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Observation of trapped gas during electrical resistance heating of trichloroethylene under passive venting conditions

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ABSTRACT

A two-dimensional experiment employing a heterogeneous sand pack incorporating two pools of trichloroethylene (TCE) was performed to assess the efficacy of electrical resistance heating (ERH) under passive venting conditions. Temperature monitoring displayed the existence of a TCE-water co-boiling plateau at 73.4 °C, followed by continued heating to 100 °C. A 5 cm thick gas accumulation formed beneath a fine-grained capillary barrier during and after co-boiling. The capillary barrier did not desaturate during the course of the experiment; the only pathway for gas escape being through perforated wells traversing the barrier. The thickness of the accumulation was dictated by the entry pressure of the perforated well. The theoretical maximum TCE soil concentration within the region of gas accumulation, following gas collapse, was estimated to be 888 mg/kg. Post-heating soil sampling revealed TCE concentrations in this region ranging from 27 mg/kg to 96.7 mg/kg, indicating removal of aqueous and gas phase TCE following co-boiling as a result of subsequent boiling of water. The equilibrium concentrations of TCE in water corresponding to the range of post-treatment concentrations in soil (6.11 mg/kg to 136 mg/kg) are calculated to range from 19.8 mg/l to 440 mg/l. The results of this experiment illustrate the importance of providing gas phase venting during the application of ERH in heterogeneous porous media.

1. Introduction

Soil and groundwater contamination by dense, non-aqueous phase liquids (DNAPLs) such as chlorinated solvents, coal tar and creosote is a common occurrence in many industrialized areas of the world. Upon release to the subsurface, DNAPL will distribute itself in the form of disconnected blobs and ganglia of organic liquid referred to as residual DNAPL, and in continuous accumulations referred to as pooled DNAPL. Remediation technologies aimed at removing residual and pooled DNAPL from the subsurface are based on a variety of processes including oxidation, enhanced dissolution, hydraulic displacement, excavation and thermal heating. Within the subset of thermal heating technologies, common approaches include the use of electrical resistance heating (ERH), thermal conductive heating (TCH), and steam enhanced extraction (SEE).

ERH involves the delivery of electrical current to the subsurface, thereby generating heat and bringing about contaminant mass removal through boiling and volatilization. Although there have been numerous field pilot and full-scale applications of ERH (Triplett-Kingston et al., 2010) as well as numerical modeling studies (e.g., Carrigan and Nitao, 2000; Hendricks, 2006; Krol et al., 2011), there have been relatively few laboratory studies allowing detailed observation of the heating and mass removal processes occurring during application of ERH. Beyke and Fleming (2005), Buettner and Daily (1995), Cacciatore et al. (2004), Heron et al. (2004, 2005), and Powell et al. (2007) and discuss field implementation of ERH with limited observations of processes occurring in the subsurface. Heron et al. (1998) conducted laboratory studies using ERH in combination with SEE to treat silty soil containing dissolved phase

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trichloroethylene (TCE). Näslund (2003) performed a column study investigating the use of ERH coupled with vacuum extraction to treat soil containing dissolved phase tetrachloroethylene (PCE). Krol and Sleep (2011) present the results of an experiment investigating the use of ERH to heat saturated soil to sub-boiling temperatures and the effect of temperature induced buoyant flow and solute transport. Heterogeneity has been addressed in only very specific contexts, such as Kluger and Beyke (2010), who address ERH in fractured sedimentary rock.

Previous studies have not examined ERH in horizontally bedded porous media, where significant lateral spreading of gasses produced in the ERH process is possible. Studies addressing gas production and accumulation due to coboiling of pooled DNAPL, accumulation of this gas beneath capillary barriers, and associated temperature indicators of coboiling are absent from the existing literature. The objective of this laboratory study is to observe, through visualization and temperature monitoring, the removal of pooled DNAPL from heterogeneous porous media using ERH. This study is expected to be well suited for validation of numerical models, such as the one proposed by Krol et al. (2011). Interactions with fully confining low permeability capillary barriers are included to determine their impact on gas accumulation under passive venting conditions.

