Modeling capillary forces during convective drying of gels: influence of product and process paramaters on structure

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Introduction. The drying of highly porous particle aggregates – such as gel structures – is a challenging process which affects both the production rate and the quality of the end product. Processes such as freeze drying, supercritical drying, and vacuum drying have been employed for this task. These techniques preserve the solid structure, but they need to be conducted at specific temperature and pressure conditions and are thus rather expensive and of limited use for large-scale production. An alternative might be convective drying, which can be carried out under normal atmospheric conditions. In this technique, however, the receding liquid–gas interface causes large capillary forces in the small pores of the material resulting in mechanical damage (shrinkage, breakage or cracks) of the aggregates. The study of fundamental mechanisms causing mechanical damage during convective drying may eventually improve the preservation of the solid structure and help in the process design.

Problem definition

Convective drying is not yet suited to produce highly porous dry gels: high capillary stresses in small pores result in mechanical damage of the solid. An understanding of the micro-scale phenomena inducing shrinkage and cracks during convective drying is expected to extend the range of applications for this inexpensive and safe process.

Objectives

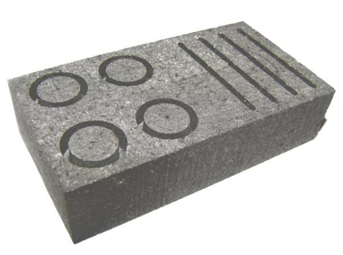
- Perform a series of drying experiments with beds of sintered particle structures by using an X-ray microtomograph;
- Develop a 3D micro-scale model for convective drying of these particle beds, which resolves the three phases as well as the interfaces between them.

Cooperation

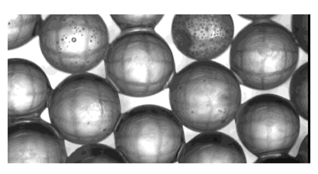
- Dr. Christoph Kirsch (ZHAW, Switzerland): volume-of-fluid model
- Dr. Petter Müller: discrete element method
- MSc. Yujing Wang: drying and X-ray tomography measurements

Drying experimens with sintered particle structures

Model aggregate and X-ray microtomography (μ-CT) setup



graphite mold



sintered glass beads
(600 °C, 6 minutes)

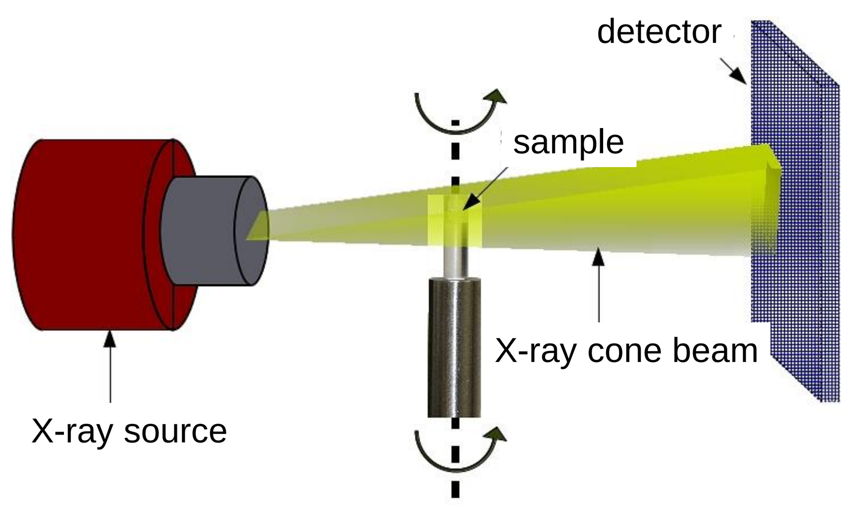
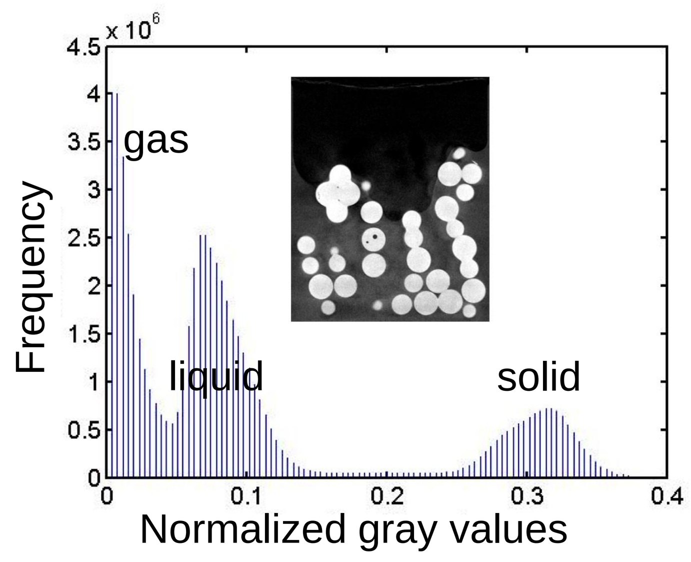


