Micro-CT imaging of reservoir condition CO_2 during multi-phase flow in natural rock

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Micron-resolution X-ray microtomography has allowed researchers to examine the processes controlling fluid flow behaviour at the pore scale, offering the promise of a transformation in our understanding of flow and transport in porous media. Until very recently, however, the imaging of fluids at conditions of temperature and pressure representative of subsurface flow has remained an outstanding problem.

Wettability analysis

Until recently wettability has only been directly accessible in extremely simplified systems such as pure mineral surfaces, or indirectly at the core scale, such as with the use of the Amott-Harvey index as a proxy for wettability and contact angle. A new method is presented for the measurement of the contact angle and capillary pressure of multiple immiscible fluids at the pore scale at reservoir conditions (10MPa and 50^oC) in real rocks by the use of X-ray microtomography. It is applied in the scCO_2-brine-carbonate system.

Contact angle is found by resampling the micro-CT data onto planes orthogonal to the contact lines, allowing for vectors to be traced along the grain surface and the scCO_2 – brine interface. A distribution of contact angles ranging from 35^o to 55^o is observed. This distribution can be understood as the result of contact angle hysteresis and surface heterogeneity on a range of length scales. Surface heterogeneity is examined by comparison of micro-CT results with optical thin sections and SEM images. Contact angles are also observed to be time dependent; the angle is observed to return from receding angles to an equilibrium angle over time.

Capillary pressure measurements, Snap-off and Remobilization

Ganglion capillary pressure for each ganglion was found by measuring the curvature of the CO_2-brine interface, while the pore structure was parameterised using distance maps of the pore-space. The formation of the residual clusters by snap-off was examined by comparing the ganglion capillary pressure to local pore topography. The capillary pressure was found to be inversely proportional to the radius of the largest restriction (throat) surrounding the ganglion, which validates the imbibition mechanisms used in pore-network modelling.

The potential mobilization of residual ganglia was assessed using a new formulation of both the capillary (N_{cmacro}) and Bond numbers (N_{bmacro}), rigorously based on a balance of pore-scale forces, with the majority of ganglia remobilized at N_{cmacro} around 1. Buoyancy forces were found to be small at residual saturation ($N_{bmacro} << 1$), meaning the gravitational remobilization of CO_2 after residual trapping would be extremely difficult.

Dynamic Displacements

By the use of synchrotron tomography it is possible to create high quality 4D images of dynamic processes involving the flow of multiple fluid phases. For this we used beamline I13 at Diamond light source, where the high photon flux allowed for extremely rapid scanning. We use this capability to examine the pore-scale processes involved during CO_2 drainage. This is used to not only validate the traditional types of events seen in pore-network models, but also provide new insights into the importance of both local pore structure and the pore-space fluid arrangements on displacement processes.

We show how the drainage process take place as a series of discreet events, called Haines jumps. Two different types of Haines jumps were seen, one where CO_2 moves into a pore and remains connected with the rest of the CO_2 and one where it immediately snaps off, forming a disconnected ganglion in the filled region. We also observe the change in capillary pressure associated with a Haines jump, showing that the capillary pressure reduction during the event can cause snap-off far away from the Haines jump.

These techniques represent a new and unrivalled method to look at pore-scale fluid displacements with an unprecedented potential to look at fundamental problems in flow in porous media.

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