Flow in porous media — pore-network models and multiphase flow

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Abstract

In the last 3 years there has been a huge increase in the use of pore-scale modeling to study multiphase flow and transport in porous media. Starting from single pore models of fluid arrangements, computations of relative permeability, interfacial area, dissolution rate and many other physical properties have been made. Combined with a realistic description of the pore space, predictive modeling of a variety of processes, including waterflood relative permeability and mass transfer coefficients, is now possible. This review highlights some of the major advances, with an emphasis on models of wettability and three-phase flow. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

The first use of a network of pores to represent multiphase flow in porous media was by Fatt in the 1950s [1–3]. In the 1980s, percolation theory was used to describe multiphase flow properties (see, for instance Koplik [4], Wilkinson and Willemsen [5], Heiba et al. [6]). In addition, the pore-scale displacement mechanisms for both imbibition and drainage were observed directly in micromodel experiments [7]. These displacements were then coded into three-dimensional network models. With suitable adjustment of parameters, some experimental data could be matched and the trends in behavior explained in terms of pore-scale phenomena (for one of the best papers on this, see [8]). However, the predictive properties of these models were limited to very simple systems — namely random close packings of spheres [9,10], and most of the research concentrated on two-phase flow in water-wet media. By the early 1990s, interest in pore-scale modeling had waned. The reasons for this included the move away from fundamental research sponsored by oil companies, and a recognition that something more than percolation-type models and simple pore-space geometry would be necessary to develop genuinely predictive models and to explain the whole range of flow and transport phenomena in porous media.

Recently, there has been an explosion of interest in pore-scale modeling, with a variety of both petroleum and environmental applications. Pore-scale models are no longer limited to simple two-phase flow processes and the computation of relative permeability. They are now used as a platform to explore a huge range of phenomena, including the effects of wettability, three-phase flow, hysteresis, and mass transfer between phases. Furthermore, it is now possible to represent the complex geometry of the pore space more adequately. This work leads the way towards truly predictive modeling, which has proved so elusive in the past. This review will briefly describe recent
advances in the field, concentrating on descriptions of new physical processes.

2. Descriptions of the pore space — geometry, spatial correlation and macroscopic predictions

Traditionally, network models represented the void space of a rock by a regular two- or three-dimensional lattice of wide pores connected by narrower throats. Each pore or throat was assumed to be cylindrical or spherical and hence contain just one phase (Fig. 1a). In addition, the pore sizes were spatially uncorrelated. However, real systems allow two (or even three) phases to be simultaneously present in a single pore, have a random topology, and have correlated pore sizes. A major challenge for pore-scale modeling is to determine the amount of detail in the description of the pore space geometry necessary to make accurate predictions of macroscopic properties.

Micromodel experiments have demonstrated that in pores with a rough or angular cross-section, the wetting phase may occupy the crevices in layers of order a micron across, while the non-wetting phase occupies the center of the pore space [7]. This provides extra connectivity for the phases. It is only recently that the full significance of allowing multiple phases in a single pore on macroscopic behavior has been appreciated. Schematically, a pore may be described as having, for instance, a square or triangular cross-section, as illustrated in Fig. 1b. Now, of course, real pores are not exactly triangular. However, the essential feature is that wetting phase can reside in the corners — the exact shape or nature of the corners is not qualitatively significant. Having said this, models based on three-dimensional reconstructions of porous media have successfully predicted relative permeability using pores with an irregular triangular cross-section [11*,12*]. The irregular triangle is not an exact replica of the real pore, but does have the same shape factor (ratio of cross-sectional area to perimeter area squared) as measured for the real system. The assumption is that the triangular shape reproduces correctly the balance between flow in corners (or roughness) and flow in pore centers. Some authors have used a grain boundary pore shape, formed at the junction of four spherical grains (see Fig. 1c) [13**,14*,15*,16**,17], while others have advanced a fractal-type model of pore wall roughness [18*,19,20*]. The use of these pore shapes has been shown to be vital to reproduce even the qualitative behavior of electrical properties, three-phase flow, relative permeability hysteresis, and dissolution rate [11–21*,22**, 23*,24**,25*,26**,27,28*,29*,30*,31,32*,33,34**,35– 37*]. In these examples, having pores with a circular cross-section and single-phase occupancy allowed insufficient connectivity of the wetting phase and resulted in poor comparisons with experiment. At very low wetting phase saturation, adsorbed water films, nanometers in thickness, in addition to wetting layers, have a significant impact on capillary pressure [34**,35*].

