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Editorial: Physics of Porous Media

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Editorial on the Research Topic

Physics of Porous Media

The physics of porous media is, when taking a broad view, the physics of multinary mixtures of immiscible solid and fluid constituents. Its relevance to society echoes in numerous engineering disciplines such as chemical engineering, soil mechanics, petroleum engineering, groundwater engineering, geothermics, and fuel cell technology. It is also at the core of many scientific disciplines ranging from hydrogeology to pulmonology.

Perhaps one may affix a starting point for the study of porous media as the year 1794 when Reinhard Woltman introduced the concept of volume fractions when trying to understand mud [1]. In 1856, Henry Darcy published his findings on the flow of water through sand packed columns and the first constitutive relation was born [2]. Wyckoff and Botset proposed in 1936 a generalization of the Darcy approach to deal with several immiscible fluids flowing simultaneously in a rigid matrix [3]. This effective medium theory assigns to each fluid a relative permeability, i.e., a constitutive law for each fluid species. It remains to this day the standard framework for handling the motion of two or more immiscible fluids in a rigid porous matrix even though there have been many attempts at moving beyond it.

When the solid constituent is not rigid, forces in the fluids and the solid phase influence each other. von Terzaghi realized the importance of capillary forces in such systems in the thirties [4]. An effective medium theory of poroelasticity was subsequently developed by Biot in the mid fifties [5]. Biot theory remains to date the state-of-the art for handling matrix-fluid interactions when the deformations of the solid phase remain small. For large deformations, e.g., when the solid phase is unconsolidated, no effective medium theory exists.

The situation today in porous media research is a patchwork of domains, some of which are advancing at high speed, whereas other domains remain where they have been for decades. For example, pore scale visualization techniques together with advances in numerical techniques and hardware have today reached a level of refinement that makes it possible numerically to reproduce the motion of immiscible fluids and their interfaces in complete detail at the pore level. On the other hand, to derive effective equations at the large-scale continuum level based on what happens at the pore scale the upscaling problem remains a rather stagnant endeavor as proven by the popularity of the 80-year old relative permeability theory of Wyckoff and Botset.

It is the aim of any physical theory to join experimental observations into a common framework reducing the field to solving mathematical problems. Here is an example. The flow of Newtonian fluids remained a catalog over experimental observations until the advent of the Navier-Stokes equations. Afterwards, the problem became solving these equations with the proper boundary conditions. The fact that it is extremely difficult to solve these equations in the majority of instances is a different story. The science of porous media is still at the catalog stage with no general theory of porous media flow in existence nor in sight.

This Research Topic attempts to present a snapshot of the state-of-the-art in some of the domains that constitute the physics of porous media. The physics of porous media is of course far too wide to make it possible to give a comprehensive picture of the field. Interdisciplinarity is a key word.

The paper by Xu et al. studies the dissolution of plaster by water in a two-dimensional Hele-Shaw cell. The water is drained from the center of the cell which has a radial geometry. This causes fingers to grow inwards from the surface of the plaster. There has been a number of numerical studies of similar phenomena, but the experimental work is sparse—in spite of the importance of this process in geological settings.

In another experimental and numerical study, Xu et al. inject a reactive fluid into an open fracture with the result that the fracture surface is modified locally by creating a ramified structure around the injection point. A tracer is then injected and the influence of the modified fracture surface on stability of dispersion front is studied.

Roy et al. consider theoretically and numerically two-phase flow in the capillary fiber bundle model. This is a model that can be solved analytically. At high flow rates, the authors find a linear relation between flow rate and pressure drop across the model, i.e., a standard Darcy law. However, at smaller pressure drops, there is a crossover to a non-linear regime where the flow rate is a power law in the pressure drop. This is precisely what is seen in experiments (see references in the paper), but the exponent of the power law depends on the disorder in the model. This is a surprising result.

