Measurements of Capillary Pressure-Saturation Relationships and DNAPL Distribution in Silica Sands Using Light Transmission Visualization (LTV)

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Background and Motivation

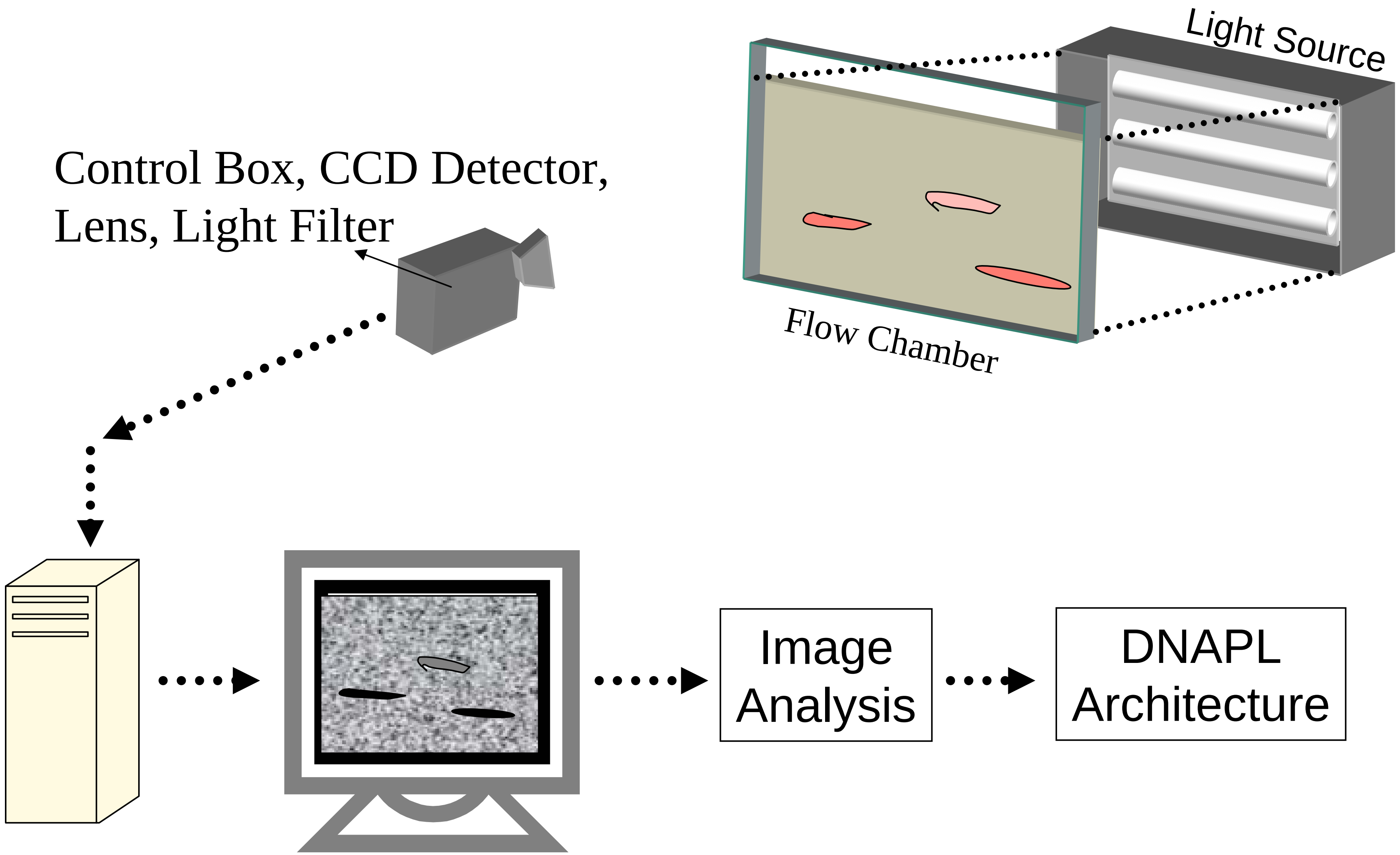
- Determining DNAPL architecture before and after remediation is essential in predicting remediation effectiveness.
- LTV could be an effective technique for DNAPL characterization and for water saturation measurements that are needed to determine DNAPL architecture:
  - The whole experimental domain (2-D Model) can be captured in one image.
  - Spatial resolution of camera can be 1 mm^2 or less.
  - It is non-invasive technique.
  - It is very safe since no high energy radiation is involved
  - It is cost-effective.

Objectives

- To validate LTV technique by:
  - Measuring water saturation in a water/air system as a function of capillary pressure by LTV and compare results to Tempe cell or frozen column measurements.
  - Measuring water saturation in PCE/water system by LTV as a function of capillary pressure and compare results to Tempe cell measurements.
  - Performing the above measurements for different sand size fractions.