For predictive modeling, two different approaches have been used to characterize the porous network. In the first, the geometric parameters of a regular network model (often having pores of circular cross-section) are tuned to match available experimental data. This may involve removing throats on a cubic lattice to reduce the coordination number, and adjusting the pore size distribution [38*,39**,40,41*]. Then the model is used to predict other properties that are more difficult to measure [24**,25*,39**,41*]. Fischer and Celia used a network model adjusted to match capillary pressure measurements to predict relative permeability. This approach was more accurate than using simple correlations, but some of the predictions were still rather poor [41*]. The second method is to model the random topology of the pore space directly.

![Fig. 1. Different types of pore shape. The figures show a cross-section through a single pore. A circular pore (a) allows only one phase to occupy the pore at a time. In pores with an angular cross-section (b), wetting phase may occupy the corners while non-wetting phase occupies the pore center. (c) Another common model for pore shape is a grain boundary pore, formed by the intersection of four spherical grains. Again, wetting phase can occupy the crevices with non-wetting phase in the center.](image-url)
The sedimentation and compaction of sedimentary systems can be simulated explicitly using only a grain size distribution inferred from thin section analysis as input [11••, 12••, 37†, 42†, 43]. This approach works well for sedimentary systems, but statistical methods are required for other materials, such as carbonates. Such statistical reconstruction algorithms have been used to generate random pore networks, which have similar flow properties to the rocks on which they are based [20†, 44–46†, 47]. In addition CT scanning images have been used to determine the distribution of pore sizes [48, 49] and residual saturation [50].

Geological media have structure on all length scales, and the scale of a few pores is no exception. While most network models assume spatially uncorrelated pore sizes, recently a number of authors have shown that spatial correlation leads to better multiphase permeability for a given saturation than uncorrelated systems [51–53]. Such correlations are necessary to reproduce qualitative trends in experimental data. Spatial correlation is automatically incorporated into networks derived from reconstructions of real systems.

The conclusion of this section is that simple network models based on regular lattices and cylindrical pores, with parameters tuned to available data, are likely to have a limited predictive ability because the data match is non-unique and essential features of the pore space are missing. In some cases for representing qualitative trends in behavior, let alone making accurate predictions, a spatially correlated, disordered pore network is required, with each pore allowing multiple phase occupancy.

### 3. Physically-based modeling of wettability

Most petroleum reservoirs and many heavily polluted soils are not strongly wetting to water in the presence of oil, even though most of the minerals making up soils and rock are naturally water-wet. The mechanisms by which solid surfaces are rendered oil-wet have been the topic of several recent studies (see, for instance [54]). The pore-level modeling of this process was first proposed by Kovscek et al. [55••]. During oil migration, oil invades the pore space by a primary drainage process (meaning that the system behaves as though it is water-wet). Where the oil directly contacts the solid, surface-active components of the oil (called asphaltenes) adhere to the surface, altering its wettability. Regions of the pore space for which a wetting film of water coats the surface remain water-wet, as do the corners of the pore space where water still resides, and pores that remain completely water-filled. The degree of wetting alteration depends on the composition of the oil, the mineralogy of the solid surface and the capillary pressure imposed during primary drainage [54]. Kovscek et al. examined the pore-scale configurations of fluid and the macroscopic behavior for a bundle of parallel tubes with a grain boundary shape, Fig. 1c [55••]. Within a single pore, the surfaces have different wettability, as shown in Fig. 2. This results in a number of different possible fluid configurations during waterflooding, Fig. 3. Most importantly, oil may reside as a layer in the pore space, sandwiched by water in the corner and water in the center (Fig. 3f). This provides connectivity of the oil and allows for very low residual oil saturations to be reached. Using this pore-level scenario in three-dimensional network models of wettability has enabled the effects of waterflood relative permeability on wettability to be explored in detail [23†, 30••, 40†]. Dixit et al. introduced the regime theory that explained hitherto puzzling experimental trends in recovery in terms of wettability characterized by a contact angle for the oil-wet regions and the fraction of pores that become oil-wet [39••, 56].

