A METHOD OF ANALYZING TRACER DATA TO CALCULATE SWEPT PORE VOLUME AND THERMAL BREAKTHROUGH IN FRACTURED GEOTHERMAL RESERVOIRS UNDER TWO-PHASE FLOW CONDITIONS

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ABSTRACT
One of the goals of using tracers in geothermal reservoirs is to predict the thermal breakthrough as early as possible. Shook (2001) has shown how this can be accomplished for the case of single-phase flow. In this paper, we show how the thermal breakthrough can be calculated from tracer data for the case of two-phase flow of steam and liquid water in a fractured reservoir without matrix permeability. In particular, we present a method to estimate the swept pore volume of the fracture in a hot, dry geothermal reservoir using partitioning tracers of high volatility. When a tracer with a high partition coefficient (concentration in the vapor divided by the concentration in the liquid) is injected in water, it will partition into the vapor phase and subsequently transport in the vapor phase (steam) toward the production wells. The method uses the first temporal moment of the tracer concentration distribution recorded at the producer to calculate the pore volume contacted by the injected tracer (the swept pore volume). This method has a rigorous theoretical basis and has been widely used in both groundwater and oil field applications. It can be used in the absence of detailed reservoir characterization data or flow and transport models since only a very simple, fast and easy integration of the production data is needed to yield the mean residence time of the tracer. Once the pore volume of the fracture is known, then the thermal breakthrough can be calculated using a retardation factor that takes into account the latent heat of the water.

INTRODUCTION
Reinjection of spent water into a geothermal reservoir is a standard reservoir management practice to maintain the pressure, replenish reservoir fluids, enhance energy extraction efficiency, and dispose of condensed water for environmental reasons. However, reinjection is not risk-free. For example, short-circuiting of injected water can lead to premature thermal breakthrough if injectors are placed too close to the producers. On the other hand, if the injection wells are located too far away, the injected water does not provide sufficient pressure support for production.

Tracer testing is a powerful tool for reservoir characterization and management. Appropriately designed tracer tests yield information such as heat transfer area, reservoir volume, fluid velocities and thermal sweep efficiency (Kumagai et al, 2004; Pruess et al, 2005; Shook, 2001a). Tracers are usually injected in finite slugs and monitored in the surrounding producers to get the tracer return curve. Tracer breakthrough is more rapid than thermal breakthrough (Bodvarsson, 1972; Shook, 2001b), which implies that thermal breakthrough and consequently energy extraction efficiency can be predicted using the tracer return data. However, although 100+ tracer tests have been conducted in the past decade, most of tracer analysis is still qualitative (Shook, 2003).

Fractures are one of the most common characteristics in geothermal reservoirs. In naturally fractured geothermal reservoirs, the rock matrix stores most of energy, while the fracture network serves as flow conduits. The matrix often has very low permeability, typically of the order of 1 micro-darcy or less (Finsterle and Persoff, 1997). The permeability contrast between fracture and matrix is also very high. In a vapor-dominated reservoir, when a tracer with a high partition coefficient (concentration in the vapor divided by the concentration in the liquid) is injected together with spent water, it will partition into the vapor phase and subsequently transport in the vapor phase (steam) toward the production wells. Suitable tracers are available that will partition almost entirely into the vapor, so even though they are injected in the liquid water phase, they will transport almost entirely in the vapor phase. By analyzing the tracer data from the vapor phase, the swept pore volume of the fractures can be calculated in a very simple way as shown in this paper.
A synthetic case study is set up to demonstrate the methodology. A geothermal reservoir simulator is used to calculate synthetic tracer concentration data. The produced tracer concentration data are then integrated to yield the mean residence time and swept pore volume and this pore volume is compared with the known pore volume of the fractures in the part of the reservoir contacted by tracer. Results indicate that accurate calculations of swept pore volume are possible for reservoirs with a high permeability contrast between the fracture and the matrix. After the calculation of swept pore volume, thermal breakthrough is calculated by applying a thermal retardation factor. The whole procedure is very easy to perform and the estimated thermal breakthrough time is close to the time given by the simulator. Although a more complete investigation is needed, these preliminary results indicate that this remarkably simple and robust method of treating geothermal tracer data shows good potential for yielding useful early information to predict energy production from geothermal reservoirs under the special conditions tested described in this paper.

