Thermal Remediation Behavior in High and Low Permeability Systems

Ron Falta
Professor
Clemson University
Outline

• Introduction

• High permeability systems
  • Cold air injection during steam injection above water table
  • Steam override during steam injection below water table
  • Numerical simulations of field pilot test
  • Full scale simulations

• Low permeability fractured systems
  • Importance of the boiling location
  • Rock core experiments
  • Clay core experiments
  • Simulations of field scale fractured systems
Introduction

• Thermal methods are used primarily to remove volatile organics from subsurface

• Heat is delivered by injecting steam, passing electrical current through the ground, or by direct thermal conductive heating

• The main removal process is transfer of the contaminant from a NAPL or dissolved phase to the gas phase

• Development and control of the steam zone in the desired location is of key importance
High Permeability: Steam Injection Below the water table

- Steam is much less dense than water
- There is a tendency for steam to rise due to buoyancy forces
- This can cause steam override, resulting in poor contact with contaminated zone
- Tendency is proportional to ratio of permeability to steam mass flux (van Lookeren, 1983; Basel and Udell, 1989)
- Strong permeability anisotropy reduces this effect
Numerical Simulations of Steam Injection into the Regional Gravel Aquifer, Paducah, KY

- Use the DOE TMVOC multiphase flow numerical code with the PetraSim interface
- Simplified r-z radially symmetric model around a single steam injection well
- RGA formation has very high K; bounded by lower K UCRS and McNairy formations
- Water table is located just above the top of the RGA
- Simulate steam injection into two screens at 500 lbs/hr each
- Perform simulations over a range of horizontal K and anisotropy values

[Diagram showing numerical grid used for simulations]

Ground surface, open to atmosphere, 15°C

UCRS, 0 to 60 ft; $kh = 1.e-13 \text{ m}^2; \ kz = 1.e-14 \text{ m}^2$

McNairy, 90 to 120 ft; $kh = 1.e-13 \text{ m}^2; \ kz = 1.e-14 \text{ m}^2$

RGA, 60 to 90 ft

No flow boundary at bottom of grid

120 ft
Simulation of Steam Injection at 500 lbs/hr into each screen; \( K_h = 200 \text{ ft/d} \) \( K_v = 20 \text{ ft/d} \) (10:1)

Temperature after 10 days

Temperature after 30 days

Gas saturation after 30 days

Top of steam zone extends to a radius of 35 ft

Bottom of steam zone extends to a radius of 7 ft
H$_2$O Mass Flux Vectors and Gas Saturation at 30 Days
Steam Pilot Test at C-400, DOE Paducah Gaseous Diffusion Plant

• 2015 test performed by ERM and Fluor Federal Services (Dablow, et al., 2016)

• Phase I: inject steam at 500 lb/hr into two screens for 20 days

• Phase II: 14 day cool down

• Phase III: Inject steam into lower screen only at 1000 lb/hr

• Monitor temperature at 186 points in 11 vertical arrays
3D Numerical Model Calibrated to Phase I; used to Simulate Phases II and III
RGA gravels and sands represented by tan and blue zones, $K=300$ and $100$ ft/d

Grey zones represent silty sand, $K=1.5$ ft/d

Anisotropy ratio is 20:1 to 30:1
Simulated and Observed Temperatures at the end of Phase I Injection
Simulated Steam Zone at End of Phase I Injection
Simulated and Observed Temperatures near the end of Phase III Injection
Simulated Steam Zone at End of Phase III Injection
3D Model of Full Scale Conceptual Design

Design with 23 nested pairs of steam injection wells
17 dual phase extraction wells
Inject 500 lb/hr in upper screens, 1000 lb/hr in lower screens
Simulated Temperatures after 10 and 20 days of Steam Injection
Boiling in Fractured Rocks and Clays

- Low permeability materials can be heated by electrical or thermal conduction
- Once a rock is hot, boiling can be induced by dropping the pressure in the fractures.
- One liter liquid water produces about 1600 liters of steam vapor when boiled
- Chlorinated VOC’s preferentially partition into the steam by Henry’s Law partitioning
- Theoretical model by Udell (1996) predicts geometric reduction of concentration with boiling
Initial Simulations (2006)

- 1 m³ block of rock with a single fracture. Fracture and matrix initially saturated with water containing 10 ppm TCE.
- Heat the block with 200 W power.
- Drop pressure in fracture and simulate mass in matrix with time.

Consider three conditions:

a.) vapor mobile in matrix

b.) vapor immobile in matrix

c.) intermediate vapor mobility

Large fracture maintained at a vacuum of 0.3 ATM
Initial Simulations – Location of Boiling Makes a Big Difference!

