Two Phase Flow of Dense Non-Aqueous Phase Tetrachloroethene in a Microfluidic Groundwater Model

Lindsey M. Watch, Ph.D. Candidate, Jennifer Becker, Ph.D., Eric Seagren, Ph.D.
Civil & Environmental Engineering Department, Michigan Technological University, Houghton, MI

Background

- Chlorinated ethenes, like tetrachloroethene (PCE), are known/suspected carcinogens.
- They form non-aqueous phase liquid (NAPL) pools that slowly dissolve into groundwater and serve as long-term pollution sources (Figure 1).
- Complete remediation of NAPL pools has been difficult to achieve because of the complex subsurface environment.
- Microfluidic groundwater models provide a means to examine these complicated processes at the pore scale.
- A two-dimensional pore network pattern was etched onto a silicon wafer to create a microscale model of a groundwater aquifer with a NAPL, PCE channel to simulate a NAPL pool (Figure 2).

Factors Influencing Flow

- Porous systems:
  - fluid viscosity
  - fluid density
  - fluid flow rates

- Additional forces in two phase flow:
  - interfacial
  - gravitational

- The relative magnitudes of these properties determine the type and stability of displacement.

NAPL flow in the subsurface environment can be characterized by systematically evaluating the relative magnitudes of a series of dimensionless parameters that incorporate these properties:

- contact angle, \( \theta \): angle between solid phase and NAPL (Figure 5)
- porosity, \( n \): volume of voids/total volume
- NAPL saturation, \( S_n \): volume of NAPL/volume of voids
- Reynolds number, \( Re \):
  \[ \frac{L v_d}{v} \]
  inertial/advective
- Schmidt number, \( Sc \):
  \[ \frac{\mu}{\rho D_v} \]
  viscous diffusive
- Sherwood number, \( Sh \):
  \[ \frac{k L}{D_v} \]
  mass transfer diffusive
- Capillary number, \( Ca \):
  \[ \frac{k}{\sigma} \]
  capillary void
- Bond number, \( Bo \):
  \[ \frac{\rho g L^2}{\sigma} \]
  gravitational interfacial
- Viscosity ratio, \( k \):
  \[ \frac{\mu_{\text{NAPL}}}{\mu_{\text{water}}} \]
  NAPL viscosity/liquid viscosity

- Other common dimensionless groups are combinations of the above:
  - Weber number, \( We \)
  - Peclet number, \( Pe \)
  - Stanton number, \( St \)

List of variables in the equations above:
- \( L \): characteristic length (L)
- \( v \): fluid velocity (L/T)
- \( \rho \): fluid density (M/L^3)
- \( \mu \): fluid viscosity (M/LT)
- \( D_v \): effective pore diameter (L)
- \( k \): thermal conductivity (M/L^2T)
- \( \sigma \): interfacial tension (M/L)
- \( \rho_{\text{NAPL}} \): density NAPL (M/L^3)
- \( \rho_{\text{water}} \): density water (M/L^3)
- \( \rho_g \): density of fluid at ground water conditions (M/L^3)
- \( v_d \): kinematic viscosity (L^2/T)
- \( I_{\text{air}} \): air mass transfer (M/T)
- \( I_{\text{NAPL}} \): NAPL mass transfer (M/T)
- \( \sigma_{\text{air-water}} \): interfacial tension of air-water (M/L)
- \( \sigma_{\text{NAPL-water}} \): interfacial tension of NAPL-water (M/L)

Future Work

- Certain anaerobic bacteria found in groundwater aquifers can respire, and potentially destroy, chlorinated ethenes.
- The bacteria increase the concentration gradient at the NAPL-water interface, thereby bioenhancing the dissolution of the NAPL PCE and reducing the longevity of the NAPL pool.
- Due to the complexity of subsurface environments, the factors that influence the microbial ecology at the NAPL-water interface are not completely understood.
- The overall goal of this project is to use an integrated experimental and mathematical modeling approach to evaluate the effects of PCE-degrading bacteria on the longevity of NAPL pools and contaminant detoxification in groundwater.
- This microfluid model can be used to validate computer model predictions by inoculating it with PCE-degrading bacteria and measuring effluent concentrations of chlorinated ethenes.
- Additionally, we would like to evaluate the effects of bioenhancement on NAPL, PCE dissolution and degradation.

References


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