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Tracer Analysis of Fractured Geothermal Systems

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ABSTRACT

Recent field experiments in Japan have emphasized the importance of performing tracer tests in any geothermal utilization in which reinjection is in use or is planned. This is because rapid short-circuiting between reinjection and production wells may occur due to the fractured nature of the system. In cases where fracturing is such that preferred pathways exist in the reservoir, the result may be a rapid thermal drawdown of the field production. Tracer testing provides a method of evaluating the magnitude of such problems. Previous methods used to analyze the Onuma, Hatchobaru, and Otake tracer tests have used early and long time data, this paper discusses the use of the field concentration/time profile in fractured systems.

INTRODUCTION

Reinjection of waste hot water is practiced in many liquid-dominated geothermal fields (namely Ahuachapan, Otake, Onuma, Kakkonda, Onikobe, Hatchobaru, Mak-Ban, East Mesa, Brawley, and Raft River). The fundamental purpose of reinjection is to dispose of the unused hot water, although it has often been suggested that the reservoir productivity may be increased concurrently. In fact there has been only scant evidence to show support of reservoir performance by reinjection (see Horne 1981), and in fact in some cases it has been seen to be detrimental to production due to early invasion of the cooler injected water through high permeability paths in the reservoir. Furthermore, observations on the effects of reinjection have emphasized the need to pay close attention to the fractured nature of geothermal reservoirs.

The benevolence or malevolence of reinjection in geothermal reservoirs has been seen to be closely related to the degree of fracturing. The degree of fracturing has been most successfully determined by using tracer tests. For example, tracer tests summarized in Horne (1981) indicated a high degree of fracturing in Wairakei, Kakkonda, and Hatchobaru, a moderate or mixed degree in Onuma and Ahuachapan, and a low degree in Otake. In view of the subsequent experience in reinjection it was concluded that understanding the fracture system through the use of tracers should be the first step in designing a reinjection program. Unfortunately however, the methods of analysis appropriate to tracer flow in fractured systems are not yet fully developed, most surveys to date having used only the early time (or in one instance the late time) data. A method of analyzing the full tracer return profile is demonstrated in this work.

EXISTING TRACER ANALYSIS METHODS

The classic petroleum reservoir methods for analysis of tracer tests have commonly been based on uniform "sweep" flow through a porous medium in a given configuration (usually a 5-spot) - see for example Brigham and Smith (1965), Baldwin (1966) and Wagner (1977). In these analyses the system is modelled as a "stack" of non-connecting layers of porous media which are uniform but which nevertheless have differing properties. The tracer "breaks through" different layers at different times, giving rise to the characteristic multiple hump return illustrated in Figure 1. Geothermal systems however show very different returns because of the limitation of flow to fractures and commonly show a single hump return as in Figure 2. The absence of more than one strong tracer return itself emphasizes the highly fractured nature of geothermal reservoirs. It is clearly inappropriate to use the uniform sweep model of the petroleum industry in such instances.

Figure 1: Multiple breakthrough tracer return - from Brigham & Smith (1965)
FEATURES OF GEOTHERMAL TRACER TESTS

Geothermal reservoirs are usually very highly fractured. As a result, and as an indication of this fact, the tracer response almost always shows just a single peak. Thus, although the early and late time analyses are still possible, the analysis of the single peak concentration would provide little extra information, and does in any case require the formulation of a flow model. Thus, there exists a need to formulate a means of analyzing the shape of the single humped tracer response with specific reference to flow in fractures. An attempt to isolate the features of tracer transport in fractures is reported here.

TRACER TRANSPORT IN FRACTURES

Methods of signal analysis are readily applicable to the interpretation of tracer return concentration histories, reducing the observed profile to the sum of its component signals. For example, the tracer concentration in a producing well that receives flow from an injection well through two intervening fractures will demonstrate the superposed transfer functions corresponding to tracer flow through those two fractures. The difficulty in decoupling the response into its component parts depends on defining the features of those component parts. For example, Tester, Bivins, and Potter (1979) describe a method to represent the tracer concentration C at a production point in terms of M independent components, thus:

\[
C = \sum_{j=1}^{M} \xi_j \omega_j (X_j, \theta_j, \Pe_j)
\]

where non-dimensional distance and time are defined by:

\[
X_j = \frac{x_j}{L_j}
\]

\[
\theta_j = \frac{q_j t}{V_j}
\]

where \(x_j, L_j, q_j, \) and \(V_j\) are the position within, length of, flow rate through and volume of the \(j\)-th "path" through the system. \(\Pe_j\) represents the Peclet number of flow through the \(j\)-th path, defined as:

\[
\Pe_j = \frac{u_j L_j}{\eta_j}
\]

where \(\eta_j\) is the diffusivity (or dispersion coefficient) of tracer during transport.

