

# Temperature determination using thermo-sensitive tracers: Experimental validation in an isothermal column heat exchanger



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## ABSTRACT

The estimation of thermal drawdown and its spatial and temporal evolution is a major challenge in the context of geothermal reservoir management. Column experiments were performed with the aim of assessing the potential of thermo-sensitive tracers to measure prevailing in situ temperatures of the flowed-through medium. The results from 40 isothermal experiments with different residence times and temperatures using thermo-sensitive tracers are presented. The resulting precise temperature estimates were independent of the residence time and measured concentration. Considering pH, an accuracy of up to 1 K was achieved. The underlying theory was successfully verified and the general applicability proven.

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## 1. Introduction

With an estimated technical potential of up to 5000 EJ per year, geothermal energy is considered as one of the largest renewable energy resources (WEA, 2000; IPCC, 2011). Due to its widespread distribution, the challenge lays in the technical ability to exploit this huge potential (WEA, 2000). While various factors can impact geothermal power generation efficiency, one of the biggest exergy losses can be attributed to the reinjection of geothermal fluids (Yari, 2010). This practice leads to thermal drawdown in the injection region. There is also the potential risk of early thermal breakthrough, since the extracted energy exceeds the natural heat flow in nearly all geothermal reservoirs (O'Sullivan et al., 2010). Nevertheless, reinjection can serve a beneficial role in reservoir management as it can provide for the safe disposal of the geothermal wastewater, the maintenance of reservoir pressures and the reduction of subsidence due to compaction (Stefansson, 1997). Consequently, there is a demand for new sophisticated reservoir tools that can help to guide management procedures and improve the efficiency of geothermal power generation.

In this context, knowledge of the position of the thermal front would provide valuable information toward quantifying the thermal drawdown and estimating the risk of early thermal breakthrough. However, all currently available monitoring and characterization techniques, e.g., geophysical, borehole and/or tracer methods lack a direct in situ measure for quantifying this

drawdown. New chemical compounds may close this gap. Today, tracer tests are an established tool, which provides an increasing number of reservoir-relevant metrics. In addition to the classical evidence of hydraulic connections, further information can be gained such as reservoir size and recharge rates (Rose et al., 1999), mean residence times and reservoir volumes (Shook, 1998). Tracer methods have become an important characterization tool for the investigation of thermal drawdown (Axelsson et al., 2005). Commonly, the analysis is based on analytical or numerical retardation relationships linking the tracer front to the thermal front in porous media (e.g. Bodvarsson, 1972; Pruess and Doughty, 2010; Shook, 2001; Suzuki et al., 2014). Recently, the possibility of using the temperature signal itself as a “tracer” was discussed (Maier and Kocabas, 2013; Jung and Pruess, 2013). All of the existing concepts are based on idealized assumptions with regard to geometry and the parameters, that are used. Therefore, the obtained solutions are usually non-unique (Axelsson et al., 2005). Shook (2001) concluded that tracer test data can only be reliably analyzed when considering these narrow restrictions. The recently introduced thermo-sensitive tracers (TSTs) described by Nottebohm et al. (2010) have the potential to provide a new testing routine allowing the measurement of the thermal state of a geothermal reservoir. TSTs were proposed for the first time in the Mid-1980s (Robinson et al., 1984; Tester et al., 1986), but confirmation of the capability of TSTs is still pending. Previous laboratory (Robinson et al., 1984) and field (Kwakwa, 1988) experiments can be built upon with new compounds and measurement techniques. The thermal dependence of ester compounds, as the TSTs tested, is based on its pseudo-first order hydrolysis reaction (Nottebohm et al., 2010) in contact with water. In this investigation, phenol acetate (PhAc)

