Neutron tomography of axisymmetric flow fields in porous media

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A B S T R A C T

A significant problem in the study of fluid transport in porous media is the ability to visualize the structure of the flow field when moisture contents vary rapidly in space and time. Here we present a method for determining the radial and vertical saturation profiles within axisymmetric preferential flow fields using neutron radiography. Flow fields such as these are surprisingly common in nature and determining the three-dimensional structure of their wetting front region has proven difficult. In this work, the moisture profiles are determined using a simple algorithm for algebraic computed tomography, which gives the three-dimensional structure of the moisture profile with a temporal resolution that is limited only by the desired noise level. The algorithm presented can be translated to radiography done using X-rays or light and is applicable to any rotationally symmetric object.

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1. Introduction

A significant obstacle in the study of fluid transport in porous media is the ability to visualize flow field structure and how it varies with time [1]. This is a particular limitation for research on preferential flow fields. Here, wetting fronts become unstable, resulting in axisymmetric flow paths that translate rapidly through unsaturated media [2,3]. These types of flow fields are common in nature and are responsible for the rapid movement of pollutants into the subsurface, as well as problems in oil recovery from aquifers [4].

The standard techniques for measuring moisture contents within preferential flow fields have either used light box imaging [5,6] or X-rays where a thin, fan beam is used to scan the flow field by varying the location of the chamber or beam [7,8]. The former technique is limited to experiment chambers that are thin enough for the flow fields to span their width and the latter is slow because of the need to move the experiment chamber between measurements in order to capture the full profile of the flow field’s moisture content. Computed tomography (CT) provides a cross sectional view of the object under study. Modern CT scanners use well collimated, closely spaced, high efficiency detectors for counting the particles that pass through the object under study. As a result, standard medical CT scanners offer good resolution, around 80–100 μm for X-ray CT with 100–500 μm thick slices [9] and 2–5 mm for γ-ray CT [10]. Sensitivity to changes in mass density of 3% have also been reported for X-ray CT but a range for γ-ray CT’s mass resolution is not available at this writing [11].

What CT-systems typically lack is good temporal resolution. Imaging times range from a few minutes to over an hour depending on the scanner design. While X-ray and γ-ray CT have been used for imaging flows in porous media and multiphase flows in general, the work has been limited to studies requiring low temporal resolution [9,11,12]. X-ray interrogation is also limited because the fluid of interest and porous medium through which the fluid is moving can exhibit similar levels of X-ray attenuation, thereby limiting image contrast. Magnetic resonance imaging (MRI) is another option that has been explored, but it cannot always be used to establish absolute values for the moisture content within a system, especially at low saturation levels [13,14].

Neutron radiography is an alternate technique for imaging fluids in porous media that combines a high spatial resolution (typically better than 1 mm) with a field of view sufficient to capture the whole flow field and the ability to image through large volumes of dry media at video frame rates [15]. The technique works especially well when the fluid under study is hydrogenous, such as water or oil, since neutrons are heavily attenuated by hydrogen [1,12,16–18]. In contrast, the neutron attenuating properties of many porous materials (SiO₂ sands in particular) are small relative to the fluid, thereby increasing the contrast of the fluid under study above the background porous material.

Because of its sensitivity to small variations in water density, neutron imaging has been used to study fluid transport in the porous membranes of fuel cells, fluid transport in geological media, and for measurement of fluid transport coefficients, e.g. [1,18–22]. Neutron radiography has also found recent application in the...
study of phase change in capillary systems [23,24], as well as the composition of building materials [25]. Neutron radiography has been shown to have potential for applications in treaty verification, where the contents of containers need to be verified without their being physically opened [26].

Here we present a method for determining the radial and vertical moisture profiles within axisymmetric preferential flow fields using neutron radiography. Unlike conventional neutron tomography, which requires attenuation data taken from multiple angles, e.g. [21], the present technique is applicable to single view radiographs, provided that the object to be reconstructed is symmetric about an axis of rotation. The algorithm can be easily translated to radiography done using X-rays or light and gives temporally averaged snapshots of the three-dimensional structure of the flow field.