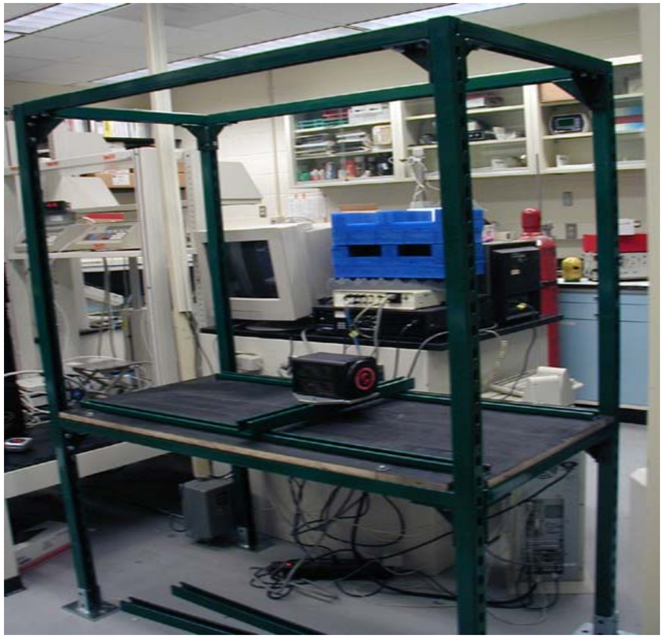
Experimental System

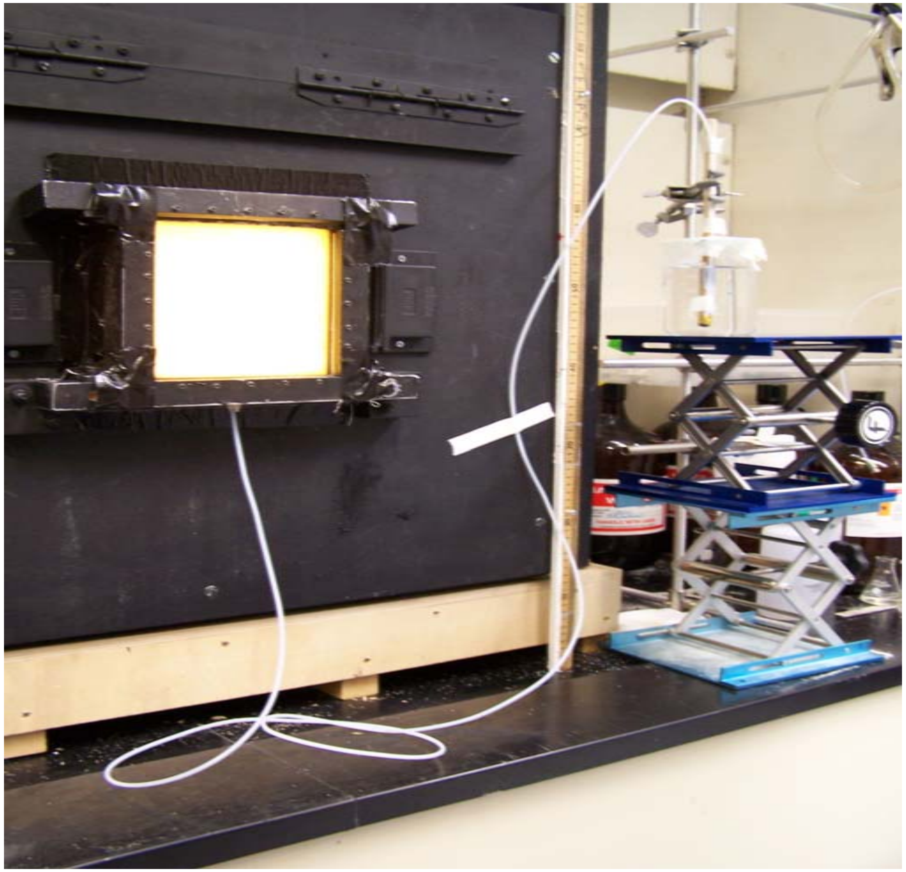
- 2-D flow chamber has 2 glass plates and has dimensions of 15.24X15.24X1.40 cm.
- 20/30 and 40/50 Natural silica sands (Accusands) are used as packing media.
- The capillary pressure is controlled by hanging column position or pressure regulators for air/water system and by water and PCE heads for water/PCE system.



2-D Flow Chamber with Light Transmission Visualization Imaging

- **CCD (VersArrayXP:512B from Princeton Ins.):_**
  - 512X512 imaging array…Spatial resolution of about 0.8 mm2/pixel
  - Dynamic Range: 16 bit
  - Air-cooled (down to -75 oC), which significantly reduces
  - dark noise (0.002e/pixel/S)
  - High quantum efficiency from Vis to NIR.





2-D Model mounted on the light box for air/water saturation measurements. Note the hanging column for controlling capillary pressure.

Mathematical Models of LTV Technique

- Images are analyzed pixel by pixel using image analyses software (Image Pro Plus, Media Cybernetics).

- Light intensity of each pixel is correlated with fluid content in the 2-D flow chamber by applying Fresnel's law:

$$I = I_o \Pi \tau_j \exp(-\Sigma d_i \alpha_i)$$

Where:

- I = Light intensity
- Io = Incident light intensity
- τ_j = The transmittance of the interface between phases i and i+1
- αi = The absorption coefficient of the phase i (1/cm)
- di = Thickness of the phase i (cm)

τ_j quantifies the light lost when a particular wave length travels between two or more phases

$$S = \frac{I - I_{oil}}{I_s - I_{oil}}$$

I_s = Light intensity when chamber is fully saturated with water

I_{oil} = Light intensity when chamber is fully saturated with oil

- This equation is used directly to determine the water/oil content of each pixel, thus determining the PCE content and spatial distribution within the chamber