One of the key problems with predictive modeling of reservoir rocks is an accurate characterization of wettability. The hope is that a macroscopic measurement of, for instance, Amott wettability indices would be sufficient to determine an effective contact angle for oil-wet regions and to estimate the proportion of pores that are oil-wet. As an illustration of this approach, Øren et al. [11••] tuned the contact angle of the oil-wet regions of their model to match the observed residual oil saturation, and from that were able to obtain a reasonable prediction of relative permeability for a mixed-wet reservoir sample.
4. Three-phase flow

The last few years have seen the development of several pore-scale models of three-phase (oil, water and gas) flows [12,16,21,22,26,27,33,57,58–61,62,63]. These models are potentially very important, since direct measurement of three-phase properties, particularly for every type of possible displacement process, is very difficult. The almost universal practice in the oil industry is to estimate three-phase relative permeability from two-phase data using empirical models that have little or no physical basis. An alternative approach is to develop physically-based three-phase network models that incorporate all the pertinent pore-scale mechanisms and which are tuned to match available two-phase data. This would significantly improve our understanding of three-phase processes and reduce enormously the uncertainty associated with the assessment of gas injection projects.

Using the wettability model described in the previous section, it is possible to determine the pore-scale configurations of oil, water and gas in a single pore for any wettability [26] (Fig. 3). There is a constraint between the oil/water, gas/oil and gas/water contact angles [64]. One of the consequences of this is that for strongly oil-wet systems, while gas is non-wetting to oil, it is not the most non-wetting phase in the presence of water. With water present, gas no longer occupies all the largest pore spaces, leading to lower gas relative permeabilities than in the presence of oil. Recently this result has been confirmed experimentally [65–67] and is important in the design of oil recovery schemes where both gas and water are in-
jected into the reservoir. Water reduces the effective mobility of gas, leading to a more stable and economically favorable displacement process. The consequences of different wettibilities on three-phase relative permeability have been explored in detail using simple bundle-of-tubes network models [26**, 57**, 61*].

One key aspect of three-phase flow is the ability of oil to form a layer sandwiched between water and gas in water-wet and mixed wet pores (Fig. 3h,i). These oil layers retain connectivity of the oil phase to very low saturations, leading potentially to high oil recovery during immiscible gravity drainage. When the oil is flowing in layers, the hydraulic conductance of the oil is proportional to the layer area squared, leading to an oil relative permeability that is proportional to the square of the oil saturation [22**, 35*, 68], as seen experimentally [65, 66].

Despite the promise, predictive pore-scale modeling of three-phase properties is still at an early stage. One problem is that during a displacement process two independent saturations may vary, leading to an infinite number of different saturation paths. A self-consistency procedure has been proposed to find the saturation path pertinent for a given one-dimensional displacement [22**, 63]. However, a general method for finding network model derived relative permeabilities with the same saturation history as observed in a three-dimensional displacement has not yet been developed. Predictive three-phase modeling has successfully determined oil relative permeability for gas injection into a water-wet Berea sandstone [12**]. The extension of this work to mixed-wet systems and different displacement sequences remains an active research topic.

5. Mass transfer, rate effects, flow in fractures and other processes

Improvements in computer power and experimental techniques together with more detailed analysis of multiphase flow phenomena at the pore-scale have lead to a blossoming of the use of network models for a wide variety of applications. Here, only a few examples will be described to illustrate the range of activity.

The dissolution rate of non-aqueous phase liquids is important for understanding the migration and clean-up of polluted aquifers. The rate of mass interphase mass transfer is related to the interfacial area. In the last year, several network modeling studies of interfacial area and dissolution rate have been published [24**, 25*, 69**, 70, 71**, 72*, 73*]. In this work, the concentration of solute in water is computed for a given pore space geometry and distributions of oil (non-aqueous phase liquid), which acts as the source of solute. By tuning the model to match measured capillary pressure data and accounting for mass transfer into wetting layers, such models have been able to predict high-flow-rate dissolution experiments [24**, 25*]. In addition, unsteady-state dissolution has been modeled by capturing the shrinkage of disconnected oil ganglia [71**]. Other work that considers mass transfer includes studies of drying processes [74*], solution gas drives [75, 76*], gas condensate systems [32*, 33, 77], water vapor transport [78] and evaporation of a binary liquid [79*].

