# Image Processing and Calculation of Interfacial Area in Unsaturated Porous Media

Subsurface Biosphere Initiative


Kendra Seniow[1] and Dorthe Wildenschild[2]

1. Dept. of Chemical Engineering, Subsurface Biosphere Initiative Summer Intern
2. Dept. of Environmental Engineering, Subsurface Biosphere Initiative Faculty
Oregon State University


**Introduction:** Properties of fluid flow and transport in porous media determine the success or failure of important operations such as groundwater management and remediation, irrigation, and oil and gas recovery. The micro-scale processes and interactions that control these operations and others of the subsurface are often ignored, however, for lack of understanding. Interaction between phases is critical to determine reaction processes and behavior of subsurface materials and needs to be understood and quantified on the micro-scale level so that larger-scale predictions may be made.

Culligan et al (2004) set to quantify interfacial areas by using synchrotron x-ray technology to produce three-dimensional images of the drainage and imbibition of columns of packed grains and columns of glass beads. Computation of the interfacial areas is possible using three-dimensional imaging software to view and analyze the images.

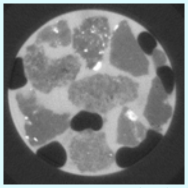
Interfacial area was found to increase with saturation, peaking around 25-30% saturation, and then decline with greater saturation. Though this general trend is consistent, actual values vary between different trials and, especially, between different computational image processing methods.

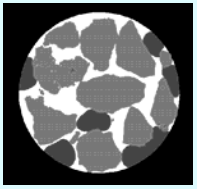
**Method:** Flow of a liquid phase through a packed column of either natural grains (volcanic tuff) or glass beads was documented using synchrotron x-ray microtomography. The 3-D images produced were analyzed in multiple ways - varying in segmentation, sampling volume, and re-sampling filter - in order to determine the most accurate measurement of liquid-air interfacial area. The images were first subjected to either:

(1) a cluster analysis or

(2) a histogram segmentation

which separated solid from water and air into easily distinguishable visual and numerical values. The dry image is then overlaid to fix holes in grains, etc. A section measuring 294x294x262 voxels was taken from full images of 650x650x280 voxels.

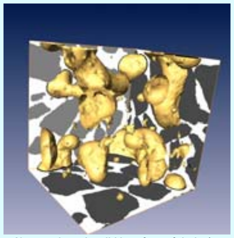

Two-dimensional cross-section of drain-1: Original Image

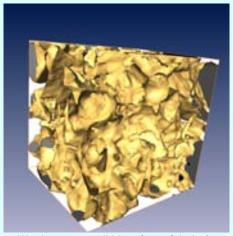

Two-dimensional cross-section of drain-1: Cluster Analysis

Using Amira 3D imaging software, a triangular filter was applied to smooth edges and maintain accurate area measurements. To define surfaces between phases, Amira required the setting of a threshold in between phase values. From this threshold, a surface could be created and its area calculated. The interface between water and air could not be defined specifically using Amira, but its area measurement, $a^{wn}$, was calculated from that of the wetting phase (water-solid interface), the non-wetting phase (air-solid interface), and the solid following the relationship:

$$a^{wn} = ½(a^{w} + a^{n} - a^{s})$$

where $a^w$ is the area of the wetting phase, $a^n$ is the area of the non-wetting phase, and $a^s$ is the area of the solid computed from a dry image.


Non-wetting, air-solid interface of drain-1.


Wetting, water-solid interface of drain-1.

A triangular filter was used to re-sample each image. To determine its accuracy, the surface area of_a sphere was measured under multiple re-sampling filters. The sphere was generated in IDL and the threshold always set to 97.