- Similarly, for a water/air system it can be shown that:

$$S = \frac{I - I_d}{I_s - I_d}$$

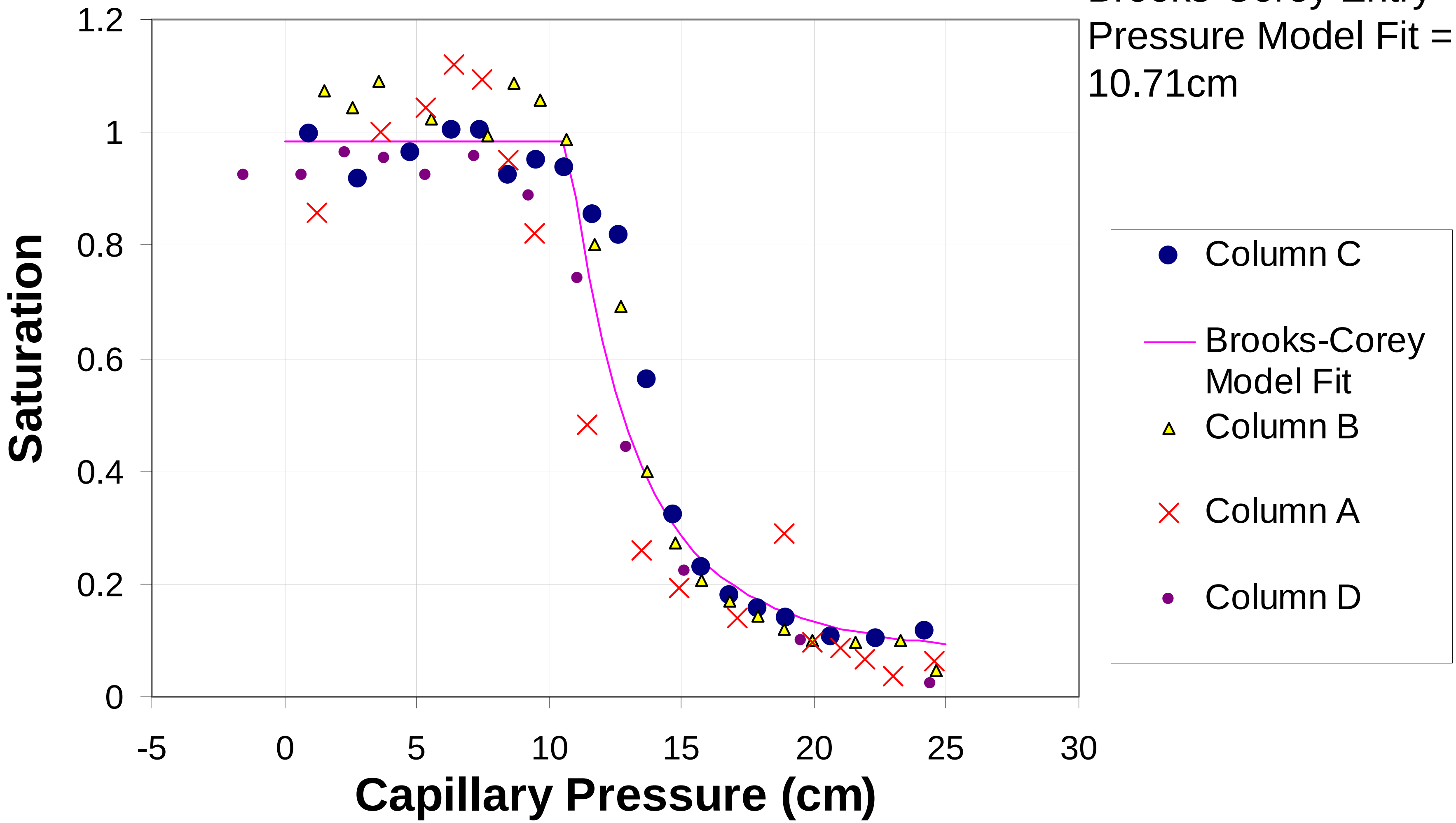
Where I_d is the light intensity through a dry system.

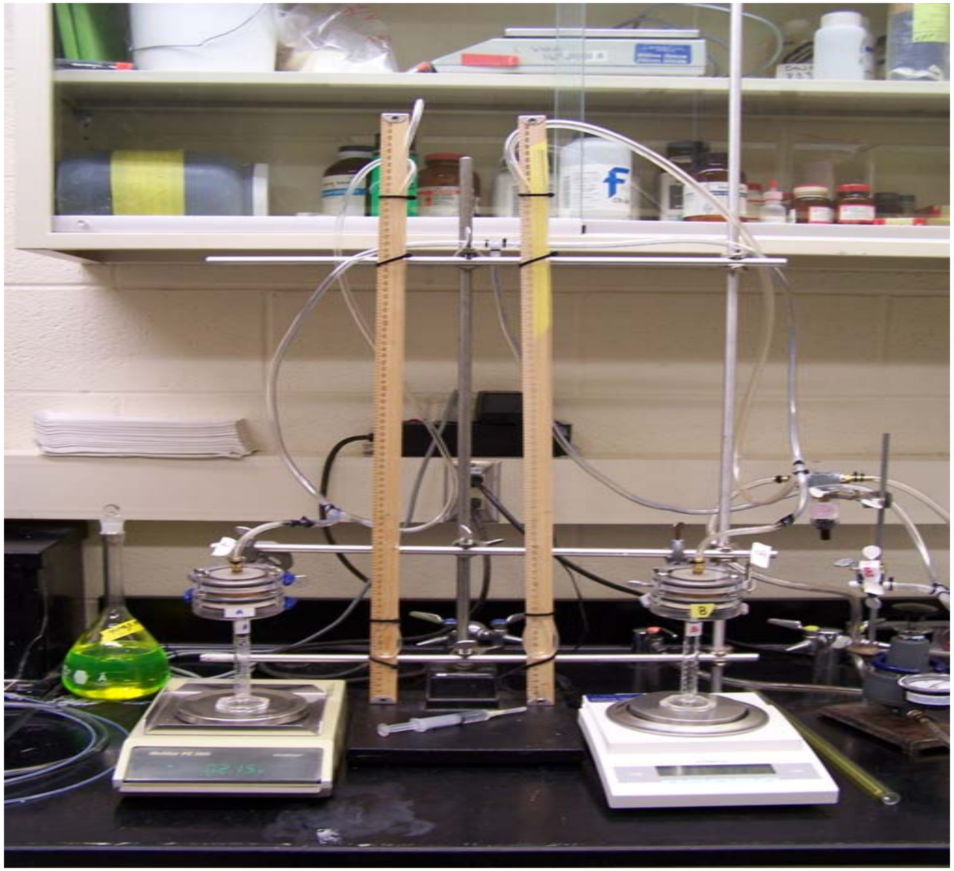
Frozen Column Measurements:

