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Effective parameters for two-phase flow in a porous medium with periodic heterogeneities

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Abstract

Computational simulations of two-phase flow in porous media are used to investigate the feasibility of replacing a porous medium containing heterogeneities with an equivalent homogeneous medium. Simulations are performed for the case of infiltration of a dense nonaqueous phase liquid (DNAPL) in a water-saturated, heterogeneous porous medium. For two specific porous media, with periodic and rather simple heterogeneity patterns, the existence of a representative elementary volume (REV) is studied. Upscaled intrinsic permeabilities and upscaled nonlinear constitutive relationships for two-phase flow systems are numerically calculated and the effects of heterogeneities are evaluated. Upscaled capillary pressure–saturation curves for drainage are found to be distinctly different from the lower-scale curves for individual regions of heterogeneity. Irreducible water saturation for the homogenized medium is found to be much larger than the corresponding lower-scale values. Numerical simulations for both heterogeneous and homogeneous representations of the considered porous media are carried out. Although the homogenized model simulates the spreading behavior of DNAPL reasonably well, it still fails to match completely the results from the heterogeneous simulations. This seems to be due, in part, to the nonlinearities inherent to multiphase flow systems. Although we have focussed on a periodic heterogeneous medium in this study, our methodology is applicable to other forms of heteroge-

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neous media. In particular, the procedure for identification of a REV, and associated upscaled constitutive relations, can be used for randomly heterogeneous or layered media as well. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

The study of nonaqueous phase liquid (NAPL) transport in groundwater requires a correct description of multiphase flow in porous media. Such a description involves a number of material-dependent parameters, including relationships between capillary pressure, saturation, and relative permeability (P^c-S-k^r) relationships. These relationships are highly nonlinear and their determination is often a difficult task. This task is made even more difficult when the material under study is heterogeneous. One of the major difficulties in defining multiphase flow properties is the presence of small-scale heterogeneities, where different geologic materials may occur over a length scale of centimetres to tens of centimetres. Such length scales correspond to the size of common measuring devices, such as laboratory pressure cells, and to the typical size of cores taken at field sites. Therefore, identification of material properties at this scale is in principle possible. The measured properties, including the nonlinear functional relationships, can vary widely over this length scale. Such variability can significantly affect overall flow properties of the system, including such factors as the spreading behavior of non-aqueous liquids. These heterogeneities can also produce localized pools of NAPL.

While the detailed structure of the porous medium governs the overall behavior of the system, for most practical purposes the detailed fluid distribution in such a medium is not of interest. Rather, we are commonly interested in more global measures and assessments of the NAPL movement. Also, even if we choose to resolve the system at the small scale, it is currently computationally infeasible to discretize a compositional multiphase model at such small scales. Furthermore, even if a detailed numerical model is constructed and run, it is virtually impossible to obtain data for all of these heterogeneities for a large domain. Thus, we are motivated to derive effective properties that incorporate the influences of small-scale heterogeneities and can be employed in an equivalent homogenous model of the porous medium applied at length scales larger than the individual heterogeneities.

Considerable work has been directed at the problem of upscaling permeabilities for single-phase flow. These works have been reviewed recently in papers by Wen and Gomez-Hernandez (1996) and Renard and de Marsily (1997). The techniques for upscaling saturated permeability range from the simple averaging of heterogeneous values within an averaging block to sophisticated inversions, after the solution of the flow equation at the measurement scale within an area surrounding the block. All techniques have their own advantages and limitations. It is now understood that upscaled permeabilities depend on the geometry and properties of the fine-scale permeabilities, the boundary conditions imposed on the region to be upscaled, and the discretisation