Predicting Thermal Velocities in Fractured Media from Tracer Tests

G. Michael Shook
Idaho National Engineering and Environmental Laboratory

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Abstract
Cooling in geothermal reservoirs arises from, among other mechanisms, the injection of cool water for enhanced heat extraction and reservoir pressure maintenance. In porous media, the velocity of the thermal front can be determined from tracer tests with the appropriate retardation factor that accounts for thermal inertia of the reservoir rock. In fractured media, the thermal velocity is further retarded by heat conduction from the impermeable native rock. This additional retardation factor can be determined from analytic solutions to the 2-D heat conduction problem and the characteristic fluid velocity obtained from tracer tests. A method previously developed for heterogeneous permeable media can therefore be extended to predict thermal velocities in fractured media as well. The method is given and examples shown.

Introduction

Reinjection of spent geothermal fluids has become a standard reservoir management strategy over the past decade. In addition to meeting environmental requirements of condensate disposal, reinjection serves to maintain reservoir pressure and increase energy extraction efficiency over the life of the reservoir. However, because the injected fluid is typically much cooler than the reservoir rock, injection also ultimately leads to cooling of produced fluids. This is a direct result of heat transfer from reservoir rock to the working fluid (water), and is a foregone conclusion whenever cool liquid is introduced into a geothermal reservoir (either via natural recharge or injection). An injection program is simply intended to postpone cooling of produced fluids by improving sweep efficiency of the injected fluids. Optimizing injection requires knowledge of reservoir volume and mean residence time of the injectate. These properties can be estimated from a tracer test.

Tracer testing has also become somewhat of a standard tool for reservoir management (e.g., Rose et al., 1997, 2000; Adams et al., 2001). By injecting a finite slug of a chemical tracer, fluid flow paths, reservoir volume, and mean residence times can be estimated (Shook, 1998). Such information can be used to design an appropriate injection program and avoid “short circuiting” of injected fluids directly to extraction wells.

Other means of analyzing tracer testing have appeared in the literature recently. Shook (1999, 2001) showed that a tracer test can be used to predict thermal breakthrough in geothermal reservoirs. Through an analysis of the governing equations, that work showed that the temperature-to-fluid velocity ratio in a single-phase (liquid) system is a constant that depends only on the ratio of rock-to-fluid volumetric heat capacities, even in the presence of heterogeneity. A variable transform of the tracer data provides a quick and simple means of predicting the onset of cooling of produced fluids. Because the ratio of heat capacities in geothermal reservoirs is typically large (>10), the method provides a means of optimizing injection programs long before the cooling actually occurs. However, the method is restricted to cases where thermal conductivity can be neglected; i.e., in heterogeneous, but *porous* (not fractured), media.

This paper represents a first attempt at extending the method presented previously to fractured media. The method is discussed briefly below, and a physical argument for the modification required is given. An additional time-dependent retardation factor is required for fractured media, which can be calculated from thermal properties of the rock and fluid, fluid velocity (determined from the tracer test), and fracture properties. A single example is given that shows the extension of the method to fractured media is appropriate. Work is continuing in order to provide a robust argument of the method, and to determine its limiting applications.

Previous Work

Propagation of thermal fronts for single-phase fluids in homogeneous media was originally studied by Bodvarsson (1972). By neglecting thermal conduction as a second-order effect, he developed analytic solutions to the governing equations, and showed two important results: that the temperature front lags behind the fluid front by a constant related to the ratio of rock/water volumetric heat capacities, and that there is an abrupt change from the initial temperature ahead of the front to the injected temperature behind the front.

Shook (1999, 2001) derived a set of equations similar to those of Bodvarsson (1972), but noted that no assumption of homogeneity need be made in the derivation. That is, even in the presence of variations in permeability or porosity, the ratio of temperature-to-fluid velocities is given as:

$$\frac{v_T}{v_w} = \frac{v_T}{u_w/\varphi} = \left(\frac{\varphi\rho_w C_{pw}}{\varphi\rho_w C_{pw} + (1-\varphi)\rho_r C_{pr}}\right) = \frac{1}{1+D_T} \tag{1}$$

where $D_T = \dfrac{(1-\varphi)\rho_r C_{pr}}{\varphi\rho_w C_{pw}}$.