- Pre-segmented plastic tube of known diameter and length is packed with 2/30 sand.
- The tube is flushed with CO_2 and saturated with water for 24 hours.
- The tube is drained up to a pre-determined point at its bottom where water is at atm pressure.
- The tube is frozen with liquid nitrogen to cut out the different segments and saturation in each segment is determined gravimetrically.

Frozen Column Measurements Results for 20/30 Sand

Brooks-Corey Entry Pressure Model Fit = 10.71cm

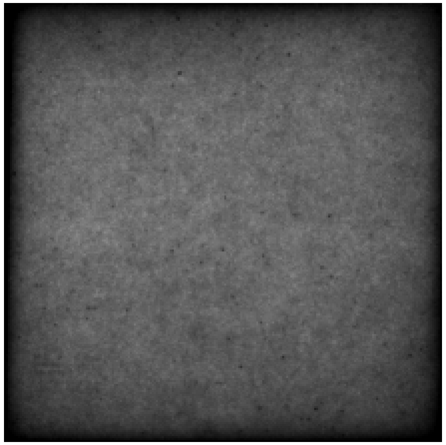




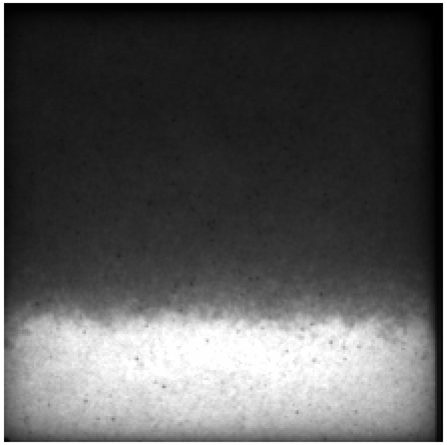
Tempe Cell Measurements: Capillary pressure is controlled by pressure regulator which is visible to the right.

LTV Results

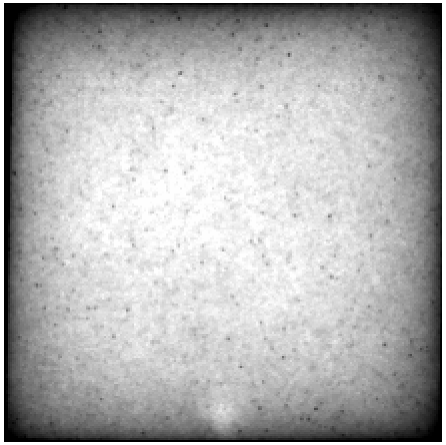
- Uniform pack of 20/30 sand in a 15.24X15.24X1.4 cm flow chamber