2. Materials and methods

2.1. Test cell specifications

The ERH experiments were conducted in a polycarbonate test cell with internal dimensions 73.66 cm × 13.97 cm × 38.1 cm (height), and 1.27 cm wall thickness (Fig. 1). All seams were joined with high temperature epoxy. The interior surfaces were laminated with optically clear 0.254 mm thick Teflon sheeting backed with an acrylic adhesive. A sheet of glass was placed against the inside viewing face of the cell, while the rear of the cell was treated with an opaque viton rubber coating, to ensure that any contact between DNAPL and the cell would be on a non-wetting surface in a water-saturated environment.

The rear face of the cell was held in place by 1.91 cm long 8–32 screws holding down a 0.794 mm viton rubber o-ring providing a gas-tight seal. The edges of the cell were further reinforced by an aluminum frame constructed of 2.54 cm square structural aluminum tubing with 3.18 mm wall thickness held tight by a series of clamps.

The rear face of the test cell was equipped with 32 thermocouple ports sealed with viton rubber o-rings. The thermocouples were arranged in a rectangular grid with 4 rows of thermocouples in the vertical direction and 8 columns in the horizontal. The tips of the thermocouples extended into the center of the test cell. The spacing between thermocouples, both vertically and horizontally, was 7.62 cm. All thermocouples were ungrounded stainless steel T-type, measuring 10.16 cm in length and 3.18 mm in diameter. Temperature data was collected from the array of thermocouples by a data logger connected to a desktop computer.

A water delivery system consisting of a Teflon well was placed vertically in the sand pack adjacent to each electrode to replace water lost due to vaporization (Fig. 2). The wells were constructed from 0.95 cm outside diameter Teflon tubing and perforated with circular pores approximately 1 mm in diameter every 90° horizontally, and 2.5 cm vertically. The perforations began at the bottom of the tubes which were aligned with the bottom of the electrodes, and extended to the top of the sand pack in the cell. The tops of the tubes led to ports that protruded through the top of the test cell alongside ports for cabling and gas collection lines.

While not in use, the wells were sealed using gas tight Viton rubber stoppers. When the watertable dropped by 2.5 cm, water was introduced to the cell to replace that lost by vaporization, following which the stoppers were immediately resealed.

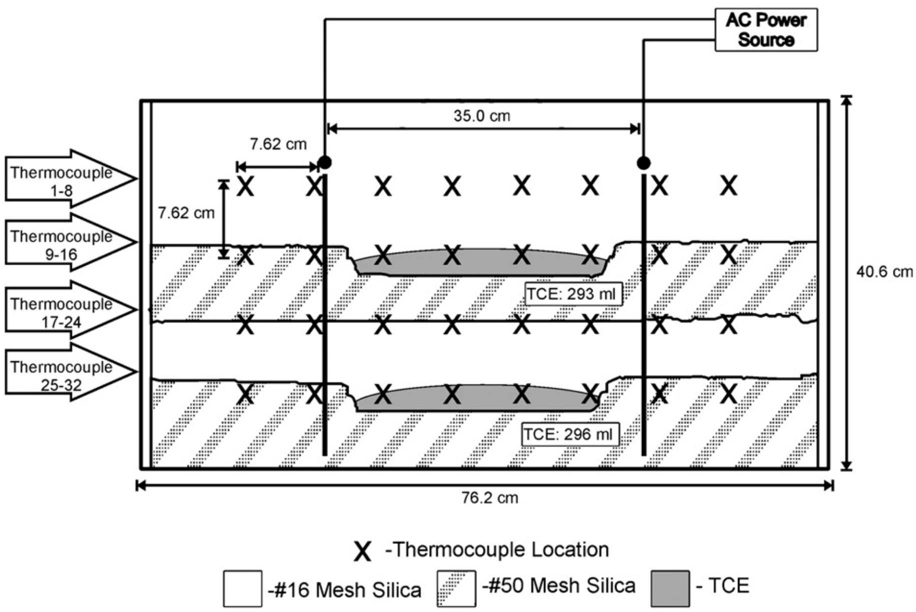

Fig. 1. Schematic of laboratory test cell. Locations of thermocouples, electrodes and pools are shown. Thermocouple numbering increases from left to right.