The thermal retardation factor, D_T, reflects the fact that energy travels through both fluid-filled pores and the rock fabric, and is therefore retarded relative to the fluid velocity. An important point to note (and which will be used shortly) is that for porous media, the fluid and energy (temperature) both flow through the same *bulk* volume. From Equation 1 above, the arrival time of a temperature front at a fixed distance (say, at an extraction well) is delayed relative to the fluid front by a constant value:

$$t_T^{BT} = t_w^{BT}(1+D_T) \ . \tag{2}$$

Shook (1999, 2001) also developed a variable transform that allowed the use of tracer data to predict temperature velocities as follows. We imagine the reservoir is made up of streamtubes that connect injection wells and extraction wells. Each individual streamtube is homogeneous; the tubes' varying length is what gives rise to the dispersed nature of a (typical) tracer recovery curve. The fractional cumulative recovery of tracer at any time, say $T_p(t)$, corresponds to the fraction of streamtubes that have delivered tracer to the production well. Temperature isotherms follow the same streamtubes; their velocity is merely retarded as given in Equation (1).

Therefore, at some time t* (greater than t as given in Equation (2)), that same fraction of streamtubes would experience an abrupt temperature change from the initial temperature T_I to the injected temperature, T_J. The aggregation of the various length streamtubes is what gives rise to the dispersed nature of the temperature decline.

Therefore, to forecast temperature decline in heterogeneous (but porous) media, transform tracer recovery data to predicted temperatures, T_p, as:

$$T_p(t) = \frac{\int_0^t q(\tau)C(\tau)\ d\tau}{\int_0^\infty q(t)C(t)dt} \tag{3}$$

and change time to t* following Equation (2):

$$t^* = t(1 + D_T) = t\left(1 + \frac{(1-\varphi)\rho_r C_{pr}}{\varphi\rho_w C_{pw}}\right) \tag{4}$$

These variable transformations can be made in a spreadsheet program, and serve as a predictor of a dimensionless temperature change, T_D vs. time, t. T_D is defined as:

$$T_D = \frac{T(t) - T_I}{T_J - T_I}\ . \tag{5}$$

Extension to Fractured Media

The simplicity of the method described above for porous media warrants an attempt to apply it to fractured media. For the purposes of this study, we assume that fluid flows only in the fracture, while heat (energy) is transported through the fracture and rock. The volume of rock matrix that supplies heat to the fracture is a complex function of time and position, but can nevertheless be estimated. In contrast with the porous media case given above, we now have a case where the temperature wave travels in the same bulk volume as the fluid *plus* a time-varying volume of rock matrix. Therefore, a reasonable modification to Equation 1 for the case of fractured media is:

$$\frac{v_T}{v_w} = \frac{v_T}{u_w/\varphi} = \left(\frac{(V_b\varphi)_{fr}\rho_w C_{pw}}{(V_b\varphi)_{fr}\rho_w C_{pw} + [(V_b)(1-\varphi)]_{fr}\rho_r C_{pr} + V(t)_{ma}\overline{\rho C}_p}\right) \tag{6}$$

where the apparent volumetric heat capacity of the rock matrix is given as:

$$\overline{\rho C_p} = \varphi\rho_w C_{pw} + (1-\varphi)\rho_r C_{pr}$$

Using similar nomenclature for a retardation factor for this case, Equation (6) can be written as:

$$\frac{v_T}{v_w} = \frac{1}{1 + D_{T1} + D_{T2}} \tag{7}$$

or $$t_T^{BT} = t_w^{BT}(1 + D_{T1} + D_{T2})$$

where

$$D_{T1} = \frac{(1-\varphi)\rho_r C_{pr}}{\varphi \rho_w C_{pw}} \tag{8}$$

and

$$D_{T2} = \left(\frac{V(t)_{ma}\,\overline{\rho C}_p}{(V_b \varphi)_{fr}\,\rho_w C_{pw}} \right) \tag{9}$$

The only difficulty being to estimate the volume of rock matrix affected by the fluid flow in the adjacent fracture, V(t). For a 1-diminsional, constant width and aperture fracture, V(t) can be determined by integrating the "thermal penetration distance" (Bird et al., 1960, p. 354) over fracture length:

$$V(t) = \int_0^L Wz(x,t)dx = \frac{8}{3} W v_w \sqrt{\kappa} \left(t^{3/2} + \left(\frac{\rho_w C_{pw} b}{K_r} - 1 \right) \left(t - \frac{L}{v_w} \right)^{3/2} \right) \tag{10}$$

In order to implement this method, fracture parameters width, W, aperture, b, and length, L, must be estimated. Given these values and estimates of the thermal properties of the rock matrix, the time-dependent retardation factor, D_{T2} can be determined.