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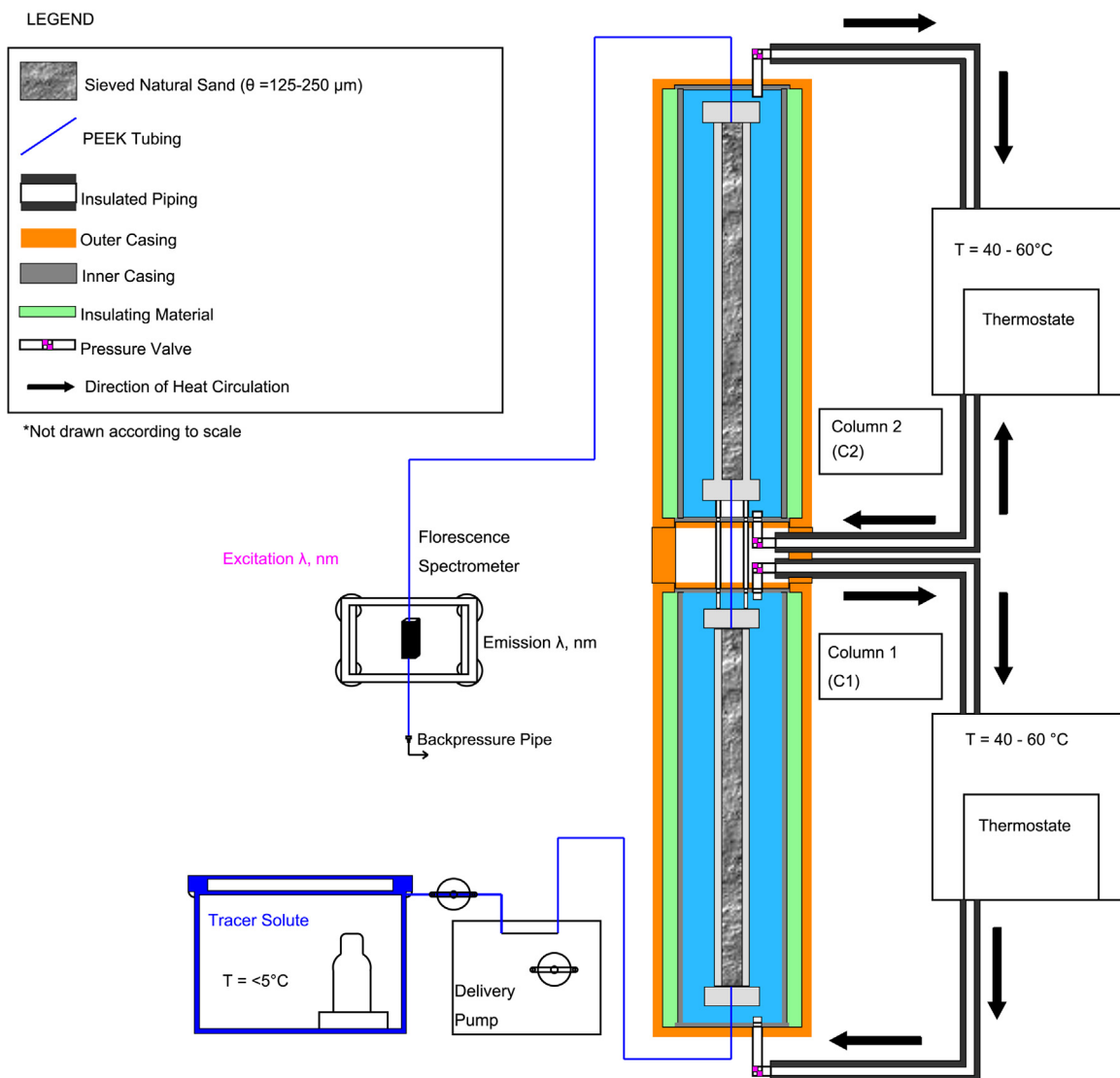


Fig. 1. Sketch of the experimental setup.

was used, as it has well defined kinetic parameters and releases the fluorescent product, phenol, allowing for online measurement (Nottebohm et al., 2012). Results from the analysis of TST column experiments are presented, providing a valuable contribution in the currently ongoing theoretically/numerically based discussion (Behrens et al., 2009; Plummer et al., 2012) on the applicability and sensitivity of TST experiments. The main focus of this work is on the general behavior of TSTs in isothermal flow fields under various temperatures and flow rates.

## 2. Material and methods

### 2.1. Experimental setup of the column heat exchanger

The experimental setup provided a controlled thermal flow environment. It was designed to reduce the number of occurring processes to the lowest possible extent. As a result of this idealization/simplification, well-defined, adjustable boundary conditions were guaranteed in order to obtain reliable results (Maier et al., 2013; Schaffer et al., 2013). Fig. 1 shows the experimental setup of the double column heat exchanger. The core of the system consists of two columns (preparative HPLC column, Alltech Grom GmbH, Rottenburg-Haifingen, Germany), each with a length of 50 cm and

a diameter of 3 cm. The columns were mounted coaxially in vertically positioned vented chambers, where connected thermostats (F40, Julabo GmbH, Seelbach, Germany) allow for heating/cooling of the columns between 0 and  $100^\circ\text{C}$  ( $\pm 0.2^\circ\text{C}$ ).

The columns were filled with sand (Type S80, Euroquarz GmbH, Dorsten, Germany), which was sieved to grain sizes from 125 to  $250\ \mu\text{m}$ . Before filling, the sand was ultra-sonicated for several hours to reduce the turbidity. The initially alkaline sand ( $\text{pH} > 8$ ) was titrated according to Niedbala et al. (2013) with an HCl solution until a neutral pH ( $\text{pH} = 7$  at room temperature) was established. Polyether ether ketone (PEEK) tubing connected all parts of the experimental setup.

### 2.2. Chemicals

In the experiments, the carboxylic acid ester phenol acetate (PhAc) was used as a TST tracer. PhAc undergoes a hydrolysis reaction in aqueous media. A 0.01 M aqueous *N,N*-bis(2-hydroxyethyl)-2-aminoethanesulfonic acid (BES, CAS: 10191-18-1) buffer solution ( $\text{pH} = 7$  at room temperature) containing  $5\ \text{g L}^{-1}$  NaCl was used as the working fluid. The addition of NaCl is intended to reduce microbial activity during the experiments. For the tracer experiments,  $0.4\ \text{mg L}^{-1}$  of the conservative reference tracer 2-OH-3,6-NDS

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