THEORETICAL APPROACH

Shook demonstrated that the reservoir pore volume and geometry could be estimated from conservative tracer tests corresponding to single phase flow (Shook, 1998, 2003). The analysis uses the first temporal moment of the tracer concentration distribution recorded at the producer to calculate the pore volume contacted by the injected tracer (the swept pore volume). This method has a rigorous theoretical basis and has been widely used in both groundwater and oil field applications (Dwarakanath et al, 1999; Sinha et al, 2004). It can be used in the absence of detailed reservoir characterization data or flow and transport models, since only a very simple, fast and easy integration of the production data is needed to yield the mean residence time, which can be done with a spreadsheet. A classical derivation of method of moments theory is available in the work by Himmelblau and Bischoff (1968) with application to packed bed reactors and was later generalized to three-dimensional flow fields (see Sinha et al., 2004, for a recent application to oil reservoirs).

The mean residence volume can be calculated for a finite tracer slug using the following expression.

$$V = \frac{\int V C(t) \text{d}V}{\int C(t) \text{d}V} - \frac{V}{2}$$

(1)

$$N = \frac{\sum V C(t_i) \Delta V_i}{\sum C \Delta V_i} - \frac{V}{2}$$

(2)

In the above equation, \(V_i\) is the total vapor production volume over time interval \(i\) and \(C(t_i)\) is the concentration of the tracer at time \(t_i\). \(V\) is the vapor production volume during the period of tracer injection, and the \(V/2\) term accounts for the finite size of the tracer slug.

TETRAD (Vinsome and Shook, 1993) was used to perform the numerical simulations. Tracers with \(K\) values of 1 and 4500 were used. The \(K\) value is defined as:

$$K_i = \frac{y_i}{x_i}$$

(3)

For a specific component, the \(K\) value is a function of temperature and pressure. In TETRAD, the \(K\) value is calculated from the following equation:

$$K_i = \left(\frac{A}{P} + B + CP\right) e^{-\frac{D}{T-E}}$$

(4)

Where \(A, B, C, D\) and \(E\) are component-dependent constants. The parameters in equation (4) can be calculated using standard thermodynamic data from sources such as Sander (1999). In particular, \(A\) and \(D\) can be calculated from Henry's law constant \((k_H^0)\) and the enthalpy of solution \((\Delta H)\) as follows:

$$A = \frac{\rho_0^0}{k_H^0} e^{\frac{\Delta H}{R}}$$

(5)

The values of \(B, C\) and \(E\) were taken as zero in this study. For specific tracer candidates, their \(K\) values can be estimated using equation (4) and (5). For example, the \(K\) values of tritiated water and 1,1,1,2-tetrafluoroethane (R134a) are about 1 and 4500 under the reservoir conditions of 240°C and 3380 kPa. Tracers with high \(K\) values (more volatile tracers) give early information concerning thermal breakthrough as shown in Figure 1. In this paper, R134a is used in the simulations since it can be used to obtain earlier information about reservoir conditions than low \(K\) value tracers.
MODEL DESCRIPTION

Geothermal reservoirs are usually very complex with features as fractures, heterogeneity, multiple fluid phases and phase transitions, chemical reactions, and thermal effects. A conceptual model of a vertical fracture network in a geothermal reservoir is shown in Figure 2. In this diagram, a producer or injector penetrates a series of parallel, equally spaced, vertical fractures uniformly separated by isotropic and homogeneous matrix blocks. Usually the producer is located in the upper part of the reservoir and the injector is located in the lower part of the reservoir to prevent instability caused by gravity.

Initially, a single fracture was explicitly modeled so the transient process of the heat and mass transfer could be easily visualized. In addition, the single vertical fracture model is sufficient to capture the essential features of tracer transportation and phase transition. Besides, the symmetry of the problem permits the proposed single fracture model. Since the matrix blocks are equally spaced and symmetric in the x direction, only a half plane of the fracture and matrix block was modeled as shown in Figure 3.