Dry Sand Image
Average Light Intensity = 724
Standard Deviation = 214

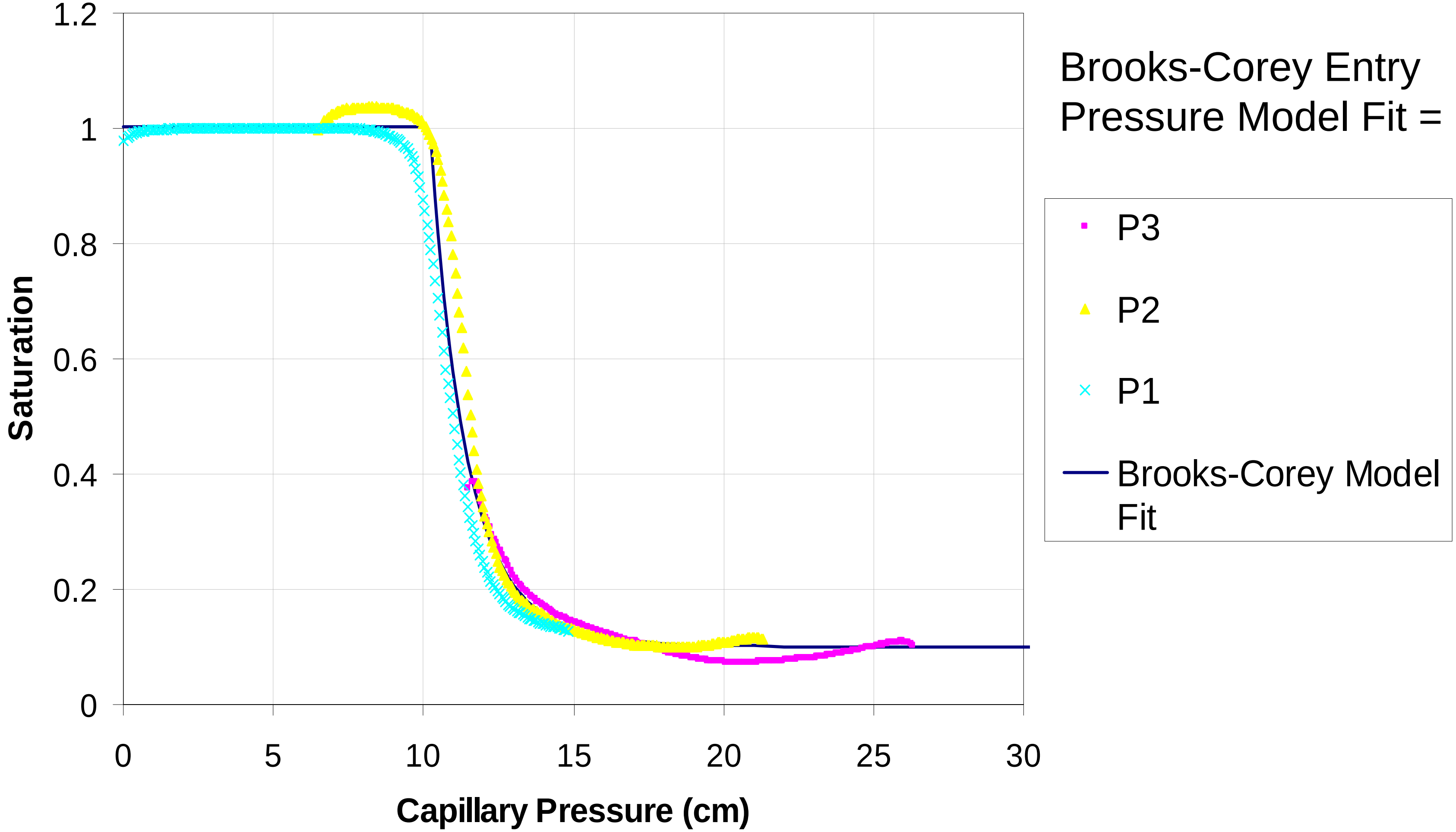


Partially-Saturated Sand



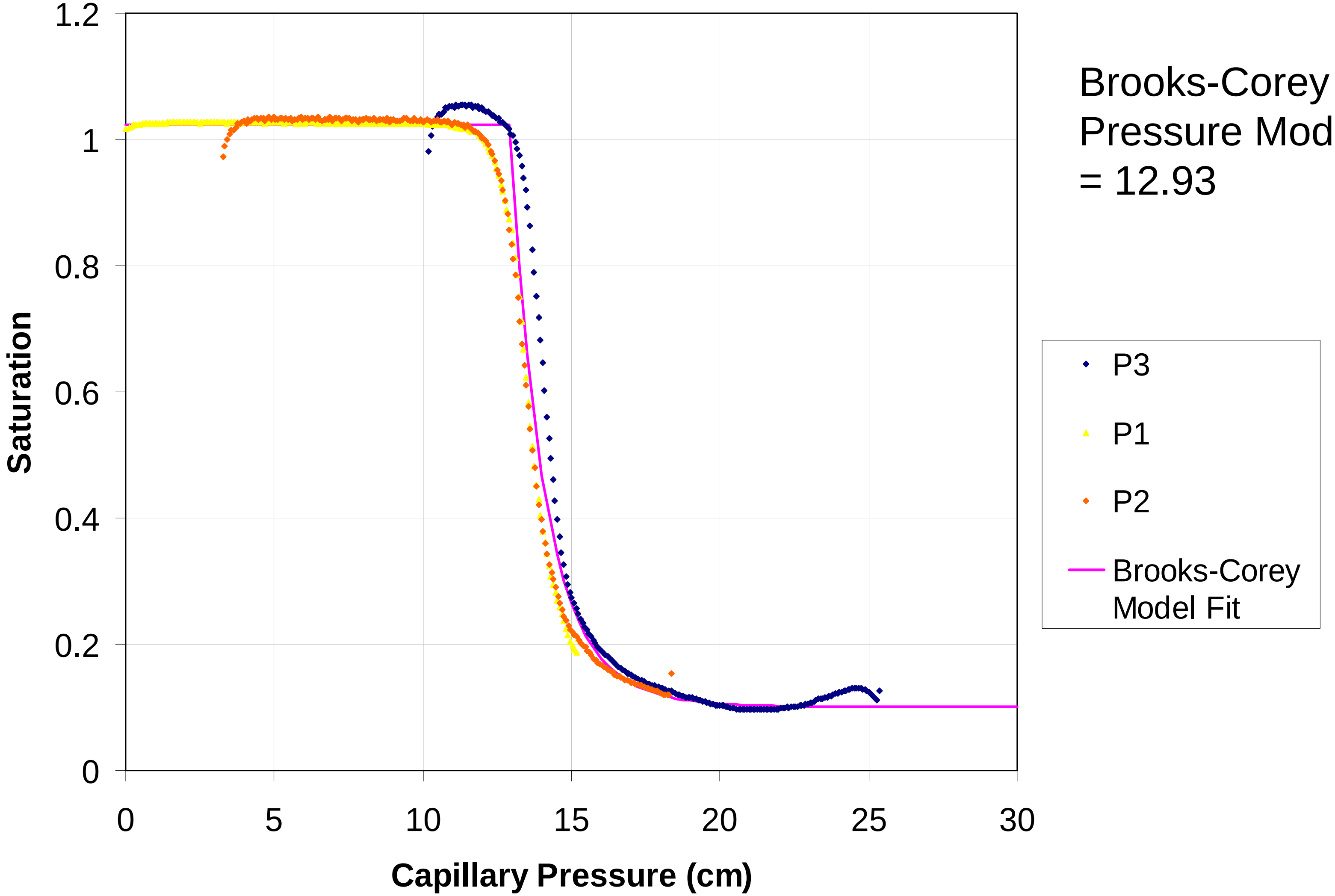
Water-Saturated Sand
Average Light Intensity = 34558
Standard Deviation = 9774

