VISUALIZATION AND MEASUREMENTS OF MULTIPHASE FLOW IN POROUS MEDIA USING LIGHT TRANSMISSION AND SYNCHROTRON X-RAYS

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Non-aqueous phase liquids (NAPLs) enter the vadose zone as a result of spills or leaking underground storage facilities, thus contaminating groundwater resources. Measuring the contaminant concentrations is important to assess the risk to human health and the environment and to develop effective remediation. This research presents the development and application of the Light Transmission Method (LTM) for three-phase flow systems, aimed to investigate unstable fingered flow in a soil-air-oil-water system, as compared with synchrotron x-rays.

BACKROUND

Multiphase flow and transport phenomena in the unsaturated and saturated zones of the subsurface environment are the focus of numerous research efforts. One of the less understood transient flow phenomena is unstable fingering. Fingering decreases the fluid retention time in the vadose zone, thus increasing groundwater contamination. Consequently, there is a need for fast, non-destructive, and accurate measurements of transient three-fluid phase flow in porous media.

Transient visualizations (but not direct measurement of fluid contents) have been made in Hele-Shaw cells with smooth walls or with imprints of porous media on glass. Currently, very few methods exist that allow rapid determination of fluid contents in three-phase, NAPL-air-water systems. Most of the methods that allow determination of fluid contents in these three-phase systems involve some form of radiation. Synchrotron X-rays allow accurate and fast measurements of fluid contents in transient flow fields, in any soil type, but can measure only a small section of the flow field at one time due to the small beam size of 1 mm by 8 mm[1]. The LTM is a non-destructive method that allows visualization and measurement of fluid contents in transient air-oil-water flow occurring in sandy porous media, over the whole flow field, with a time resolution of tenths of seconds[2].

EXPERIMENTAL

The Light Transmission Method (LTM)

For fluid measurements in porous media, the LTM involved placing a two-dimensional (2D) chamber in front of a uniform light source and recording the transmitted light[2]. A light source composed of a bank of 24 fluorescent, high-frequency light bulbs, located in front of a white background, was used. The transmitted light was recorded with a Sony Color Video Camera employing three ½ inch CCD (Charge Couple Device) images, each having a total of 250000 effective picture elements. The camera was located 1 m in front of the chamber with constant settings (zoom = 0.95 m and aperture = f 5.6). The images were stored on a Hi8 videocassette in RGB format. Recorded images were converted from RGB to HSI format and analyzed using a Power Macintosh equipped with a video digitizer (RasterOps 24 XLT from RoasterOps Corporation, 1992) and scientific image processing software (IPLab Spectrum V3.00 software from Signal Analytics Corporation, 1989-1995). The advantage of the HSI format is that it treats color roughly the same way that humans perceive and interpret color.

Calibration and Materials

A calibration method was developed to measure the water, oil and air contents in porous media as a function of hue, intensity and porosity with LTM[2]. This calibration involved a 2D chamber consisting of cells filled with a porous media and known quantities and fluid ratios of oil and water, air and water, oil and air, or air-oil-water, allowing to obtain relationship for water, oil and air contents as a function of hue, intensity and porosity.

The oil used was Soltrol 220, a transparent isoparaffine solvent. The distilled water was dyed blue with $CuSO_4$ at a concentration of 28%. The calibration chamber was 62 cm high, 52 cm wide, and 1 cm thick. It was divided into 24 cells: 3 cm high by 23 cm wide. The cell walls were constructed from the same 1 cm thick Hyzod polycarbonate sheet as the experimental chamber. The cells were packed to a porosity of 38% with 20/30-sieve size, industrial-quartz silica sand. The sand packed cells were then filled with all possible fluid combinations. The fluid contents of each of the three fluids were varied by 0.076 cm^3/cm^3 increments.

Average hue and intensity values were plotted versus the corresponding water and liquid contents to obtain the calibration curves; fluids contents were expressed by a set of equations[2], where water content was uniquely related to hue and oil content was a function of hue and intensity.

RESULTS & CONCLUSIONS

Validation of LTM by Synchrotron X-rays

X-ray measurements of the fluid contents in the soil-air-oil-water systems were performed at the F-2 beam line at the Cornell High Energy Synchrotron Source, using dual-energy attenuation measurements. It consists of an initial white X-ray beam which is reflected off a double-bounce Si(220) monochromator producing a beam of two distinct energies (20 and 40 Kev) that enter the experimental hutch[2]. The accuracy of the LTM in determining water, oil and air contents was compared with synchrotron x-rays for a static oil-water-air system (Fig 1). Both water and oil contents are depicted with depth and compared with those obtained with the synchrotron x-rays. In general, the fluid contents compare well; the water contents are nearly identical for both methods. The oil content shows the same trend for both methods.