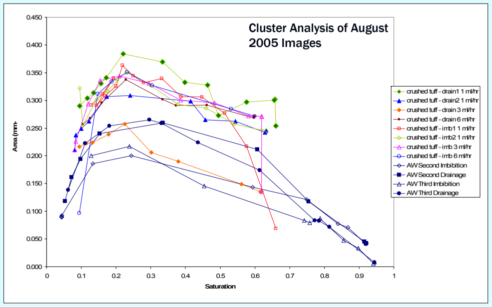
Since the radius of the sphere was 97 its actual surface area was accepted to be

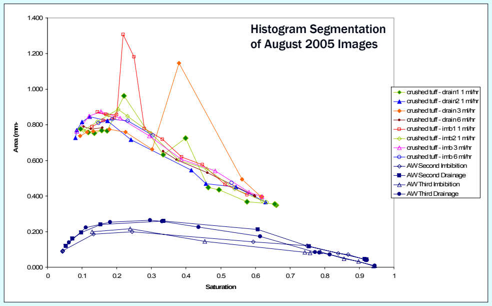
$S_a = 4\pi r^2$
$= 118236.98$

| Re-Sampling Filter | Voxel = 3x3x3 | | Voxel = 6x6x6 | |
|---|---|---|---|---|
| | Surface Area | Percent Error | Surface Area | Percent Error |
| *NO Re-sampling | 118232 | -0.00421% | —— | —— |
| Lanczos | 118185 | -0.0440% | 118074 | -0.134% |
| Mitchell | 118162 | -0.0634% | 118079 | -0.134% |
| Triangle | 118160 | -0.0651% | 118105 | -0.112% |
| Bell | 118148 | -0.0753% | 117708 | -0.447% |
| B-Spline | 118141 | -0.0812% | 117273 | -0.815% |
| Box | 117367 | -0.736% | 118105 | -0.112% |

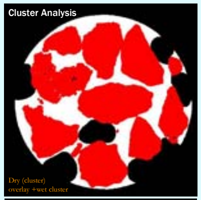
*For NO re-sampling, voxel size = 1x1x1

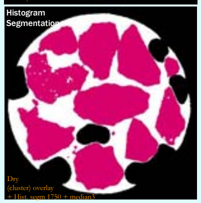
**Results:** Interfacial area measurements were compared to respective saturation values.




**Conclusion:** Interfacial area is shown to peak around 25-30% saturation, increasing up to this point and decreases afterwards. Despite this generalization, however, there are great discrepancies between image processing methods which are seen in both the image output and area calculations.




__Cluster Analysis:__

- Performed in batch mode using the wet and dry grey-scale volumes
- Comparison to nearby voxels and later re-examination contributes accuracy
- Fairly consistent trends, but widely dispersed

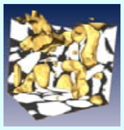
__Histogram Segmentation:__

- Segmentation based solely off wet data histogram and performed upon individual voxels.
- Air separated first from water and grains. Dry image overlay separates grains.
- More extraneous data points

The two methods produce radically different results, but neither carries much certainty since there is no standard of comparison.

*A third method proposed:*


Drain-1 grey-scale, grains set to 29999


Threshold at air-water interface (3000) drain-1

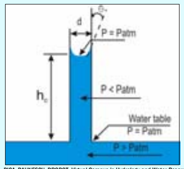
- Original Grey-scale images
- Solid grains separated from water and air (set to a value of 29999 compared to 0-6000 of other objects)
- Still dependent on histograms as reference
- Still lacks control comparison

**Future Work:** To make full use of images and glean accurate data, a correct method of surface area measurement needs to be determined. Though the surface area of the sphere is able to be calculated, a better control would be an interface imaged and analyzed by exactly the same procedure as the samples.

Capillary tubes of liquid will provide this accurate standard as they can be imaged by the same synchrotron x-ray microtomography. Laplace's equation relates the radius of a capillary tube to the height and curvature of the meniscus which then determines its surface area.

$r/R = \cos\Theta \qquad P_c = 2\sigma/R = \Delta\rho g h$

Where, r = radius of capillary tube
R = radius of curvature
$\Theta$ = contact angle
$P_c$ = capillary pressure
$\sigma$ = surface tension
$\Delta\rho$ = density difference between air and water phases



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Capillary tubes of different radii will provide multiple samples of known curvatures and surface areas. Comparison to surface area measurements by different techniques will determine that which is most accurate.

This method will be carried out in the coming fall.