Pressure-Saturation Curve for 20/30 Sand (Pack 16)



Brooks-Corey Entry Pressure Model Fit = 10.23

Pressure-Saturation Curve for 20/30 Sand (Pack 17)



Brooks-Corey Entry Pressure Model Fit = 12.93

Summary of Water/Air Saturation Measurements for 20/30 Sand

Experiment	*Entry Pressure (cm)*	*PSD Index*
Frozen Column Measurements	10.71	4.29
LTV- Pack 16	10.23	8.84
LTV- Pack 17	12.93	11.61

The differences in the answers are currently under evaluation

PCE/Water System

- Because it is not practical to measure I_{oil}, it is calculated using the relation:

$$I_{oil} = I_s \tau_{wo}^{2K}$$

- Where τ_{wo} at 600 nm = 0.996 and K is calculated as:

$$K = \frac{\ln(\frac{I_s}{I_d})}{2\ln(\frac{\tau_{sw}}{\tau_{sa}})}$$

(Niemet and Selker (2001))

- **PCE Release in Homogenous Media for Mass Balance Calculations:**

10 ml of PCE injected from the top center (no dye)

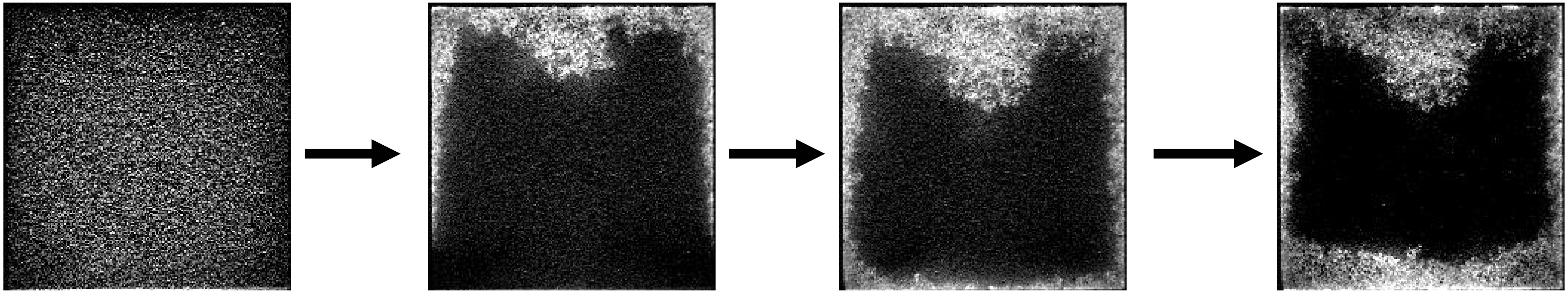
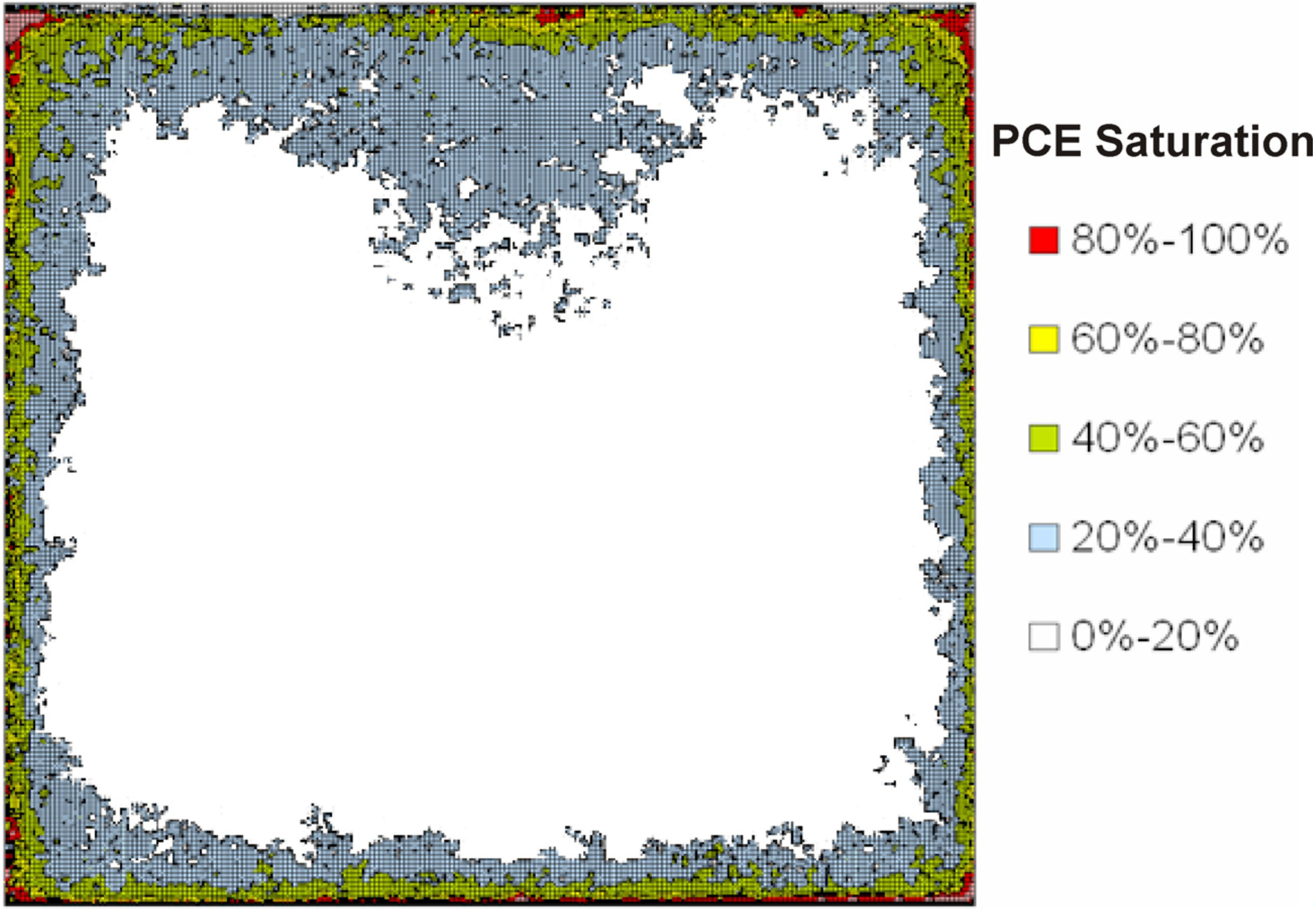


