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Fractional derivative-based tracer analysis method for the characterization of mass transport in fractured geothermal reservoirs

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ABSTRACT

The fractional advection-dispersion equation (fADE) has been proposed to describe mass transport in a fractured reservoir. This study develops a finite discrete method to solve the fADE and tests its accuracy against analytical solutions. Tracer simulation uses a three-dimensional simulation of flow analysis (FRACSIM-3D). The solution to the fADE incorporating a spatial fractional derivative shows reasonable agreement with the tracer response from FRACSIM-3D, which shows highly anomalous behaviors such as a long tail. The prediction by the fADE model is reasonably similar to those of FRACSIM-3D irrespective of differing well intervals.

1. Introduction

The lifespan of geothermal resources may be prolonged by a reinjection process, thereby delaying pressure decline and preventing run-out of water in a geothermal reservoir (Stefansson, 1997; Kaya et al., 2011; Axelsson et al., 2005). However, one of the important problems with reinjection is the possibility of an early thermal breakthrough in production wells. Premature breakthrough and injection-induced cooling continue to be problems associated with injection into the geothermal reservoir. Evaluation of the effect of injected water on flow and thermal properties within the geothermal reservoir is essential for the optimal management and protection of subsurface fluid resources.

Tracer testing is a standard method of determining mass transport within a geothermal reservoir and can be a valuable tool in the design and management of production and injection operations (Horne, 1985; Niibori et al., 1995; Pruess, 2002). Methods have also been discussed for predicting thermal breakthrough in fractured reservoirs based on information from tracer tests, e.g., by Lauwerier (1955), Gringarten et al. (1975), Gringarten and Sauty (1975), Pruess and Bodvarsson (1984), and Kocabas (2005). Shook (2001) discussed the potential application of tracer data to provide relatively simple reservoir properties and to predict thermal breakthrough. Such information could provide a means of optimizing injection conditions and managing energy extraction (Wu et al., 2008). Furthermore, Lovekin and Horne (1989) and Juliusson and Horne (2013) reported methods for optimizing injection schedules in geothermal reservoirs based on tracer return data using numerical simulations. In these cases, the production and injection wells were supposed to be already installed. The proposed method can be advantageous to predict mass transport at a location without any wells; and, based on field tracer data obtained from a limited number of wells, to determine where to optimally locate injection and/or production wells.

The inter-well properties provided by tracer tests are strongly controlled by the fracture geometries. Flow simulation models based on geological observation are often used to attempt quantitative assessment of tracer response curves. Discrete and continuum approaches form the two main branches in modeling the fluid flow and solute transport in fractured rocks. Simulations using the dis-

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crete fracture system or the hybrid discrete continuum system with hundreds or thousands of fractures were developed from a need to represent more realistic fracture system geometries (Long and Witherspoon, 1985; Zimmerman and Bodvarsson, 1996). Since the discrete fracture network models incorporate many details and data, understanding and quantifying the geological and physical uncertainties remains the main task for the development of such models (Neuman, 2005). Numerical simulations used commonly in the previous studies depict the rock as a dual continuum, and include the dual porosity method (Barenblatt et al., 1960; Coats and Smith, 1964), dual permeability method (Gerke and van Genuchten, 1993), and the more general multi-interacting continua (MINC) method (Warren and Root, 1963; Kazemi, 1969; Pruess and Narasimhan, 1985). The continuum approaches can be managed to simulate the flow and mass transport in a fractured reservoir using relatively few parameters compared with the discrete fracture approach. Nevertheless, in order to characterize complicated structures, a simulation model is required to incorporate many input parameters, and thus model calibration requires either time-consuming statistical treatment or subjective evaluation.

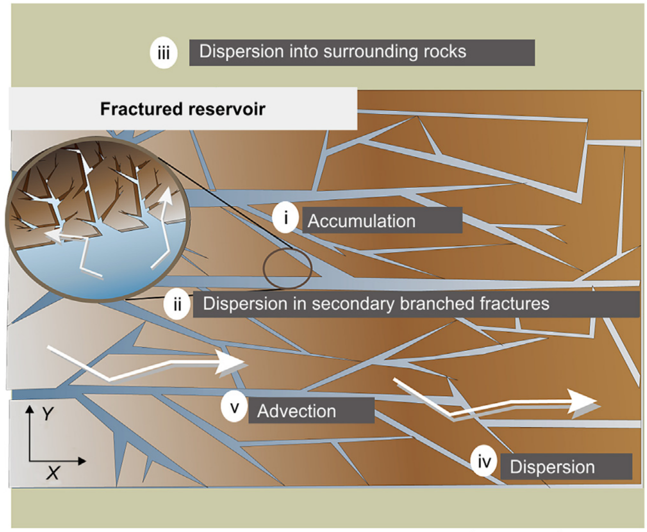
A classical transport model, which can be used to analyze the tracer experiments, is the one-dimensional form of the well-known advection-dispersion equation (ADE) (Bear, 1972):

$$\frac{\partial c}{\partial t} = -u\frac{\partial c}{\partial x} + D\frac{\partial^2 c}{\partial x^2} \tag{1}$$

Here, c is solute concentration, u the average linear velocity, x the distance, τ the time, and D [m^2/s] is the dispersion coefficient. This model describes mass transport in the standard continuum description using the macroscale mass transport variables such as velocity and dispersion coefficient.

