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Establishing a Quantitative Functional Relationship Between Capillary Pressure Saturation and Interfacial Area

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Research Objective

Through an integrated and focused research program that is comprised of theoretical, computational and experimental efforts this research effort is directed at: 1) improving on newly developed laboratory techniques to quantify and directly measure the functional relationship between phase interfacial area (a), saturation (S) and capillary pressure (Pc), 2) developing new computational algorithms in conjunction with laboratory measurements to predict Pc, S and a, 3) testing existing theory and developing new theory to describe the relationship between Pc, S and a at the large scale, and 4) synthesizing the results of the experimental, computational and theoretical investigative efforts to develop a generic model based upon an intrinsic soil metric to describe the functional dependence of Pc, S and a.

The results of this research could be used to generate a site specific soil moisture characteristic surface. Ultimately the results of this research could serve as the foundation upon which the true health and safety risk of a site could be evaluated, the applicability of various remediation technologies examined, and the performance of implemented treatment strategies controlled.

Research Progress and Implications

This report summarizes work after 18 months of a 3-year project. We are working to integrate the theory, experiments, and numerical simulations into a coherent approach to study the role of interfacial areas in porous media flow physics. Our recent efforts have focused on quantifying the relationship between capillary pressure, saturation, and interfacial areas. The theory developed by Gray et al. (1998) indicates clearly that the traditional relationship between capillary pressure and saturation is incomplete, and interfacial area per unit volume must be added to the functional dependence. The theory does not, however, provide the form of that functional dependence; determination of this relationship must be done experimentally. To this end, both the network modelling and the PVI approach are being pursued.

The first results that investigated the relationship between Pc, Sw, and awn were reported by Reeves & Celia (1996). The results were based on a standard pressure-cell experimental setup, with capillary pressure imposed by controlling phase pressures along boundaries. A pore network with approximately 200 000 pore bodies was used, with saturation and interfacial area calculated for approximately 8000 discrete values of capillary pressure. While the relationship between Pc and awn, and between Sw and awn, are very complex, the relationship between Pc, Sw, and awn is remarkably smooth and well-behaved. The general shape of the Pc-Sw-awn surface is consistent across a number of different lattice realizations and sizes.

A number of additional results come from the theoretical developments. For example, as mentioned earlier, the theory suggests that the permeability coefficient should be a function of interfacial area. The computational network can again be used to examine the form of this proposed functional dependence. The work of Reeves (1997), presents a calculated relationship between relative permeability to the wetting phase, krw, saturation Sw, and fluid-fluid interfacial area awn. This initial result, which has not been extensively tested over a range of pore networks, indicates that the functional dependence of permeability on interfacial area is relatively weak.

Another conjecture that arises in the theoretical development is that hysteresis in the relationship between Pc and Sw arises because of the incomplete functional dependence, and that proper inclusion of areas will mitigate, or even eliminate, hysteresis. Reeves (1997), and Celia et al. (1998), have examined the question of hysteresis between the Pc-Sw-awn surfaces generated by both drainage scanning curves and imbibition scanning curves, and found that hysteresis does not disappear. Whether it is reduced in any significant way remains open to debate.

While these results, and others such as those reported in Reeves (1997), demonstrate how the network models can be used to test some of the theoretical results, the network models themselves remain relatively untested. Network models can be used to match measured capillary pressure - saturation and relative permeability - saturation relationships (see, for example, Rajaram et al., 1997). However, this does not mean that the interfacial area calculations are representative of actual porous media. Therefore the PVI experimental technique (Montemagno and Gray, 1995) is critical to both validation of the network models, and to provision of a “ground-truth” data set against which to compare the theory.

The overall objective of our joint work is to use innovative experimental techniques to test (and, we hope, validate) both the computational network models and the theoretical results. PVI will allow the relationship between Pc, Sw, and awn to be determined directly. If the network models can be validated using PVI results, then the models can be used to test a variety of additional theoretical results with much more confidence. In support of this objective the performance and capability of the PVI experimental method has been significantly enhanced in the past 18 months. A stable system has been developed for conducting the long-term experiments (ca. 6 months) necessary for creating a Pc, Sw, and awn data set (Zang, 1998). Additionally, a new mathematical algorithm for calculating the interfacial surface areas of PVI data sets has been developed (Ma and Montemagno, 1998). This new technique eliminates the manual analysis of PVI data thereby drastically reducing the time required to analyze the multi-gigabyte data sets and ensuring repeatability.

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Planned Activities

During the 18 months remaining on the project we will: 1) extending the network models to include dynamics, so that the theoretical results regarding dynamic capillary pressure can be tested, 2) incorporate realistic geometries into network models, based on pore-space imaging produced by the PVI technique, 3) obtain real Pc, Sw, and awn surfaces and use this information to validate network models, and 4) use the validated network model to develop a methodology for predicting interfacial area based on the soil moisture characteristic curve and soil grain geometry.

Other Access To Information

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