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Micro-positron emission tomography for measuring sub-core scale single and multiphase transport parameters in porous media

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ABSTRACT

Accurate descriptions of heterogeneity in porous media are important for understanding and modeling single phase (e.g. contaminant transport, saltwater intrusion) and multiphase (e.g. geologic carbon storage, enhanced oil recovery) transport problems. Application of medical imaging to experimentally quantify these processes has led to significant progress in material characterization and understanding fluid transport behavior at laboratory scales. While widely utilized in cancer diagnosis and management, cardiology, and neurology, positron emission tomography (PET) has had relatively limited applications in earth science. This study utilizes a small-bore micro-PET scanner to image and quantify the transport behavior of pulses of a conservative aqueous radiotracer injected during single and multiphase flow experiments in two heterogeneous Berea sandstone cores. The cores are discretized into axial-parallel streamtubes, and using the reconstructed micro-PET data, expressions are derived from spatial moment analysis for calculating sub-core tracer flux and pore water velocity. Using the flux and velocity measurements, it is possible to calculate porosity and saturation from volumetric flux balance, and calculate permeability and water relative permeability from Darcy's law. Second spatial moment analysis enables measurement of sub-core solute dispersion during both single phase and multiphase experiments. A numerical simulation model is developed to verify the assumptions of the streamtube dimension reduction technique. A variation of the reactor ratio is presented as a diagnostic metric to efficiently determine the validity of the streamtube approximation in core and column-scale experiments. This study introduces a new method to quantify sub-core permeability, relative permeability, and dispersion. These experimental and analytical methods provide a foundation for future work on experimental measurements of differences in transport behavior across scales.

1. Introduction

The inherent heterogeneity present in geologic porous media has an important influence on fluid and solute transport problems from the core to the reservoir scale. Porosity and permeability heterogeneity have significant influence on advective and dispersive transport in single phase problems such aqueous CO_2 and geochemical reactions in carbon capture and storage projects (Ahmad et al., 2016; Gunter et al., 2004; Xiao et al., 2009), monitoring and preventing salt water intrusion (Abarca et al., 2007; Jamshidzadeh et al., 2013), and understanding miscible surfactant behavior for enhanced oil recovery (EOR) projects (Cao et al., 2015; Ramirez et al., 1980) (see Dentz et al. 2011 for a more complete review). In multiphase flow problems, additional heterogeneity in capillary pressure and relative permeability need to be considered in order to properly understand and predict CO_2-brine migration in carbon sequestration reservoirs (Krevor et al., 2011; Li and Benson, 2015; Pini and Benson, 2013; Saadatpoor et al., 2010), EOR waterflooding efficacy (Alyafei et al., 2016; Gulick and McCain, 1998), and non-aqueous phase contaminant transport in aquifers (Illangasekare et al., 1995; Mayer and Miller, 1996). Developing methods to quantify heterogeneity across different length scales is valuable for proper utilization of laboratory data used for building and informing reservoir and aquifer-scale models.

Advancements in imaging and experiment methods have enabled significant progress in measurement and understanding of heterogeneity in porosity, fluid saturations (Akin and Kovscek, 2003; Ferno et al., 2015; Mitchell et al., 2013; Perrin and Benson, 2010; Zahasky and Benson, 2016), permeability (Krause et al., 2013), and capillary pressure at the laboratory scale (Pini and Benson, 2013; Pini et al., 2012; Trevisan et al., 2015). The most common imaging modality used in earth sciences is clinical—or more recently micro-scale—X-ray computed tomography, however mag-

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Nomenclature

Variable	Name Units
A	cross-sectional area of core [cm^2]
a	cross-sectional area of streamtube [cm^2]
C_0	radiotracer concentration injected [mCi/mL]
C	radiotracer concentration [mCi/mL]
D_L	longitudinal dispersion [cm^2/min]
D_T	transverse dispersion [cm^2/min]
D_m	molecular diffusion [m^2/s]
d_p	grain diameter [µm]
K	core average permeability [mD]
k	streamtube permeability [mD]
k_{rw}	relative permeability of wetting phase [-]
L	core length [cm]
M_s	streamtube reactor ratio [-]
$m_{x,\, n}$	1D n-th spatial moment [-]
Pe	Péclet number [-]
P_k	fraction of radiotracer in streamtube k [-]
q_w	streamtube water injection rate/flux [mL/min]
Q_g	gas injection rate into core [mL/min]
Q_w	water injection rate into core [mL/min]
R	radiotracer activity [μCi]
S_w	core average water saturation [-]
s_w	streamtube water saturation [-]
μ_w	viscosity of water [Pa.s]
Δp	pressure drop from inlet to outlet of core [Pa]
v	pore water velocity/ average linear velocity [cm/s]
x	distance from core inlet [cm]
$\bar{x}$	center of mass [cm]
α	dispersivity [cm]
η	heterogeneity factor [-]
δ	power law factor [-]
ϕ	streamtube porosity [-]
Φ	core-average porosity [-]
σ^2	solute variance [cm^2]
σ_z	standard deviation of z [var]
$\sigma_{\bar{z}}$	standard error of z [var]

