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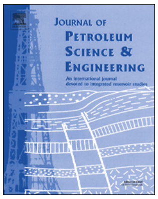

Temperature nanotracers for fractured reservoirs characterization

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ABSTRACT

Nanoparticle tracers are being investigated as a potential tool to measure temperature distributions in subsurface reservoirs. If the temperature distributions could be measured more precisely, this would greatly enhance the ability to estimate other reservoir properties, which would in turn inform reservoir engineering and field management decisions. Work toward two distinct but parallel objectives are described here. The first is to rank the informativity of various tracer candidates using modeling. The second is to develop temperature sensitive tracers experimentally, such that they would be capable of characterizing fracture properties and temperature distribution.

The design of temperature-sensitive tracers is built around the design of the temperature sensing mechanism. In other words, the mechanism by which temperature is measured and the form and resolution of the resulting data, or response, have a profound impact on how informative that tracer can be about thermal breakthrough. Therefore, it is important to model the responses of candidate tracers in the context of an inverse problem to determine their relative informativity. In order to quantify tracer informativity for the simplified case in which the reservoir consists of a single parallel-plate fracture, one-dimensional analytical models were used to calculate the responses of four tracer types: conservative solute tracer, dye-releasing nanotracer, threshold nanoreactor, and temperature–time tracer (TTT). Inverse modeling was performed for various scenarios, and thermal breakthrough curves were calculated for each solution found. Tracers investigated in this study were found to perform very well, with small ranges of uncertainty for both thermal breakthrough forecasting and fracture property estimation. This was because the problem was highly constrained by defining the reservoir as a single fracture. For more realistic reservoir models consisting of complex fracture networks, it is expected that the uncertainty ranges would be larger and that all three temperature-sensitive tracers investigated here will outperform conservative solute tracers because their responses contain information about the temperature distribution.

Experiments were performed to evaluate several potential nanosensor candidates for their temperature-sensitivity and to investigate particle mobility through porous and fractured media. Temperature-sensitive particles investigated in this study include the irreversible thermochromic, dye-attached silica and silica-protected DNA particles. A combined heat and flow test confirmed the temperature-sensitivity of the irreversible thermochromic particles by observing the color change. A detectable change in the fluorescent emission spectrum of the dye-attached silica particles upon heating was observed.

The processing and detection of silica-encapsulated DNA particles with hydrofluoric acid chemistry was tested. A protocol to release the DNA by dissolving the silica layer without completely destroying the DNA was established. The silica-encapsulated DNA particles were flowed through a porous medium at high temperature. Some dissolution of silica particles was observed, leading to a reduction in their size.

This research showed that synthesizing particles to respond to a specific reservoir property such as temperature is feasible. Using particles to measure reservoir properties is advantageous because particles can be transported to areas in the reservoir that would not be accessible by other means and therefore provide measurements deep within the formation.

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1. Introduction

In both geothermal and oil environments, reservoir description including fracture characterization plays an important role in new field development and existing asset management. Despite advances in seismic, tracer testing and other imaging and sensing technologies, reservoirs (particularly fracture networks) are still poorly known. The flow through natural and engineered geothermal reservoirs as well as through carbonate rock formations is largely fracture-dominated. This has spurred a wide interest among researchers in developing new methods to characterize reservoirs specifically with respect to fracture networks.

Using nanomaterials as reactive tracers could enhance control of their response to temperature, potentially providing more information about the reservoir temperature distribution, fracture geometry, and fracture network topology. Nanotechnology provides promising possibilities for the creation of threshold reactive tracers. Redden et al. (2010) suggested the use of encapsulated nanoreactors to infer the temperature history in geothermal reservoir applications. Encapsulating the reactants in a nanoparticle or nanoreactor could provide more control over the conditions under which reaction can proceed. Particle tracers that release dye upon reaching a threshold temperature are another possibility (Alaskar et al., 2011). Williams et al. (2010) also proposed a dye-release mechanism, in which encapsulated dyes are released once a threshold temperature is reached. Rose et al. (2011) proposed surface-modified quantum dots to measure the fracture surface area at the interwell spacing in enhanced geothermal systems. Saggaf (2008) envisioned futuristic multifunctional nanorobots (called resbots) to measure and store information about pressure, temperature and fluid type. Temperature-sensitive nanomaterials have already been used in the biomedical industry for drug delivery to particular types of body cell that differ in temperature from normal cells (Sutton et al., 2007). Nanoparticle drug carriers are made to target disease-specific locations and release the drug at controlled rates (Kreuter, 1994; Moghimi et al., 2001; Panyam and Labhasetwar, 2003; Panyam et al., 2003). Thermally-activated nanoparticles in biomedical applications were designed to respond to temperatures slightly above 37 °C (Chilkoti et al., 2002). Although this temperature is much lower than that in subsurface reservoirs, this concept shows promise. Thus, synthesizing temperature-sensitive nanomaterials that are applicable for subsurface reservoirs may be feasible. Because such sensing mechanisms are central to the design of these tracers, it is important to know which scheme would provide the most useful information.

