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Multi-phase flow in porous media: Can time resolved multi-scale 3D imaging help bridging the gap between pore scale mechanisms and core scale properties?

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Transport phenomena in porous media are encountered in many situations of practical and scientific interest, where determination of transport properties remains a challenging issue. They may concern natural porous media, such as soils and water or hydrocarbon reservoirs, as well as artificial ones, such as filters, fuel cells, catalysts, concrete.

Multiphase flow in natural porous media is central in a wide range of phenomena and applications in geosciences, including hydrocarbon formation and migration, oil and gas production, enhanced oil recovery or CO2 sequestration. Understanding and predicting fluid displacement mechanisms at the relevant scale is one of the big challenges in basin and reservoir modeling.

The description of the transport of fluids in geological formations relies upon advances on the characterization and modeling of natural systems in a large spectrum of time and length scales. The complexity of transport in these systems is due to the complex and heterogeneous geological structure as well as to the dynamics of the multiphase fluid displacement and its coupling with mechanical, thermal, chemical and biological processes.

Information on the pore space geometry and topology and on fluid displacement is essential to understanding of mechanisms and modeling. Experiments in 2D micromodels bring information on the motion of fluid/fluid interfaces in model systems, while advances in microfluidics extended the observations to the micron scale. In 3D, X-Ray 3D-imaging has proved to be a key technology to study multiphase flow in porous media with a continuous quest for space and time resolution.

Observation and experimental study have to be intimately linked to pertinent theoretical modeling taking into account the relevant physics of the studied phenomena at the right scale. Advances in molecular dynamics, lattice-Boltzmann or pore-network modeling methods combined to upscaling considerations permit to simulate complex flow regimes and to run laboratory and numerical experiments on comparable sample volumes.

Some of the most important contributions in this area have been presented by A.C. Payatakes and his coworkers. His pioneering work goes from the pore structure recognition and characterization to the modeling and simulation of particulate flows in porous media and to the complex multiphase flows including simultaneously connected fluid motion, ganglia dynamics and drop traffic flow. In the frontiers between academic and applied research, Prof. Payatakes' outstanding work is characterized by the combination of the experimental observation and the theoretical analysis at different scales, emphasizing the importance of the physical meaning of the average macroscopic properties and their link to the pore scale phenomena and mechanisms.

As an illustration of the recent advances we will present a workflow combining high speed CT-scan, laboratory based micro-CT and synchrotron X-ray ultra-fast tomography to investigate chemical enhanced oil recovery processes from pore-scale to core-scale. We show how the combination of these multi-scale imaging techniques allows to understand the dynamic phenomena involved in oil recovery by surfactant injection, and to better assess the impact of rock structure on oil trapping and mobilization. We propose a dimensional analysis that helps linking pore-scale to macroscopic properties, such as the capillary desaturation curve and the relative permeabilities. Finally we discuss how laboratory scale parameters can be used in reservoir simulation to predict EOR process efficiency. The importance of pore-scale investigation of other dynamic phenomena, such as spatial and temporal wettability variations or property evolution due to reactive flows, will be also highlighted.