So far we have assumed capillary-dominated flow at the pore-scale, leading to quasi-static displacement governed by local capillary pressure. In many cases, such as gas flows near wells [32*], and displacements that are significantly dependent on flow through wetting layers [28*], rate effects are important. To model this the fluid pressure in the network model is periodically computed and used to determine the filling sequence for pores [32*]. For drainage displacements, methods for including rate effects are well established [80]. In imbibition, despite some recent successes, it is difficult to simulate flow and swelling of wetting layers in fully dynamic simulations [81*, 82, 83]. Even making some approximations, the simulations are often very slow, requiring several recomputations of the pressure for every pore filled [80–84]. A perturbative approach, that is much more computationally efficient, offers an elegant method for capturing the effects of pressure drops in wetting layers. This method has been applied to study two- and three-phase flow [16**, 28*] and has successfully predicted the trend in residual oil saturation with capillary number [28*]. However, these methods are approximate, and cannot, for instance, simulate movement of trapped ganglia. The Payatakes group has challenged the conventional wisdom that connected, percolation-like models of flow are applicable at low flow rates. They have developed a theory based on prototype flows, including the movement of disconnected phases to predict macroscopic properties [85]. Truly dynamic simulations, especially of imbibition, are still an active area of research.

Multiphase flow in fractures is a new application for pore-scale modeling. Although a variable aperture fracture is not a pores-and-throat lattice, it is possible to represent a fracture by an equivalent network of conceptual pore spaces [29*, 30*, 86], or alternatively to derive appropriate threshold capillary pressures for fluid invasion into different regions of the fracture [87**, 88]. To model fracture/matrix interaction, the two-dimensional fracture plane can be coupled to a conventional three-dimensional porous network [29*]. Rate effects, that can be very important for fracture flow, are included using the perturbative method described above [29*, 30*]. Such pore-scale models have
successfully reproduced the features of several experiments, including drainage and infiltration, and macroscopic measurements of fracture relative permeability [29•30•87•88].

Other physical effects that have been treated recently using pore-scale modeling include foam flow [89], flow in polymer gels [90], biological activity in porous media [91], non-Darcy effects for high-speed gas flows [92], percolation-like models of gravity-driven displacement [93–95], imbibition into cement pastes [96], bubble transport [97], applications of critical path analysis [98,99] and asphalt precipitation [100].

6. Conclusions

Pore-scale modeling of multiphase flow in porous media is now able to explain and interpret experimental results for a wide variety of different situations, including the effects of wettability in two- and three-phase flow, multiphase flow in fractures, mass transfer and the influence of flow rate on residual oil saturation. With realistic descriptions of the pore space, dependent on statistical or explicit reconstruction of a topologically disordered three-dimensional pore space, or through tuning network model parameters to match available data, predictions of properties can be made. More research is needed to determine if we can characterize the pore space and wettability of reservoir rocks with sufficient ease and accuracy to make predictions of relative permeability and other properties a practical reality. If this is possible, then pore-scale modeling will have a huge impact on improved core analysis and characterization of multiphase flow properties.

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References and recommended reading

- of special interest
- of outstanding interest

[18] Tsakiroglou CD, Fleury M. Pore network analysis of resistiv-
The authors studied the effects on electrical properties of trapped wetting phase saturation. The resistivity index can be described by three parameter functions. The parameter values are related to the geometrical properties of the pore space.


Used a bond percolation model with a fractal model of roughness in each pore to compute electrical properties of porous media.


Thin section analysis was used to construct three-dimensional networks. Then mercury injection capillary pressure curves and absolute permeability are predicted. A fractal model of pore-wall roughness was used.


Developed a three-phase network model for water-wet systems. Described six different double displacement mechanisms and discussed the stability of oil layers. Showed the importance of saturation path on predicted relative permeability.


Further development of the reference above. Emphasized the importance of oil layers in maintaining connectivity of the oil phase at low saturation. Explained the \( k_{ow} \) dependence seen in some experiments. Introduced a self-consistency procedure to obtain relative permeabilities consistent with a predicted displacement sequence.


Used a model of wettability alteration at the pore scale to study trends in oil recovery and wettability indices with contact angle and oil-wet fraction of the porous medium.


Developed a pore level model for dissolution of components of a nonaqueous phase liquid into water. Emphasized the importance of flow in corners of the pore space in reproducing experimental behavior.


Extended the work in the previous reference to a network of pores. By tuning the network model to match the capillary pressure, the model was able to predict the results of dissolution experiments.