Tester, Bivins, and Potter (1979) proposed the analysis of \(N\) measured values of exit tracer concentration \(C_i\) by minimizing the objective function \(F\), where:

\[
F = \sum_{i=1}^{N} (C - C_i^*)^2
\]

and \(C\) is given by equation (1). Decision variables will be \(\Pe_j, q_j,\) and \(V_j\).

This method can straightforwardly provide estimates of the Peclet numbers associated with the various flow paths, and their relative (but not absolute) rates of flow and relative (but not absolute) values. It does however depend strongly upon the transfer function \(C_j(X_j, \theta_j, \Pe_j)\) assumed in equation (1) for the transport of the tracer. Brigham and Smith (1965) based their determination of the transfer function on flow
through a porous medium between wells in a five spot formation. Tester, Bivins, and Potter (1979) determined transfer functions for one- and two-dimensional flow through porous media.

These two studies do not, however, correctly represent the flow through a fracture in that a tracer front is modelled as propagating perpendicularly to the direction of flow. In a fracture, however, in either laminar or turbulent flow, the tracer will be transported faster in the center of the fracture than on the walls (in fact, due to boundary layer effects, it will not be transported along the walls at all). This is illustrated in Figure 3.

\[ t^* = \frac{2}{3} \frac{x}{u} \]  

where \( t^* \) is the first arrival time of tracer and is given by:

In a practical case, of course, the tracer would not be injected continuously, nor would it be injected at a concentration of 100%. Equation (11) may however be used to superpose the behavior of the leading edge and trailing edge of a tracer slug of initial concentration \( C_0 \), after which:

\[ C = C_0 \left( H(t - t^*) \sqrt{1 - \frac{t^*}{t}} - H(t - \Delta t - t^*) \sqrt{1 - \frac{t^*}{t - \Delta t}} \right) \]

where \( H(x) \) is the Heaviside step function:

\[ H(x) = \begin{cases} 1 & x > 0 \\ 0 & x < 0 \end{cases} \]

and \( \Delta t \) is the length of time the tracer is injected.

Figure 4 shows the normalized tracer return concentration \( C/C_0 \) as a function of normalized time \( t/t^* \) for various values of injection time \( \Delta t/t^* \). The similarity between Figures 4 and 2 should be noted.

**DISCUSSION**

The fact that equation (13) does not appear to include the effects of dispersion may at first trouble some readers, however on closer examination this is not so. The inclusion of the velocity profile across the fracture actually takes the place of the "velocity dependent" dispersion which is normally assumed. This velocity dependent dispersion is commonly included on empirical grounds - this study has demonstrated its physical origin in this problem. A constant (velocity independent) dispersion is usually also included to take account of the effects of tortuosity in porous medium flow as well as molecular diffusion. Since in this case the flow occurs mainly in substantial sized fractures and the travel times are
only of the order of hours, the tortuosity term is zero, and the molecular diffusion is likely to be negligible. Thus, this derivation does in fact implicitly include the fundamental dispersive mechanism for high speed flow in fractures, and furthermore does so from a physical standpoint. The concentration/time profile resulting from equation (13) may be substituted in the general expression for the transfer in equation (1) and then a least squares analysis of field results performed as in equation (5). The results of such an analysis will be the effective length and width of the fracture system connecting reinjection and production wells. This information is essential in estimating the likely effects of thermal drawdown during reinjection.

ACKNOWLEDGEMENT

This work forms part of the cooperative geothermal program between Stanford University and Instituto de Investigaciones Electricidad, Mexico. Funding for Stanford University's participation in this work was provided by the U.S. Department of Energy under contract number DE-AT03-80SF11459.

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