Image acquisition and processing

Scanning parameters:
- X-ray source: 90 kV, 160 μA
- 800 projections

From image processing:
- phase discrimination
- particle center coordinates
- evolution of liquid phase distribution



Evolution of liquid phase distribution from μ-CT

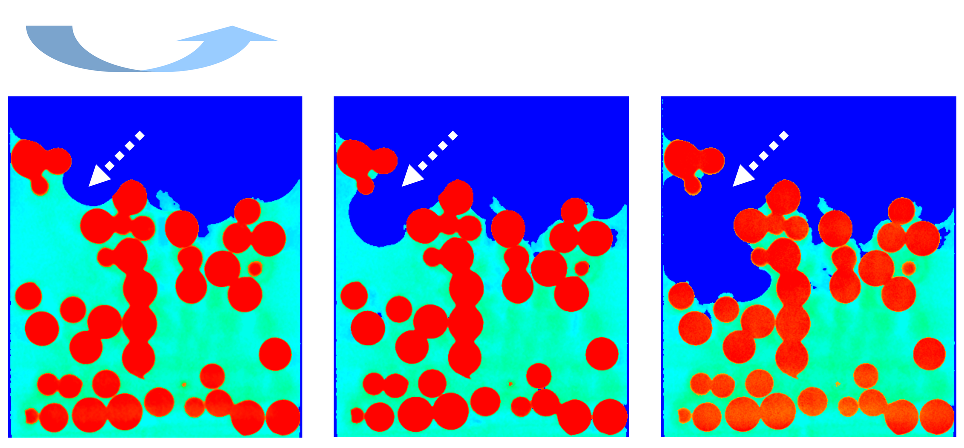


Figure 1. Cross sections of 3D tomograms for a packing of sintered glass beads at various liquid saturations (saturation decreases from left to right).