Analyzed the pore-scale configurations for three-phase flow with wettability alteration. Studied the generic behavior of three-phase relative permeability for a bundle of parallel tubes of different size.


Similar to the reference above. Discussed oil layer drainage and the functional dependence of three-phase relative permeability.


Used a perturbative rule-based model similar to Mani and Mohanty [16] to study the effects of flow rate, initial wetting phase saturation and contact angle on imbibition. The behavior was described in terms of different flow regimes.


Used a conceptual network model to study multiphase flow in fractures and the interaction with a porous network. Used the perturbative model described in the reference above.


The authors developed a perturbative model of viscous forces and showed how to use a pore-and-throat numerical model to study fracture flow.


Principally a paper describing field observations of the capillary fringe, but the results were interpreted using pore-scale modeling of imbibition.


Studied gas condensate evolution and flow, including high flow-rate effects. Used a converging/diverging pore geometry with pores of square cross-section.


Used three-phase pore-scale modeling to estimate the critical condensate saturation.


Developed a model that accounts for wetting phase in corners and true film adsorption in very narrow regions, computed using the augmented Young–Laplace equation. It was shown that at very high capillary pressure (or low wetting phase saturation) the effects of adsorbed films can be significant. Relations between saturation, capillary pressure and interfacial area were derived for bulk-flow, corner-flow and film-flow regimes.


An extension of the work in the reference above, describing the macroscopic consequences of their pore-scale model of wetting phase retention.


Studied the hydraulic conductivity of water retained in the surface roughness of fractures and showed agreement with recent experimental measurements.


Developed a predictive pore-scale model for two-phase flow similar to the work of Ören et al. [11], but with different expressions for pore conductances.


Studied hysteresis in relative permeability for water-wet and weakly water-wet systems and were able to explain trends in experimental
data in terms of the competition between snap-off and piston-like advance.

[39] Dixit AB, McDougall SR, Sorbie KS, Buckley JS. Pore-scale modeling of wettability effects and their influence on oil recovery. SPE Reservoir Eval Eng 1999;2:25–36. Used a pore-scale model with contact angles distributed among throats to study the effect of wettability on waterflooding oil recovery. The results were explained in terms of a regime theory that explained the puzzling non-monotonic variation in recovery with wettability observed experimentally.

[40] Dixit AB, Buckley JS, McDougall SR, Sorbie KS. Empirical measures of wettability in porous media and the relationship between them derived from pore-scale modeling. Transp Porous Media 2000;40(1):27–54. Used the model in the paper above to compare the USBM and Amott wettability tests and to explain the results in terms of displacement mechanisms and the fractions of oil-wet and water-wet pores. They showed that these two tests do not necessarily give similar results, nor do they unambiguously distinguish between the full range of possible wettability types.

[41] Fischer U, Celia MA. Prediction of relative and absolute permeabilities for gas and water from soil water retention curves using a pore-scale network model. Water Resour Res 1999;35(4):1089–1100. The pore space distribution was tuned to match capillary pressure data and then used to predict absolute and relative permeability. The methodology was tested against a variety of soils and worked moderately well. However, in some cases the prediction of water relative permeability was poor. The model had pores of circular cross-section and so ignored wetting layer flow.


[44] Liang ZR, Philippi PC, Fernandes CP, Magnani FS. Prediction of permeability from the skeleton of three-dimensional pore space. SPE Reservoir Eval Eng 1999;2:161–168. Generated a three-dimensional representation of the pore space from a two-dimensional image using statistical methods. The skeleton of the pore structure was obtained from a thinning algorithm. This defines a network of nodes and links (pores and throats). The effective hydraulic radius of each link in the network was used successfully to predict permeability.


[48] Xu B, Kamath J, Yortsos YC, Lee SH. Use of pore-network models to simulate laboratory corefloods in a heterogeneous carbonate sample. SPE J 1999;4:179–186. Simulated immiscible and miscible core-flood data from a heterogeneous carbonate using pore-scale modeling. A correlated distribution of pore sizes was used that matched CT scanning results for porosity variations in the core. Models with 100,000–500,000 pores were modeled accounting for viscous and capillary effects.