Application of LTM: Fingered Flow

Unstable fingered flow experiments were performed with a slab chamber filled with quartz silica 20/30 sand and saturated with a combination of oil-air-system to meet the initial experimental conditions. The experimental chamber had 1 cm thick polycarbonate walls and interior dimensions of 45 cm wide, 1 cm thick, and 55 cm tall. A manifold of five fluid ports was located at the bottom. To form a finger, water was applied as a point source through a needle, 1 cm above the sand surface, at a rate of 3 ml/min. The oil level was kept constant via overflow tubing located 1 cm below the oil in the chamber. Vertical profiles were analyzed for fluid contents, at the center of the finger, as the finger progressed into the different sand-oil-air saturated phases and interfaces.

Fluid content profiles for the fully formed fingers in different soil-oil-air-water systems are presented in Fig 2d. Figure 2 shows the image of a fully form water in soil-air-oil systems in (a) RGB format, (b) hue image and (c) intensity image. As expected from previous experiments[1], and as clearly observed in Fig 2d, the tip of the finger is the wettest while the remainder of the finger is much dryer. In all fingering experiments, the finger does not expand once it is formed due to hysteresis in the soil constitutive relationships. The LTM measurements, in conjunction with simultaneous matrix potential measurements, can be used to determine the constitutive relationship for fingered flow in porous media.

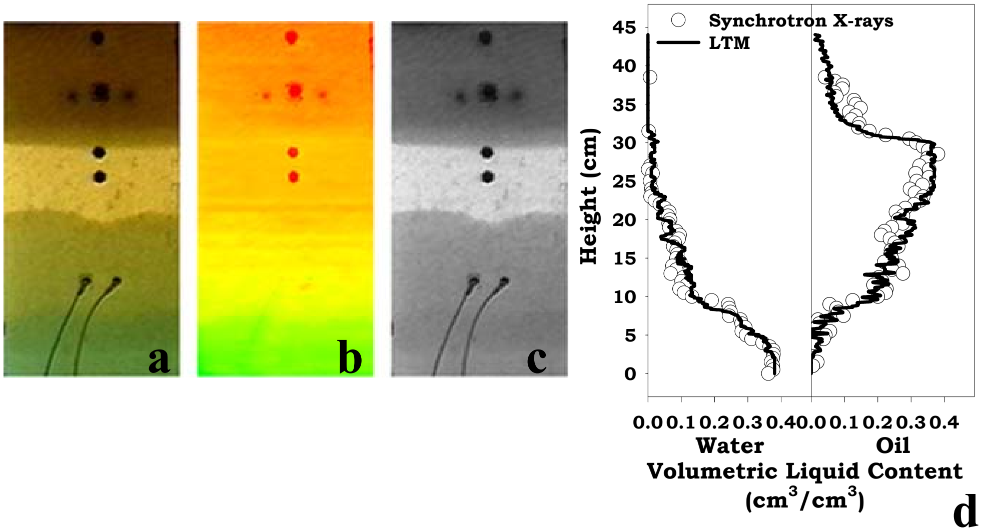

Figure 1.Visualization of a static experiment in soil-air-oil-water systems, using (a) RGB system, (b), hue image, (c) intensity image, (d) Vertical fluid contents profile from the drainage experiment using LTM and synchrotron x-rays

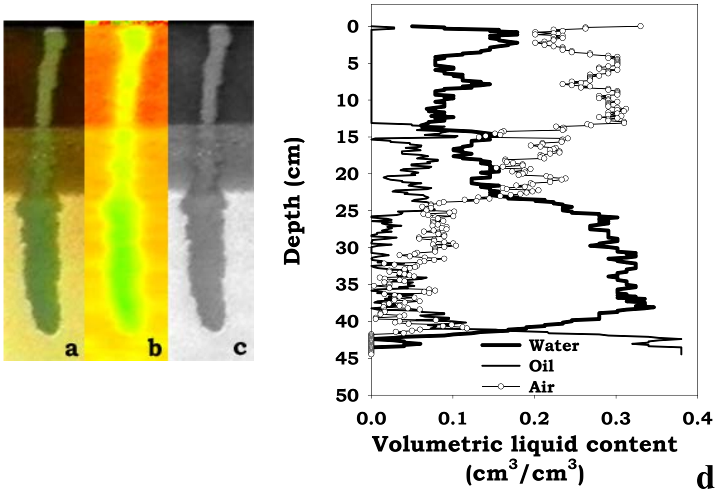

Figure 2. Visualization by LTM of water fingering phenomena in soil-air-oil system using (a) RGB system, (b) hue system, (c) intensity system, (d) Vertical fluid content profile of unstable fingered in three-phases flow system: water finger in soil-air-oil system.

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