Simulated Example

To evaluate the utility of the modifications described above, consider the following simulated example. A tracer test was simulated using TETRAD (Vinsome and Shook, 1993), and the tracer effluent history was used to predict the temperature decline in the extraction well. The reservoir consists of a single, 100 m long, homogeneous fracture in contact with a 78.5 m thick, low permeability and porosity rock matrix. Fracture permeability is taken as 1000 md, and porosity is 1. Rock properties are k=0.001 md and φ = 0.05. Initial temperature and pressure are such that the reservoir is single phase liquid. Dimensions, initial and boundary conditions, and petrophysical and thermal properties for the example are summarized in Table 1.

Property	Fracture	Matrix
L	100 m	100 m
H	0.1 m	78.5 m
$_w$	1000 kg/m^3	1000 kg/m^3
C_{pw}	4 kJ/kg- ^{o}C	4 kJ/kg- ^{o}C
$_r$	N/A	2650 kg/m^3
C_{pr}	N/A	1 kJ/kg- ^{o}C
K	N/A	181.5 kJ/m- ^{o}C -d
K	1000 md	0.001 md
J	1.	0.05
T_I	175 ^{o}C	175 ^{o}C
P_I	1400 kPa	1400 kPa
Injection rate	0.0035 kg/s	

Table 1. Summary of properties for example problem.

At t=0, liquid water at T=35^{o}C is injected at a rate such that fluid velocity in the fracture is 3 m/d (the permeability contrast between fracture and matrix precludes essentially any flow of injectate into the matrix). A conservative tracer is added to the injectate for the first day of injection. The simulation proceeds for 10,000 days, at which time the extraction temperature has fallen to about 78 ^{o}C.

The tracer recovery history for the example is given in Figure 1. The slight asymmetry in the tracer data shows the small extent of tracer flow into the rock matrix. This data can be integrated numerically using a spreadsheet program to determine *Predicted Temperatures* following Equation 3. Fluid velocity and fracture volume can be determined from the first temporal moment of the tracer data (e.g., Shook, 1998). Because fracture porosity is unity, D_{T1} is zero, and D_{T2} can be calculated from Equations 8 and 10 above. A spreadsheet program again is adequate to calculate *Predicted Time*, t*.

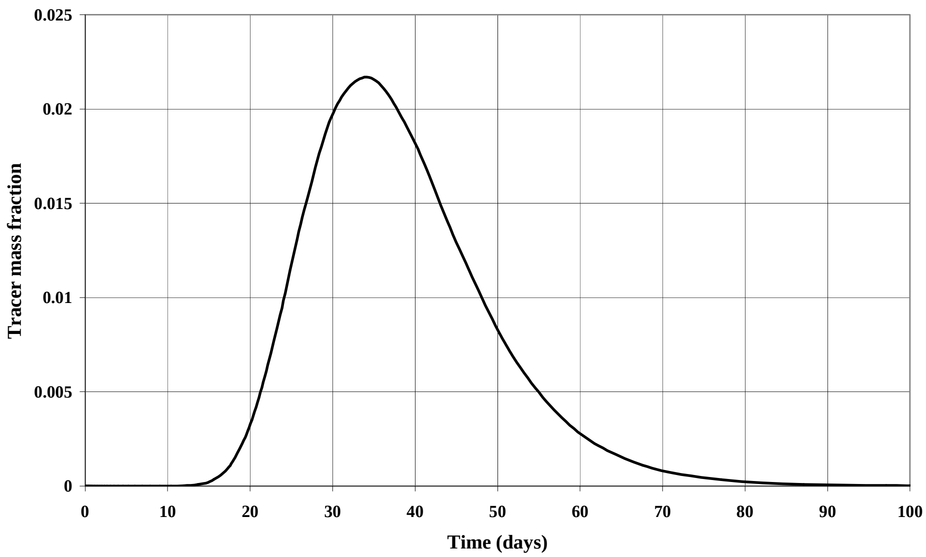

Figure 1. Tracer recovery history for sample problem.