[50] Hilpert M, McBride JF, Miller CT. Investigation of the residual-funicular nonwetting-phase-saturation relation. Adv Water Resour 2000;24(2):157–177. Used CT scanning to measure residual non-wetting phase saturation in two porous media. Then network modeling was used to determine the relation between the maximum and the residual non-wetting phase saturation. The model accounted for film flow and snap-off, and was shown to be superior to empirical relations in the literature.


Spreading of oil films and double displacement were simulated.

Different generic functional forms for three-phase relative permeability were explored. Here different generic functional forms for three-phase relative permeabilities were proposed.


The effects of wettability on three-phase flow were explored. Here different generic functional forms for three-phase relative permeabilities were proposed.


Developed a self-consistency scheme for finding three-phase relative permeabilities similar to Fenwick et al. [22] to study WAG processes.


Experimental study of three-phase flow in a single triangular capillary. Tested theoretical correlations for oil and water layer conductance and stability.

networks spanned a hierarchy of length scales. Results were compared to experimental measurements. 


The evaporation of a binary liquid mixture into a ternary gas phase was simulated. The effects of surface tension gradients caused by composition variations were studied. 


A two-dimensional dynamic model of primary drainage ignoring film flow is developed. Very careful tracking of oil/water interfaces in pores lead to a very time-consuming algorithm. 


Computed the sensitivity of residual oil saturation to contact angle, flow rate and aspect ratio using a dynamic model of imbibition applicable to chalk samples. 


Similar to the reference above. A dynamic network model of waterflooding was developed. 


The evolution of wetting layers through micro-roughness on pore walls was simulated. The residual oil saturation was predicted as a function of capillary number, viscosity ratio and roughness. The presence of wetting layers significantly increased the residual oil saturation since snap-off was possible.


Provided a comparative study of different linear solvers for computing the pressure for network modeling. The conjugate gradient method, preconditioned by successive overrelaxation was found to be faster and more robust than the other solvers tested.


Macroscopic properties of the flow were derived semi-analytically from pore-scale parameters. The authors suggested that capillary-controlled percolation-like displacement patterns represent only one of a number of possible types of flow regime, and are only observed for a restricted range of flow rates and saturations.


Used a simple two-dimensional network model to compute relative permeability and capillary pressure for two-phase flow in fractures. Experimentally determined aperture distributions were used in the simulations.


Developed a modified invasion percolation model to simulate immiscible displacement in a fracture. The effect on local capillary entry pressure from the in-plane curvature of the interface was accounted for. This was analogous to Lenormand et al.‘s \( I_n \) mechanism [7]. The model correctly captured the effects of wettability on the displacement patterns and agreed well with experimental results.


Used an invasion percolation model with rearrangement of the non-wetting phase to simulate drainage displacement in a variable aperture fracture. The simulations of the fluid configuration in a selected region of the fracture agreed well with experimental measurements.


Developed a dynamic model of foam formation and propagation accounting for gas invasion and pressure differences across a disconnected gas phase.


Analyzed the pore-scale mechanisms of oil and water flow through polymer gels using micromodel experiments and single-pore theory.


In this paper biofilm build up in a porous medium was simulated using a five species model.


General correlations between the non-Darcy coefficient in the Forchheimer’s equation and the permeability, porosity and tortuosity were derived using pore-scale modeling.


Used invasion percolation in a gradient to study the displacement patterns when fluids spread on an impermeable boundary under the influence of buoyancy forces. The patterns had fractal-like properties that cannot be captured by conventional continuum equations.


Used an invasion percolation model with gravity and approximate accounting for viscous forces to simulate the downwards migration of DNAPLs below the water table.


The authors discussed the use of different types of growth models to represent DNAPL migration and showed good agreement between their simulations and experimental results.


The dynamics of imbibition in a cement paste was studied using magnetic resonance imaging. Network modeling of flow in a lattice of interconnected pores was able to reproduce the experimental behavior.

The motion of bubbles in porous media was studied as a function of capillary number and the volume fraction of bubbles. As the bubbles occupy more of the pore space, the interactions between them increased.


Used critical path analysis (this assumes that conductance is controlled by the smallest pore that has to be occupied) to relate absolute permeability and electrical properties. The approach worked well for extremely heterogeneous systems.


Provided a discussion of critical path analysis to determine conductance and other transport properties in highly heterogeneous systems. The paper combined a review of the theory with a large body of new work by the author.


Used pore-scale modeling to study asphalt precipitation.