netic resonance imaging (MRI) and positron emission tomography (PET) are emerging as valuable imaging platforms. Computed tomography relies on the generation and transmission of x-rays during discrete time intervals in order to image a 3D material and it is widely established as an essential tool for quantification of saturation behavior and structural properties of geologic materials (e.g. Akin and Kovscek 2003; Perrin and Benson 2010). Magnetic resonance imaging, or more generally, nuclear magnetic resonance imaging, uses strong magnetic fields and radio waves in order to image and quantify the contrast between different materials. Positron Emission Tomography, and other emission tomography techniques such as Single-Photon Emission Computed Tomography (SPECT), rely on the detection of photon emissions produced during radioactive decay of radiotracers injected into a 3D system. Using robust reconstruction techniques it is possible to produce quantitative four dimensional images of the radiotracer transport in the material.

A growing number of studies are employing positron emission tomography for solute transport quantification (Boutchko et al., 2012; Brattekas et al., 2016; Ferno et al., 2015; Goethals et al., 2009; Hu et al., 2017; Kulenkampff et al., 2015; Lippmann-Pipke et al., 2017; Pini et al., 2016; Zahasky and Benson, 2017), as it is ideally suited for measuring solute advection, dispersion, and diffusion in geologic porous media. One of the advantages of PET over many CT and MRI systems is the temporal resolution. Over the duration of a PET scan, coincident photon events are collected continuously by a cylindrical array of photon detectors located in the PET scanner. Coincident events are collected everywhere along the axis of the scanner, which is therefore able to image cores less than 12 cm long (the length of the bore of the micro-PET scanner used in this study) without physically moving the core. During the reconstruction of a PET scan these events can be binned temporally to create time lapse images of the scan. Depending on the intensity of the radiotracer and scanner properties, these time frames can be as short as 10–20 seconds. This capability provides the necessary temporal resolution to quantify solute spreading at many time steps between tracer injection initiation and tracer breakthrough, even with fairly rapid flow rates. Fig. 1 highlights this capability by illustrating the distribution of a radiotracer pulse, injected at 5 mL/min along the length of a relatively heterogeneous Berea sandstone core, at four different times prior to tracer breakthrough. This data will be examined in greater detail in the following sections.

A second major advantage of using PET imaging for tracer transport quantification is the high sensitivity to small changes in tracer concentration. X-ray CT imaging relies on the electron density contrast between fluids (i.e. water and water with a high density tracer) to produce different levels of attenuation which is then converted into concentration measurements. At lower concentrations, small changes in signal relative to imaging noise can make accurate concentration profiles difficult to acquire. The contrast between no radioisotope and full pore saturation is much larger during a PET scan than the contrast created by the electron density of the fluids, thus allowing PET to measure small changes in solute concentration with a greater sensitivity than CT. The final advantage of PET is that due to the high energy of the 511 keV gamma rays produced during positron annihilation, it is possible for the photons to travel through nearly all geologic materials without major losses in resolution—particularly with high quality attenuation correction. The presence of paramagnetic minerals in many geologic materials can sometimes limit MRI imaging to quantification of solute transport in artificial porous media (Nestle et al., 2003; Reeves and Chudek, 2001; Werth et al., 2010).

The biggest disadvantage of using PET for imaging studies has been the limited spatial resolution. The resolution of reconstructed PET scans is a function of the physical imaging system, optimization of radioactivity levels, and the quality and method of image reconstruction and attenuation correction. Using clinical PET scanners, the fundamental resolution limits are around 3 mm, depending on the radioisotope being imaged, and radiotracer concentration optimization. However as the system size is decreased, the fundamental limit drops to less than 1 mm due to reductions in errors from photon non-collinearity and smaller detector element widths (Levin and Hoffman, 1999). These smaller systems are known as pre-clinical micro-PET scanners, which are commonly used in small animal imaging studies, and have only recently been employed for earth science applications (Brattekas et al., 2016; Hu et al., 2017; Kulenkampff et al., 2015; Zahasky and Benson, 2016; 2017).

While the image resolution can be significantly better with smaller system size, PET scans also experience losses in resolution during the image reconstruction process. In order to reduce errors during the reconstruction process it is usually necessary to obtain an attenuation correction map of the object being scanned. An attenuation correction map is generally obtained with a CT scanner or other x-ray transmission source and provides information about how positron-sourced photons may attenuate as they travel between the source (i.e. radiotracer) and the scanner detectors. Finally, optimal radiotracer activity dosing is essential to obtain high quality images—the optimal activity level will maximize detection events without saturating the scanner photon detectors.