The goal in making temperature-sensitive tracers is to make a tool that is capable of providing the best possible information about future reservoir behavior. Therefore, the central design attributes for such tracers is their informativity and the type of information they provide. There are other very significant attributes, such as the cost of manufacturing and the level of technical challenge, but these are secondary to the informativity. For example, if a tracer that can measure the highest temperature it encountered in the reservoir is cheap to make and technically easy to implement in a tracer test, but the information it provides cannot be used to reliably forecast future reservoir behavior, then it is not a good tracer candidate. Therefore, it is important to know how informative a tracer is with respect to future behavior prior to designing its specific attributes such as material and structure. Modeling can provide such insight, which can in turn be used to help direct effort and resources toward the most robust tracer with respect to informativity, level of technical challenge, and cost.

The work described here was performed with two distinct but complementary goals in mind. The first was to model the responses of tracer candidates and quantitatively rank their informativity for characterizing fracture networks in the reservoirs and forecasting their future behavior. Simple inverse modeling was performed for several promising tracer candidates and a reservoir model consisting of a single fracture. The second goal was to develop nanotracers experimentally capable of acquiring specific data about the reservoir temperature near the wellbore and far out in the formation and correlate such information to fracture geometry and fracture network topology. Experiments were used to investigate a number of temperature-sensitive nanoparticle candidates that have a reaction temperature within a temperature range appropriate to geothermal and oil reservoirs.

2. Temperature-sensitive nanotracer modeling

It is critical in the design of temperature-sensitive tracers to rank candidate tracers by their informativity. To this end, analytical models were used to calculate responses for four types of tracers flowing in a single fracture: traditional conservative solute tracers (CSTs), dye-releasing nanotracers (DRNTs), threshold nanoreactors (TNRs), and temperature–time tracers (TTTs). The reservoir temperature distribution was modeled using the analytical solution for a single fracture. Inverse analysis was carried out for this simple problem, and an ensemble of 1000 solutions was obtained for each tracer candidate.

2.1. Modeling tracer responses

Return curves for all tracers were calculated using the one-dimensional analytical solution to the advection–dispersion equation with flux initial and boundary conditions (Kreft and Zuber, 1978), which is given as

$$C(x,t) = mx/q\sqrt{4\pi D_{Taylor}t^3}\,\exp\left(-(x-ut)^2/4D_{Taylor}t\right) \tag{1}$$

where C, x, t, m, q, D_{Taylor}, and u are tracer concentration, position, time after initial tracer injection, tracer mass injected, volumetric injection flowrate, Taylor dispersion coefficient, and average fluid velocity, respectively.

All temperature distributions used to model tracer responses were calculated using the analytical solution for temperature in a single fracture derived by Gringarten and Sauty (1975). When the flow channel has a porosity of 100%, this solution reduces to the parallel plate solution, which is given as

$$T(x,t) - T_0/T_{INJ} - T_0 = \mathrm{erfc}\left[\left(x/2bu\rho_W C_W\right)\cdot\left(t-(x/u)/K_R\rho_R C_R\right)^{-0.5}\right] \tag{2}$$

where T, T_0, T_{INJ}, b, ρ_W, C_W, K_R, ρ_R, and C_R are reservoir temperature, initial reservoir temperature, injection temperature, fracture half-aperture, water density, water specific heat capacity, rock thermal conductivity, rock density, and rock specific heat capacity, respectively, and all other parameters are previously defined.

Random Gaussian noise was added to all tracer responses to create the synthetic datasets to be fit in the inverse analysis.

2.1.1. Conservative solute tracers

Conservative solutes such as fluorescein and naphthalene sulfonates are used commonly as tracers to characterize reservoirs. These tracers are very useful for characterizing well connectivity, but lack the capability to measure fracture properties or reservoir temperature distribution. Therefore, these tracers are expected to represent the lower bound on tracer informativity, which is useful to model in order to establish a baseline for comparison. The dispersion coefficient was modeled using the analytical solution for the Taylor dispersion coefficient in a parallel-plate fracture given by James and Chrysikopoulos (2003). This solution is shown as

$$D_{Taylor,\,Sol} = \mathfrak{D}_{Sol} + \left(2u^2b^2/105\mathfrak{D}_{Sol}\right) \tag{3}$$