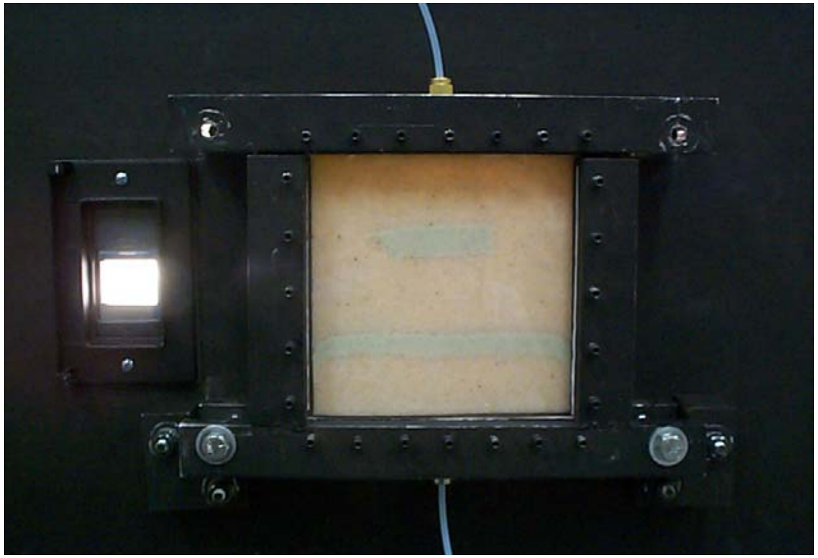
Image Analyses:

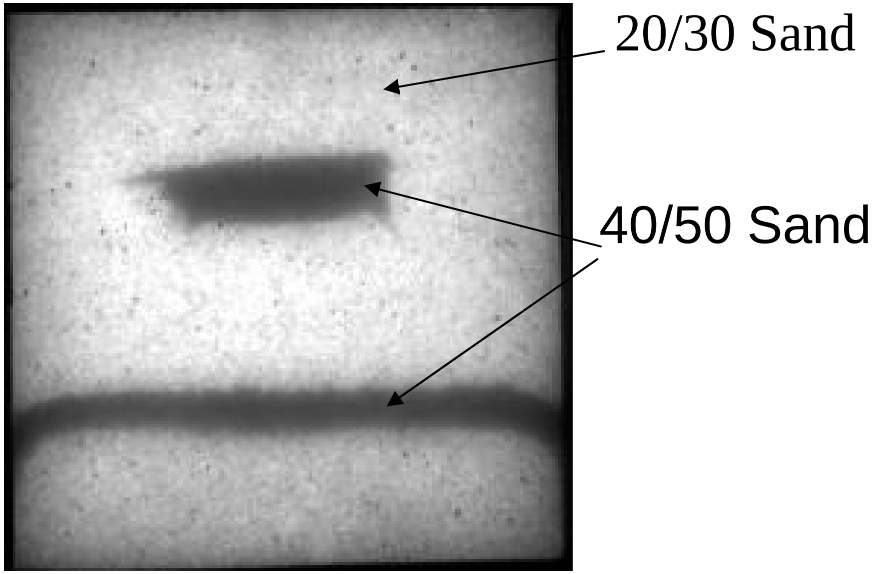
- Spatial Resolution =0.7 mm2/pixel
- Estimated PCE = 11 ml
- Error in PCE Estimation = 10%