Vapor phase forms as isolated bubbles in matrix, pushing liquid water into fracture where it boils. Heat to sustain fracture boiling comes from thermal conduction.

Vapor forms in matrix and is mobile, flowing freely to fracture. All boiling occurs in matrix, and steam stripping effect is similar to Udell (1996) model.

Initially vapor phase pushes liquid water into fracture where it boils. Later, vapor phase becomes more mobile and flows out to fracture. Boiling moves from fracture to matrix with time.
Laboratory Experiments

Field Scale

Fracture-matrix interaction is locally ~ 1-D

Unfractured matrix material (silt, clay, limestone, sandstone, etc.)

Simulated fracture on one end
Experimental Design – Rock Cores

1. Contaminate matrix by pumping contaminated water through it at a high pressure gradient until concentrations stabilize at the outlet. This is only possible at higher permeabilities (~100 millidarcy).

   - Inject water with 1,2-DCA, NaBr.
   - Produce water

2. Seal and insulate column, turn on heaters, open fracture to atmosphere. Measure $T$, $S_w$, steam flow rate, contaminant flow rate at outlet.

Chen et al., 2010
Experiments with rock cores

- Used 2” diameter Berea Sandstone cores from a quarry in Ohio
- Permeability is ~100 millidarcy ($10^{-4}$ cm/sec conductivity)
- Measured dry and water saturated thermal conductivity
- Measured capillary pressure curve and air relative permeability curve (Daniel B. Stephens, Inc.)
- Core is contaminated by pumping water with dissolved CVOC and NaBr under high pressure
- Seal column, and heat; open outlet when boiling temperature is reached
Experimental Results – cumulative CVOC removal

The core pore volume is 116 ml
Experiments with clay cores (Liu et al., 2013)

- Pure kaolin clay mixed with water at optimum water content (maximum density)
- Permeability extremely low, ~ 100 microdarcy (~10^{-7} cm/sec)
- Water used to make clay was contaminated with 1,2-DCA
- Clay is packed into two 2” Teflon heat shrink tubes; one serves as a control to establish starting soil concentrations
- After heating to a certain point (for example 40% water removal), core is removed, and sliced for soil sampling

Water content (by weight): 0.43±0.02
Selected for maximum density; pore volume is 260 ml and $k=\sim10^{-16}m^2$
A Flexible-wall Cell inside Pressure Vessel

2-inch diameter and 1 ft long

Outflow condenses and is recovered in sample bottle

Pressurized vessel containing sample. ~15 psi confining pressure typical.

Liu et al., 2013
Sampling and Analysis – Destructive Sampling During Many Repeat Experiments

**Solids** - slice up the cores before and after heating

**Water Content** along core by oven drying samples

**DCA concentration** remaining in the clay using a.) headspace extraction and b.) methanol extraction
Results of 8 different experiments that are stopped at different times and sliced apart

DCA profiles in clay cores with different fractions of pore water boiled out. IN is initial DCA concentration.

DCA relative concentration

Sample length (cm, from bottom to top)
Fractures!
Field scale simulations of fractured systems

• Numerically challenging due to small size of fractures compared to large size of model

• Large contrasts in permeability and capillary pressure between fractures and rock matrix

• Discretization issues – need to discretize both the fractures (very small) and the matrix (very large), with transitions in size between the two
Multiple Interacting Continua (MINC) discretization

Spatial domain is discretized normally into volume elements. The fracture elements are globally connected in all directions. This is similar to a dual porosity formulation, but gradients in the matrix are resolved much more accurately.

Each gridblock is subdivided into a fracture element, and multiple nested matrix elements. The fracture and matrix elements are locally connected to each other in 1-D.

Groundwater contaminated with 10 PPM of TCE in both fractures and matrix.
Field Simulation Example (Chen et al., 2015)

Idealized field scale simulation – single element of a repeated 6-phase electrical heating pattern.

3-D orthogonal set of 200 micron fractures with 1m spacing, matrix $k=10^{-15}$ m$^2$; model uses MINC for matrix blocks.

Add 800 kW (200W/m$^3$) power for 15 days, then pump vacuum well at 0.5 ATM for 1 year. Re-energize for 3 days and pump vacuum well for another year.
Simulation Result

Simulations with lower matrix permeability show a slower reduction of TCE concentration with time.
Summary

• Steam override is a concern during steam injection below the water table in high permeability systems.

• Steam override can be controlled using aggressive engineering designs where high injection rates are used in the bottom of the formation.

• Contaminant removal from lower permeability fractured materials occurs when only a fraction of the pore water is boiled away.

• We observed intense fracturing during heating of low permeability clay cores, leading to high removal efficiency.

• Contaminant removal from low permeability fractured rocks may be slower due to boiling that occurs mainly near the fractures.