A comparison between the simulated production temperature history (which is taken as "truth") and the predicted temperature history is given in Figure 2. There is excellent agreement between simulated and predicted dimensionless temperatures for T_D less than about 0.4 (T>120 ^{o}C). This confirms that the method originally developed for porous media can be modified for use in fractured media as well.

Summary

A method previously developed for predicting thermal velocities in porous media has been modified for use in fractured media. An additional retardation factor that accounts for the thermal inertia of the rock matrix results in an excellent match between simulated and predicted temperature histories. The additional retardation factor is time dependent, and is a function of fracture properties, thermal properties of the rock matrix, and fluid velocities in the fracture. Many of these properties can be estimated from a tracer test, the balance (e.g., thermal properties of the rock) must be either measured or estimated.

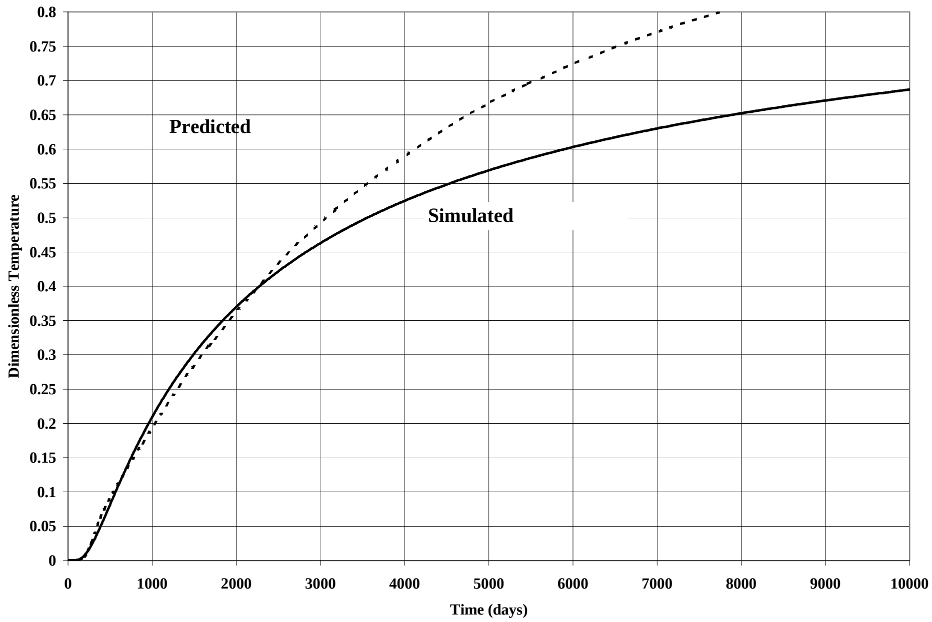

Figure 2. Comparison between simulated and predicted dimensionless temperature for example problem.

Additional work is required to determine the limitations of the method developed. For example, the thermal penetration distance was determined by assuming an infinite rock matrix thickness. While that assumption is likely good at early times (e.g., small dimensionless temperatures) the duration of the infinite acting time should be dependent on other properties such as fracture length-to-matrix width ratios. A more robust argument for determining the new retardation factor, D_{T2}, and limitations of the method are currently being investigated.

Acknowledgments

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Nomenclature

C	tracer concentration in effluent
C_{pr}	rock specific heat (J/g ^{o}C)
C_{pw}	liquid specific heat (J/g ^{o}C)
K	thermal conductivity for rock, r, or fluid, w (W/m ^{o}C)
T	temperature (^{o}C)
t	time (s)
t^*	predicted time, as defined in Equation (4)
t^{BT}	breakthrough time for either fluid (w) or temperature (T)
T_D	dimensionless temperature as defined in Equation (5)
T_I	initial temperature (^{o}C)
T_J	injected temperature (^{o}C)

T_p predicted dimensionless temperature (from tracer test analysis)
u_w Darcy velocity of liquid phase (L/t)
v_T velocity of thermal front (L/t)
v_w interstitial velocity of fluid (L/t)
φ porosity
κ thermal diffusivity (L^2/t)
ρ_r rock density (kg/m^3)
ρ_w liquid density (kg/m^3)

Subscripts
ma related to rock matrix properties
fr related to fracture properties

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