In many field experiments effluent tracer breakthrough curves often display a persistent skewness or leading and/or trailing edges that cannot be explained by the ADE. Some researches suggest that long tailings are attributed to recycling of the tracer, or injection conditions (Rose et al., 2004; Juliusson and Horne, 2013). However, non-Fickian tails have also been observed on a simple experiment conditions in laboratory-scale and field-scale tracer tests (Hatano and Hatano, 1998). Complexity of fracture distribution in a reservoir has been discussed to interpret the observed tailings in previous studies. Mathematical models accounting for diffusion and interaction of solutes with the intact rock matrix (Neretnieks, 1983; Moreno et al., 1985), discrete flow channeling (Neretnieks et al., 1982; Tsang and Tsang, 1987), and fracture-matrix model (Bullivant and O'Sullivan, 1989) have been proposed. A generalization of the mobile/immobile phase transport equation was given by the fractional advection-dispersion equation (fADE) (Benson et al., 2000a, 2000b; Schumer et al., 2003; Zhang et al., 2009). Fomin et al. (2011), amongst others, focused on the effects of fracture (fractal) geometry in a fractured reservoir on mass transport and derived the fADE through the use of fractional derivatives in time and space. Understanding of the complex fracture pattern in geothermal reservoirs is of crucial importance for the design of reinjections. The fADE can provide anomalous behaviors of tracer responses using limited parameters, which makes it possible to quickly and efficiently analyze mass transport in a fractured reservoir.

In this study, we discuss the applicability of the fADE derived by Fomin et al. (2011). Recently, we reported that the fADE (Fomin et al., 2011) showed good agreement with tracer responses including tailings, which were simulated by a numerical simulation of fractured reservoirs. The tracer test was performed during reinjection operation, namely in the case where water is introduced at an injection well and reaches a production well at atmospheric pressure. In that case, the prediction was verified for confined well spacing (50–80 m). The objective of this paper is to extend the tracer analysis of Suzuki et al. (2012). This paper presents tracer tests performed in one-dimensional flow as natural condition, and fADE was applied for prediction at wider well spacing (~500 m).



$$\underbrace{\frac{\partial C}{\partial \tau}}_{\text{i}} + \underbrace{b\frac{\partial^\gamma C}{\partial \tau^\gamma}}_{\text{ii}} + \underbrace{\frac{\partial^\beta C}{\partial \tau^\beta}}_{\text{iii}} = \underbrace{\frac{1}{Pe}\frac{\partial J}{\partial X}}_{\text{iv}} - \underbrace{\frac{\partial C}{\partial X}}_{\text{v}}$$

$$J = D\left(p\frac{\partial^\alpha C}{\partial X^\alpha} + (1-p)\frac{\partial^\alpha C}{\partial (-X)^\alpha}\right)$$

C : concentration
T : time
J : mass flux
b : retardation factor
Pe : Peclet number
p : skewness parameter
D : dispersion coefficient
α,β,γ : fractional derivative
$(0<\alpha\leq 1)$ $(0<\beta\leq 1)$ $(0.5\leq\gamma\leq 1)$

Fig. 1. Schematic of the fADE in a fractured aquifer.

2. Mathematical model of mass transport

2.1. Governing equation

Fomin et al. (2011) proposed the one-dimensional fractional advection-dispersion equation (fADE) to model solute transport in a fracture (fractal) system. A schematic of a fractured reservoir is shown in Fig. 1. We assume that the fractured reservoir consists of a complex distribution of natural fractures, which is characterized through fractal geometry. There is natural flow in the horizontal (X-axis) direction, and the main fluid trend is flowing along fractures. The reservoir is surrounded by rock masses of lower permeability. An understanding emerged of the importance of general non-locality in upscaled transport in heterogeneous aquifer material. The non-locality arises when the underlying velocity field is uncertain and correlation scales are significantly large relative to the scale of observation (Zhang et al., 2009). On the basis of the above assumptions, the governing equation of mass transport in a fractured reservoir is derived as follows:

$$\phi\frac{\partial c}{\partial t} + a\frac{\partial^\gamma c}{\partial t^\gamma} + a'\frac{\partial^\beta c}{\partial t^\beta} = -\frac{\partial(\phi J)}{\partial x} - v\frac{\partial c}{\partial x} \tag{2}$$

where t and x are time and distance, respectively; c and J are the mean concentration and the mean diffusive mass flux in the fractured reservoir, respectively; ϕ the porosity; a and a' the retardation factors, which are related to dispersion process into secondary branched fractures and diffusion into surrounding rocks, respectively; v the mean velocity, at which the flow of solutions occurs only along fractures; and β $(0.5<\beta<1)$ and γ $(0.5\leq\gamma\leq 1)$ are the order of fractional temporal derivatives. One attempt to incorporate spatial non-locality in a tractable form assumed a power-law