In Eberhard et al., the flow of non-Newtonian fluids in porous media is addressed. The authors propose a generalization of the Darcy law to describe the flow of a certain class of non-Newtonian fluids, the Carreau fluid, based on theoretical, numerical, and experimental work.

Another work focused on the flow of non-Newtonian fluids in porous media is that of Talon and Hansen. They focus on bi-linear fluids that have one viscosity up to a given shear rate and then switch abruptly to another viscosity above this shear rate. Through analytical and numerical arguments, the authors demonstrate that there is a critical point with a diverging correlation length characterizing this transition.

Wettability alteration due to adsorbtion of nanoparticles is the topic of the experimental paper by Li et al. This is a very promising approach to mobilizing stuck liquid clusters and droplets in porous media through flooding—an important process in many industrial applications such as EOR (Enhanced Oil Recovery).

Sinha et al. pose the question: when two immiscible fluids flow simultaneously in a porous medium at high enough speeds so that capillary forces are negligible compared to the viscous forces, what would be the effective viscosity that goes into the Darcy law describing the flow? It turns out not to be so simple: The authors propose a formula that contains a parameter that is determined by the pore structure of the porous medium.

There are many very different approaches to numerical modeling of immiscible two-phase flow in porous media. Network models constitute one class of such models, and a subgroup within this class consists of models that track the motion of the fluid interfaces inside the porous medium. Gjennestad et al. present here a way to stabilize such models numerically at very low capillary numbers, i.e., at very low flow rates. This leads to a vast improvement in range of capillary number over which these models may be used.

In two papers, Kjelstrup et al. and Kjelstrup et al., present a new way to coarse grain the thermodynamic variables at the pore level to the continuum level based on the Euler theorem for homogeneous functions and classical non-equilibrium thermodynamics. This way of coarse graining the system avoids the explosion of variables and complexity seen in other approaches to this problem. It leads also to a generalization of Darcy's law, including for instance contributions from thermal forces.

What is the pressure inside a nano-porous medium containing a single fluid? This is the question that Galteland et al. pose. Based on Hill's thermodynamics for small systems (see references in paper), the authors find that there are in fact *two* pressures necessary: an integral and a differential pressure. The authors support their findings by molecular dynamics simulations.

Grimstad et al. build a bridge between porous media physics and the classical concepts in soil mechanics/geotechnical engineering. The languages used by the practitioners of these two approaches to the *same problem* are quite different. Such bridges are therefore very important if multidisciplinary is to have any meaning. Physicists, read and learn!

"Bernaise" they call it, the beautiful computational framework that Linga et al. present for dealing with immiscible two-phase electrohydrodynamic flow in complex geometries such as porous media. The flow of immiscible electrolytes is important in many geological contexts, but little is so far known about how these electrical phenomena affect the hydrodynamics. Now, we have a good tool to explore this. Expect much more to come.

Kirichek et al. present a model for the dielectric response of porous sandstone saturated with NaCl which they proceed to verify experimentally using a two-electrode setup.

AUTHOR CONTRIBUTIONS

All authors listed have made a substantial, direct and intellectual contribution to the work, and approved it for publication.

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REFERENCES

1. Woltman R. *Hydraulischen Architectur*. Göttingen: Johann Christian Dieterich (1794).
2. Darcy HPG. *Les Fontaines publiques de la ville de Dijon. Exposition et application des principes à suivre et des formules à employer dans les questions de distribution d'eau.* Paris: Victor Dalamont (1856).
3. Wyckoff RD, Botset HG. The flow of gas-liquid mixtures through unconsolidated sands. *Physics.* (1936) **7**:325–45. doi: 10.1063/1.1745402
4. von Terzaghi K. Auftrieb und Kapillardruck an betonierten Talsperren. *Die Wasserwirtschaft.* (1933) **26**:397–9.
5. Biot MA. Theory of deformation of a porous viscoelastic anisotropic solid. *J Appl Phys.* (1956) **27**: 459–67. doi: 10.1063/1.1722402

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