PCE Distribution at t = 18 min



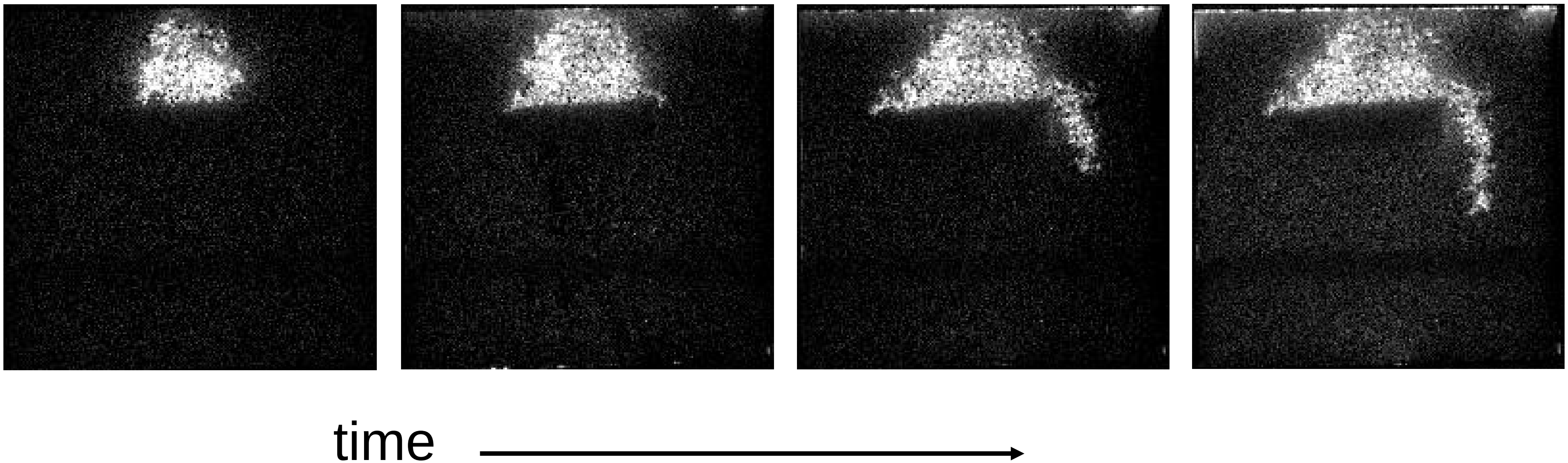
PCE Distribution in Heterogeneous Media





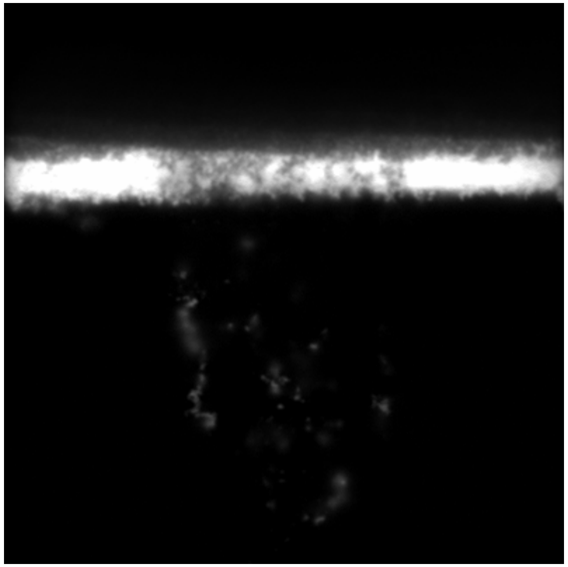
The 2-D Model mounted on the Light Box and the density wedge

PCE Distribution in Heterogeneous Media for Mass Balance Calculations

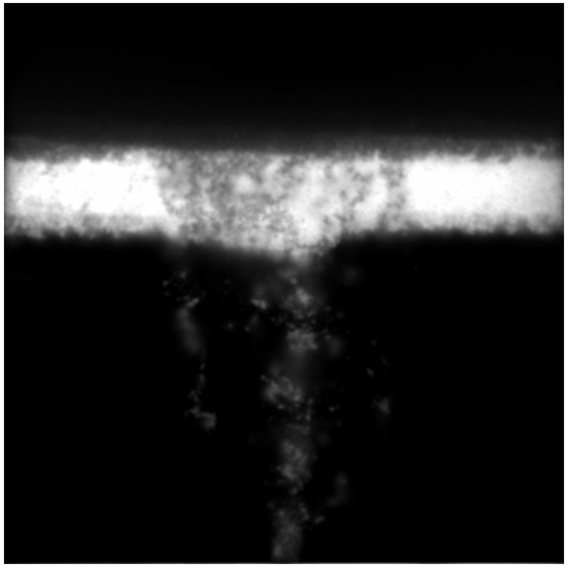


PCE released from top = 5-7.6 ml
PCE estimated by image analyses = 5.55 ml

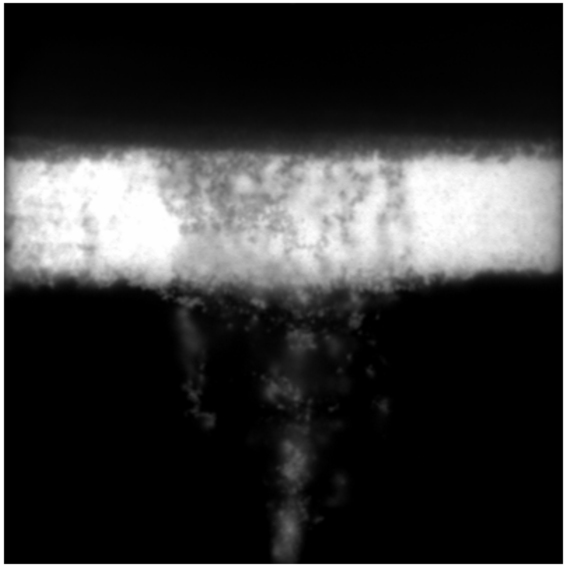
Additional Application of LTV



Tetradecafluorohexane



Dodecafluoroheptanol



Trifluoroethanol

Enhancement of the air sparging process using different surfactants to reduce surface tension.

Summary

- LTV can be used to characterize free phase PCE architecture in 2-D flow chambers without using a dye.
- Results to date suggest that error in PCE detection using LTV can be less than 10% if the imaging system is optimized.
- Mass balance calculations show a maximum error of 9.6% for the water/air system.
- Investigations underway to evaluate differences in answers obtained by LTV measurements for water/air saturation for 20/30 sand.

Acknowledgments

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