Figure 1: Tracer breakthrough time and K value relationship for a reservoir with initial water saturation of 0.3.

Figure 2: Schematic diagram of vertical fractures in geothermal reservoirs (after Gringarten and Witherspoon, 1975)

Figure 3: Diagram of the simplified model of Single Vertical Fractured

The half plane domain is discretized as shown in Figure 4. The main characteristic of this grid is that it is logarithmically spaced in the horizontal direction, which is considered to be the most accurate grid for diffusive-type problems (Bodvarsson and Tsang, 1982). In the vertical direction, 100 grid blocks of uniform size were used.

Figure 4: Grid used for the single fracture model
Table 1 is a summary of the key simulation parameters. A tracer with a K value of 4500 under reservoir conditions was injected for 0.5 days. The following relative permeability models were used:

Fracture:

\[ k_{rf} = \left( \frac{S_w - S_{wRF}}{1 - S_{sRF}} \right)^{1.5} \]  
(6)

\[ k_{rgf} = \left( \frac{S_f - S_{gRF}}{1 - S_{gRF}} \right)^{1.25} \]  
(7)

Matrix:

\[ k_{rwm} = \left( \frac{S_w - S_{wRM}}{1 - S_{wRM}} \right)^{4} \]  
(8)

\[ k_{rgm} = \left( \frac{S_f - S_{gRM}}{1 - S_{gRM}} \right)^{2.5} \]  
(9)

### Table 1: Input summary for the base case

<table>
<thead>
<tr>
<th>Input Parameters</th>
<th>Value</th>
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<td>Length, m</td>
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<td>Thickness, m</td>
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<td>Temperature, °C</td>
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<td>Initial Pressure, kPa</td>
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<td>Rock density (kg/m³)</td>
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<td>Fracture Permeability (md)</td>
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<tr>
<td>Fracture Porosity(fr.)</td>
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<tr>
<td>Fracture aperture (m)</td>
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<tr>
<td>Matrix Permeability (md)</td>
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<tr>
<td>Matrix Porosity(fr.)</td>
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<td>Initial Water Saturation (fr.)</td>
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<td>Residual Water Saturation in Matrix(fr.)</td>
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<td>Producer BHP (kPa)</td>
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<tr>
<td>Injection Temperature (°C)</td>
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**SIMULATION RESULTS**

The produced tracer concentration data are integrated to yield the mean residence time or volume and swept pore volume, and this pore volume is compared with the known pore volume of the fractures in the part of the reservoir contacted by the injected tracer. In this case, all injected fluid would flow through only the fracture since the matrix blocks are impermeable. Figure 5 shows the produced mass fraction in vapor phase of tracer R134a. Tracer breaks through at 9 days after injection, and liquid breakthrough occurs at 272 days. By the liquid breakthrough, more than 99% of injected tracer R134a has been produced.

**Multiple Vertical Fractures**

Figure 6 shows a diagram in which both producer and injector penetrate two identical vertical fractures. This model uses the same initial condition and rock properties as the base case. The calculated swept pore volume from the tracer data in the vapor phase is 1638 m³. This result is very close to the actual fracture pore volume of 1600 m³. This indicates that for a matrix with zero permeability, the method works for multiple fractures as well as for a single fracture.
ESTIMATE OF THERMAL BREAKTHROUGH TIME FROM TRACER

For one-dimensional flow, the relationship between liquid water velocity and thermal velocity is as follows (Shook, 2001c):

$$v_{n} = \frac{v_{L}}{1 + D_{n}}$$  \hspace{1cm} (8)

$$D_{n} = \frac{(1-\phi)\rho_{k}C_{pL}(T_{f}-T_{i})}{\phi \rho_{w}L_{v}}$$  \hspace{1cm} (9)

In above equations, $T_{f}$ is the initial reservoir temperature; $T_{i}$ is the interface temperature, $T = T_{i} + (P_{sw})$; $v_{L}$ is the liquid velocity, and $v_{n}$ is the thermal velocity. The transfer of heat from the rock to the fluid results in a slow down of the thermal front and this is expressed by the retardation factor in equation (9).

