=\mathbf{P}_{k/k-1}-\mathbf{K}_k\mathbf{H}_k\mathbf{P}_{k/k-1}$$

$$\mathbf{P}_{k+1/k}=\phi_k\mathbf{P}_{k/k}\phi_k^{\mathrm{T}}+\mathbf{Q}_k$$

where is **K** is the Kalman gain matrix, **P** is the error covariance matrix of estimated state vector. Superscript **-1** denotes inverse.

3.RESULTS AND DISCUSSIONS

The field data of well PN-26, Palinpinon, were analyzed for estimating a fraction of reinjected water return to the produced fluid. Production rate of fluid at PN-26 was expressed in a form of monthly measurement (Malate and O'Sullivan, **1991)** as shown in Fig.2. This step change of flow with time was used for production rate, P. Concentration of Cl was modified such that the measured values were interpolated to synchronize with the production rate in order to simplify estimating process(Fig.2). Thus, the modified concentration data were used as the measured concentration for analysis. Water fraction of produced fluid (y) was assumed to be constant as 0.65 which is an average value for Palinpinon I . Values of initial estimates for the components of the state vector were given as follows,

$x_1=[Cl]_p=4000$ mgkg, $x_2=[Cl]_{ret}=6000$ mgkg,
$x_3=[Cl]_{rec}=4000$ mg/kg
$x_4=M_p=4x10^8$ kg, $x_5=M_r=4x10^8$ kg

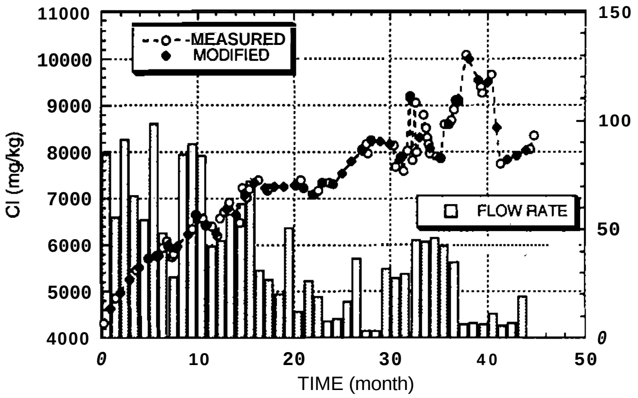

Fig.2 Flow rate history of well PN-26, Palinpinon, and measured concentration of chloride(Cl) of produced fluid. Cl concentration is modified to synchronize to the monthly flow rate data for the use of analysis.

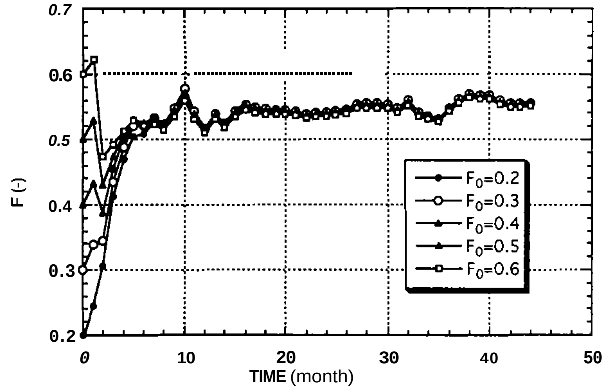

Fig.3 Estimated fraction of returning water to produced fluid for different initial values of fraction(F_0).

Initial estimate for a component x_6(=F) was given in a range of 0.2 to 0.6. During the analysis, values of other components, M_p, M_r, [Cl]„ were assumed to be constant. This is partly because that magnitude of M_p and M_r are larger compared with other variables resulting in errors in estimating. The initial values of error covariance matrix P_{nn} (n=6) were given as $P_{11}=3200$, $P_{22}=7200$, and $P_{66}=2.5x10^{-9}$. All other components were given to be 0. The matrix element of covariance, Q_k, are set to be time invariant as $Q_{11}=25$, $Q_{,,}=56.25$, $Q_{66}=2.5x10^{-9}$ with other components being equal to 0. Those of $\mathbf{R}_k$ were also given to be time invariant as $R_{11}=6.25$ with all other components being equal to 0.

Fig.3 shows changes in estimated fraction(F) with time for different initial values of F(=F_0) ranging from 0.2 to 0.6. Since the fraction of reinjected water to produced fluid was fixed to be 0.65, a value of F can not exceed 0.65. This would automatically set a upper limit for a value of F to be given. All the estimates show approximately same values during the periods from 5-7 months after the start of Cl concentration measurement. Then, all the estimated values vary in a range from 0.52 to 0.58. An average estimate of the fraction between the period of

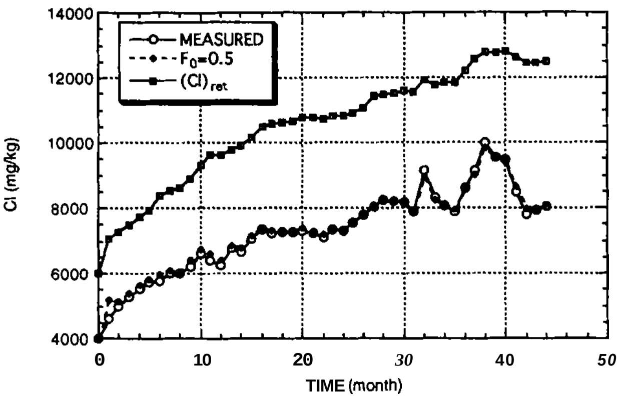

Fig.4 Comparison of estimated and measured concentrations of chloride(Cl) of produced fluid. Estimated concentration is the results for the case of F_0=0.5. Estimated concentration of Cl of returning water(Cl_{ret}) is also plotted.

5months to the last measurement of Cl is calculated to be 0.55 for the case of F_0=0.5. This corresponds to a value of 0.85 for the fraction of the returning water into the production area to the reinjected water, which is approximately the same value of 0.90 derived using a variable production rate model by Malate and O'Sullivan(1991). It should be noted that the present method can estimate an optimum value of the fraction during the early period of Cl measurement. This result implies that the data for a period of first one year would be enough to estimate a value of the fraction.

Fig.4 represents comparisons between the measured Cl concentration of produced fluid and the estimated one for the case of initial value for F_0=0.5. Estimated concentrations of $[Cl]_{ret}$ are also plotted. An excellent match between two kinds of Cl concentration of the produced fluid was obtained. Relative differences between these two kinds of concentrations are in a range from -2.2 to 3.6 % except the very first measurement. Thus, reliable estimate of Cl concentration of the produced fluid can be obtained at each moment of the measurement. Estimated concentration of $[Cl]_{ret}$ shows an continuous increase with time in consistent with the measured Cl concentration.

4.CONCLUSIONS

An on-line analysis method using the Kalman filtering was developed for estimating a fraction of reinjected water to produced fluid on the basis of a simple reservoir model developed by Malate and O'Sullivan(1991). Chloride concentration data of well PN-26, Palinpinon, were analyzed using the method. Good estimates for the fraction were obtained during the early period of Cl measurement even if the initial values of the fraction were given in a range of 0.2-0.6. Estimated chloride concentration of the produced fluid also showed an excellent fit to the measured concentration throughout the measurement period.

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