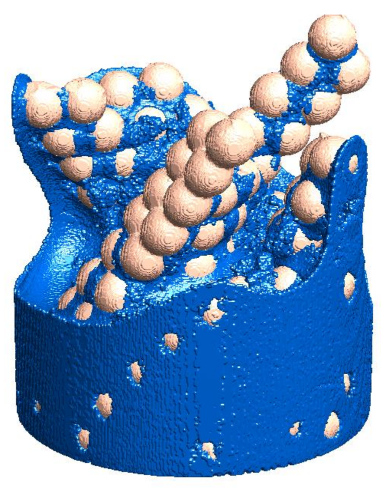
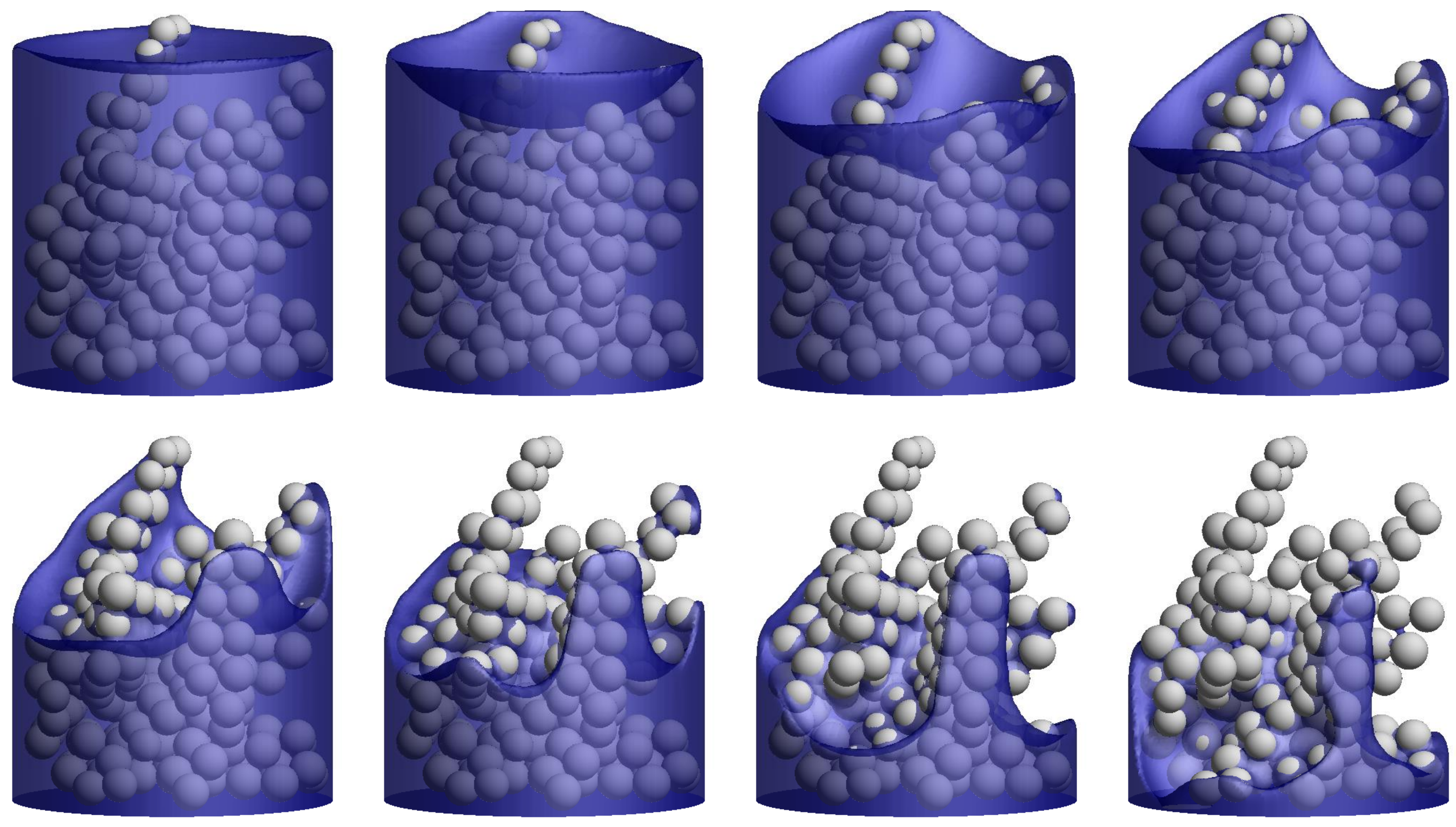


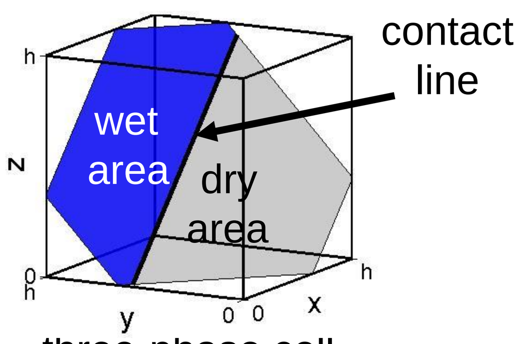
Figure 2. 3D visualization of a sintered particle aggregate partially saturated with liquid.