Although equations (8) and (9) were derived for flow in a one-dimensional porous media, they can be applied to fractured reservoirs with zero matrix permeability. First of all, the thermal breakthrough time is short in the life of a typical geothermal reservoir, and heat transferred from the matrix is limited in such a short time. Secondly, the temperature gradient between the matrix and the fracture in the vapor zone is low so that the heat flux is minimal at early times.

Since the swept pore volume can be estimated from the tracer data, we can estimate the thermal breakthrough time by performing following steps:

- Calculate the swept pore volume from tracer data, $V_{p}$
- Calculate thermal retardation factor from equation (9)
- Calculate thermal breakthrough time

$$T_{BT} = \frac{V_{p}}{q_{inj}(1 + D_{n})}$$

where $q_{inj}$ is the volumetric injection rate

The case with zero matrix permeability and 500 md fracture permeability was calculated to estimate the thermal breakthrough time. The calculated breakthrough time is 292 days, while the TETRAD simulation result is 272 days.

In general, the length of the fractures is complicated with tortuous fracture patterns, and the porosity of fracture may vary, so the thermal velocity may vary greatly in space. From equation (9), the retardation factor is inversely proportional to the porosity. For example, for a porosity of 0.4, the retardation factor $D_{n}$ is only 0.042. This indicates that a superheated initial condition does not retard the thermal velocity very much. In this case, the thermal velocity is approximately equal to the liquid velocity.

ANALYSIS OF ERROR SOURCES

When spent water is injected into superheated geothermal reservoir, it is subject to vigorous vaporization up to 10-100 kg/s regardless of the injection rates (Pruess, 1997). During the phase transition process, properties of tracer and fluid would change dramatically. The complexity of the process gives rise to some uncertainty in applying the method of moments to this problem. Some of the main sources of uncertainty are thought to be as follows:

- Unsteady-state production rate caused by the boiling of the water causes uncertainty in the calculation of the mean residence time.
- A permeable matrix would result in a large overestimation of the pore volume of the fracture.

The case of a permeable matrix is currently under investigation. In addition to the more complicated physics, issues such as the numerical accuracy of the simulation needed to compare with the simple analytical method must be carefully considered.

SUMMARY AND CONCLUSIONS

Thermal breakthrough can be calculated from tracer data for the case of two-phase flow of steam and liquid water in a fractured geothermal reservoir without matrix permeability. The first temporal moment of the tracer data is used to calculate the swept pore volume of the fracture and then a
retardation factor is applied to calculate the thermal breakthrough time. A tracer with a high partition coefficient is injected in the liquid water but quickly vaporizes and transports in the vapor phase to the production well where its concentration is measured as a function of time. The concentration data and vapor production rate are all that is needed to calculate the swept pore volume of the fracture. So far this method has been applied only to the case of zero matrix permeability and one or two ideal fractures. Extending the proposed method to multiple fractures with variable properties should not be a problem in principle. Extending the method to cases with significant flow in the matrix will be more complicated.

NOMENCLATURE

\( \overline{V} \) mean residence volume (m³)

\( V \) cumulative production volume of vapor phase (m³)

\( V_s \) cumulative production volume of vapor phase during the time of tracer injection (m³)

\( C \) tracer concentration (ppm)

\( K \) thermodynamic equilibrium ratio

\( T \) temperature (°C)

\( P \) pressure (kPa)

\( R \) gas constant (J/mol.K)

\( S \) saturation (fr)

\( k \) relative permeability (md)

\( C_p \) specific heat capacity (kJ/kg.K)

\( k_H \) Henry's law constant (mol/m³.atm)

\( x_i \) mole fraction of species i in aqueous phase

\( y_i \) mole fraction of species i in vapor phase

\( \rho \) density (kg/m³)

\( \phi \) porosity of the reservoir (fr.).

Superscript

\( \vartheta \) standard condition, T=298.15K

Subscripts

\( R \) rock

\( I \) Initial condition

\( a \) aqueous phase

\( f \) fracture property

\( g \) vapor phase water

\( i \) component i

\( r \) residual phase saturation

\( m \) matrix property

\( w \) liquid phase water

REFERENCES