2. Methods

The data obtained from neutron radiography can be used to determine the cross sectional moisture distribution within a flow field. This is particularly easy when the flows are axisymmetric. This is typically the case with preferential flow fields in porous media, and a simple algorithm for algebraic tomography [27] can be adapted to determine the cross sectional structure. It was shown previously that the response of the imaging system used in this work had the form [28]:

$$d(i,k) = -\ln \left( \frac{I(i,k)}{I_0(i,k)} - 1 \right) / \Sigma_i$$

where $d(i,k)$ (cm) is the amount of water through which the neutrons moved before being registered at location $(i,k)$ on the image.
plane. Fig. 1a. The fractional change in image intensity is $I(i,k)/I_0(i,k)$, $\Sigma_t$ is the total neutron attenuation coefficient of water, and $\alpha$ is a system calibration constant that was determined using a calibration standard, Fig. 2.

The images used in this study are digital so they can be viewed as two-dimensional data arrays, the image brightness at point $(i,k)$, $I(i,k)$, corresponds to the pixel intensity at that location (here integer values ranging from 1 to 256). For a given vertical position in the flow field:

$$d_i = \sum_j \theta_j S_{ij}$$  

(2)

where $\theta_j \text{(cm}^3\text{water/cm}^2\text{out)}$ is the average moisture fraction in the $j$th ring and $S_{ij}$ (cm) is the path length of the $i$th neutron ray traveling through the $j$th ring, Fig. 1b. Here the flow field is considered to be made of concentric rings, each of which has a uniform moisture content, see Fig. 1b. Eq. (2) can be expressed in matrix form as:

$$d_i = S_0 \theta_j$$  

(3)

Here the matrix elements $S_{ij}$ are given by:

$$S_{ij} = 2\left[(r_j^2 - S_j^2)^{1/2} - (r_{j-1}^2 - S_j^2)^{1/2}\right]$$  

(4)

For a given set of $d_i$ measurements, the radial moisture profile, $\theta_j$, can then be reconstructed by inverting the $S_{ij}$ matrix in Eq. (3). Because of the symmetry of this system of equations, it is always over determined and the best solution for the moisture content vector is found in a least squares sense.

2.1. Neutron source

The neutron source for this work was a TRIGA Mark II research reactor rated for a maximum steady state operating power of 500 kW. A collimator with a sapphire crystal was used to create a uniform beam in the tangential beam line used for this work, Fig. 3a. The sapphire helped to filter out both gammas and higher energy neutrons. The L/D for this work was $\sim 110 \pm 1.0$ and the cadmium ratio was $\sim 21.0$. The radiography system was contained inside of a beam hutch made from high-density concrete radiation shielding and lined with borated polyethylene to cut down on scattered neutrons, Fig. 3b. The unattenuated neutron flux at the image was determined using gold foil activation and found to be $\sim 5 \times 10^6 \text{ [n/cm}^2\text{/s]}$. Additional information on the neutron source and imaging system used for this work can be found in [1,28].
2.2. Imaging system and setup

A Precise Optics neutron image intensifier (model PS93NX) connected to a Precise Optics Vidicon camera (model PVC525V) was used for this work. The chamber to image plane separation used for this work was 5.0 cm which limited the spatial resolution to \( \theta > 1.0 \) mm, defined as the ability to completely distinguish adjacent points with a field of view of 410 cm\(^2\). The radioscopic images were recorded using NIH Image 1.61 running on a G3 Macintosh with a Scion LG-3 interface.

\[
\begin{align*}
\text{Distance (cm)} & \quad 0 \quad 1 \quad 2 \quad 3 \quad 4 \\
\text{Time (sec)} & \quad 0 \quad 0.5 \quad 1 \quad 1.5 \quad 2 \\
\end{align*}
\]

Fig. 4. Wetting front position-vs-time for low and high flow rate experiments. It is shown here that the high and low volume flow fields move at constant velocities.

A 16-gauge aluminum chamber with interior dimensions of 35 cm height by 20 cm width by 1.35 cm depth was loaded with 20–30 industrial quartz (Unimin) with a mean grain size of 0.6 mm and packed with vibration. The media was prepared with a thorough rinse with distilled water followed by drying. The total porosity was 0.33, determined by weighing the chamber and using a bulk density of 2.65 gm cm\(^{-3}\) for SiO\(_2\). The interior surfaces of the chamber were sprayed with Dow-Corning Silicone-20 release compound to render them hydrophobic. Degassed, demineralized water was used for the experiments and the peristaltic pump was calibrated by plotting its flow rate-vs-time. The chamber was leveled so that it stood dead vertical. The saturated moisture content \( \theta_{sat} \) (cm\(^3\)/cm\(^3\)) was determined gravimetrically and found to be equal to 0.31 (air entrapment causes the difference between porosity and saturated moisture content).