Volume-of-fluid simulations

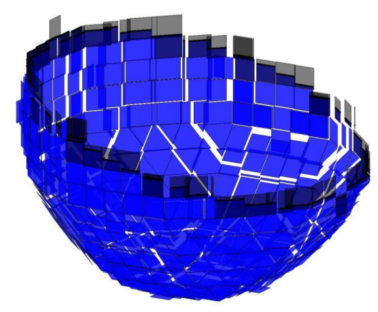
Simulated liquid distribution during drying



Reconstruction of wetted area and contact line from volume fractions



three-phase cell

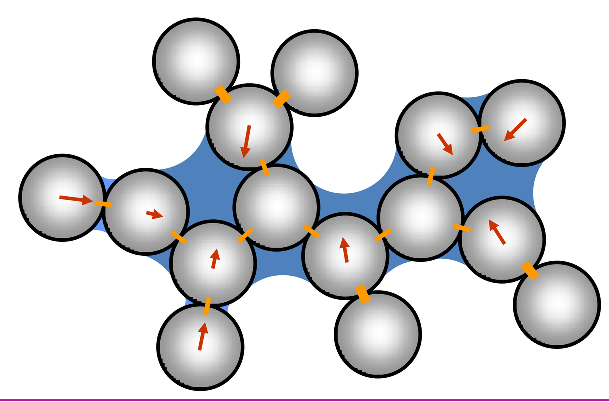


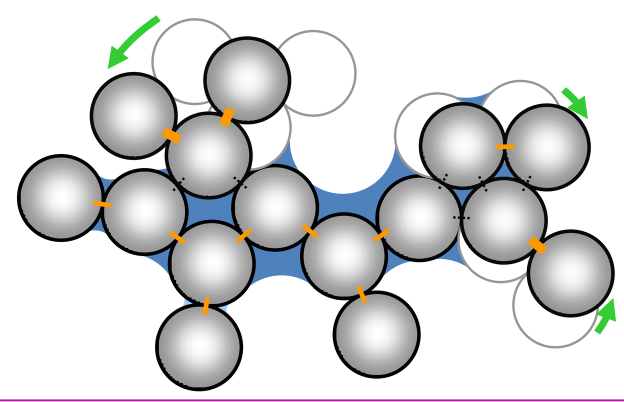
half-wetted sphere

Loads on inter-particular bonds are computed using discrete element method (DEM). Mechanical damage is indicated by bond breakage.

Application of capillary forces on aggregate

1. Compute **cracks / breakage** 2. Compute **shrinkage / restructuring**.





Summary and conclusion

We have conducted X-ray experiments with high resolution and developed a micro-scale model for the numerical simulation of drying of highly porous particle aggregates. The experimental results from X-ray microtomography measurements resolve the pore-scale phenomena in highly porous model particle aggregates made of sintered glass beads. We propose to combine several numerical methods in an iterative time-stepping scheme for the three-dimensional simulation of the process. In a quasi-steady state approach, the transport phenomena in each fluid phase were decoupled from the phase transition. Simulation results performed for the corresponding solid phase data exhibit a similar qualitative behavior. A quantitative comparison of experimental and simulation results shall evaluate the accuracy of our computational tool. (see also: DFG-SPP 1273, Kolloidverfahrenstechnik)

Outlook

The aim was to understand the macroscopic behavior of such material during convective drying (shrinkage, damage) by considering the fundamental physical phenomena at the microscopic scale. Ongoing work will include the coupling of liquid and solid phases. It shall then give insight into the pore-scale phenomena and, as a long-term objective, into the micromechanical behavior of particle aggregates during convective drying.

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