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Flow Transition during Buoyancy-Driven Gas Migration: Experiments and Theory

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"The problem of viscous fingering in immiscible systems is arguably one of the most difficult problems pertaining to porous media flow. This is so because of the wide variety of phenomena occurring that involve a myriad of pore-scale phenomena, including the details of wetting behaviour and wetting films, the movement of contact lines and dynamic contact angles, the static stability of capillary bridges, finger stability, transition from coherent to incoherent finger flow. When the invading fluid is non-wetting, the flow pattern is a probe of the topology of the microstructure and is characteristic of percolation behavior, with a backbone that may have a fractal character (Homsy, 1987)."

Despite these general findings there is an ongoing controversial discussion in the literature about stochastic continuum modeling of channelized gas flow (Stauffer et al., 2009; Riaz et al., 2007) Stauffer et al. argued that so-called sub-scale modeling, where the sub-scale is smaller than the REV-scale, can account for effective pore scale heterogeneity and is therefore able to describe coherent channelized gas flow patterns.

In order to investigate the stability of buoyancy-driven gas flow and the transition between coherent channelized flow and incoherent channelized flow we conducted high-resolution optical bench scale experiments. Our main results, which are in strong contradiction to the commonly used continuum models (CM) are: (1) Capillary trapping can already occur during injection and at the front of the plume (Lazik and Geistlinger, 2008) (2) Gas clusters or bubbles can be mobile (incoherent gas flow) and immobile (capillary trapping), and (3) Incoherent gas flow can not be described by a generalized Darcy law (Geistlinger et al., 2006, 2009). Glass et al. (2000) conducted CO_2-gas injection experiments. Based on their experimental results they also questioned the validity of CM to describe coherent and incoherent gas flow and the validity of homogeneous stability analysis to predict channel width, channel number and channel velocity in heterogeneous porous media.

We used an upscaled modeling approach from pore scale to sub-scale and to REV-scale using both uniform and log-normal pore size distributions. The corresponding hydraulic functions – permeability and capillary pressure – were derived and random and correlated stochastic fields were used. The main conclusions of our sub-scale simulation were that (1) CM are not able to describe the channelized gas flow patterns for 0.5mm- and 1mm-glass beads for realistic sub-scale heterogeneity and injections rates smaller than 100 mL/min, and that (2) CM are not able to describe the transition from incoherent to coherent gas flow pattern.

In contrast, a dynamic network model (Ezeuko and McDougal, 2010) was able to describe most of the experimental results.