In order to illustrate differences in flow field structure, preferential flow fields were generated using point infiltration into dry sand at 10 ml/min and 1.3 ml/min.

2.3. Images used for measurements

A 1000 frame sequence of the dry chamber was taken, averaged and used as the \( I_0(k) \) image for each infiltration experiment. Images of the infiltration experiments were captured at 10 frames per second. The progression of the wetting front was measured by recording the location \((k)\) on each image array for which \( I(k)/I_0(k) \leq 0.98 \). The horizontal position of the preferential flow field varied little during infiltration, which is typical with this type of flow field although the two flow fields produced significantly different wetting front velocities, Fig. 4.

The neutron intensity ratio \( I(k)/I_0(k) \) was measured at each pixel from 0.25 cm in front of the wetting front to 4.5 cm behind it for each of 100 successive images. This 10 s interval of data was then averaged at each pixel to obtain an average \( d(k) \), which was used in Eq. (3) to obtain \( \theta_{sat} \). The width of the flow field was measured in all experiments and in all cases found to be less than the chamber thickness.

2.4. Image noise and mass resolution

The frame-to-frame noise in a given pixel depends on the neutron flux at a specific location on the image plane. Images are acquired in 33 ms intervals and for the reactor power used in this study, \( I_0 \) had a standard deviation of 0.009 at 85% beam attenuation. This degree of attenuation is larger than that encountered when imaging the flow fields in this study. The noise from neutron counting followed a Poisson distribution. The system registers variations in water density within the experiment chamber of less than 0.007 cm\(^3\)/cm\(^3\) and has previously been shown to account for mass to \( \sim 1\% \) [1,28].

3. Results and discussion

Figs. 5 and 6 show the radial and axial saturation profile for the 1.3 and 10 ml/min flows, respectively, for preferential flows that move at constant velocity through the dry SiO\(_2\) sand. In Fig. 5, it is shown that the low flow rate field exhibits pronounced drainage behind the wetting front, which has been noted in many previous studies, e.g. [3,29,30]. Fig. 7 shows the corresponding radially averaged saturation profiles for the two flow fields.

In Fig. 5, the 1.3 ml/min flow tomographic reconstructions show much steeper saturation gradients in the centerline region of the wetting front than do the radially averaged profiles. This feature is not seen in the radially averaged data because the gradient in saturation is smaller away from the centerline, which brings the
average down. For the 10 ml/min flow data, Fig. 6, an important feature observed in the tomograph is the monotonically increasing saturation that occurs away from the centerline. This is in contrast to what is happening at the centerline, where the saturation peaks and then begins to drop. By contrast, the radially averaged saturation seen in Fig. 7 is monotonically increasing.

Considerable noise is evident in the reconstructions shown in Figs. 5 and 6. However, this comes not from the imaging system, but from the variation in moisture content within the flow fields as they are translated through the sand. The reconstructions in Figs. 5 and 6 represent a 10 s time average of the moisture profile within the flow field. Even so, there is still considerable variation from one location to the next. This can also be seen, to a lesser extent, in the radial averages in Fig. 7. To reduce this noise in the data, longer imaging times would be needed to get a true average for the axial and radial saturation profile, though a balance must be made between data noise and temporal resolution. Even in the noisy data shown, the tomographs show important differences in the flow field structure when compared to the radially averaged profiles.

4. Conclusions

We have developed a simple method for determining the three-dimensional structure of axisymmetric flow fields using neutron radiography. The moisture content of the flow fields is determined using a simple algorithm for algebraic computed tomography and gives the three-dimensional structure of the flow field with a temporal resolution that is limited only by the desired noise level. The tomographs reveal important differences in flow field structure when compared to radially averaged profiles. The algorithm presented is easily translatable to radiography done with X-rays or
light imaging. The type of tomography described here would work with any rotationally symmetric object.

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