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Eprints ID: 20144


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A Large-Scale Model for Dissolution in Heterogeneous Porous Media

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Key words: upscaling, Large-scale model, Darcy-scale heterogeneity, Dissolution

Abstract

Dissolution of pore-scale soluble substances occurs in applications from environmental hydrogeology to CO2 storage. Development of Darcy-scale models has been widely discussed. This paper proposes an upscaling algorithm to develop large-scale models taking into account Darcy-scale heterogeneities. The theory is based on a comparison between the characteristic length-scale of the Darcy-scale heterogeneities and the length-scale of the dissolution front controlled by a Darcy-scale Damkohler number. The obtained large-scale model is shown to confront favorably to Darcy-scale direct numerical simulations.

Introduction

In this paper we consider the dissolution of a soluble material (NAPL, deposited mineral) trapped in a porous structure as illustrated Fig. 1. The first upscaling development leading to a Darcy-scale description has received a lot of attention in the literature. The reader may refer to the theoretical work in \[1, 2\] for the development of local non-equilibrium models involving several Darcy-scale effective properties, in particular an active dispersion tensor and a source term corresponding to the mass exchange between the two Darcy-scale continua (liquid and soluble material). This latter term involves an exchange coefficient that will determine, through a Darcy-scale Damkohler number, the thickness of the dissolution front propagating into the porous medium.

Figure 1: Multiple-scale features and averaging volumes

We consider here a simple version of this Darcy-scale model corresponding to the following Darcy-scale equations:

\[ \nabla \cdot (\varepsilon_T(1-S)U_l) = 0 \]
\[ \frac{\partial (\varepsilon_T(1-S)C_l)}{\partial t} + \nabla \cdot (\varepsilon_T(1-S)U_lC_l) = -\alpha (C_l - C_{eq}) \]
\[ \varepsilon_T \frac{\partial S}{\partial t} = \frac{\rho_l}{\rho_s} \alpha (C_l - C_{eq}) \]

The large-scale model is obtained in the case of a separation of scales characterized the following inequality

\[ l_i, l_s, l_t \ll l_\omega, l_\eta \ll l_d \ll L \]

where \( l_i, l_s, l_t \) refers to the pore-scale, \( l_\omega, l_\eta \) to the Darcy-scale heterogeneities, \( l_d \) to the thickness of the dissolution front, and \( L \) to the large-scale domain, and which is enforced in the case of small Damkohler numbers. The
theory allows to develop a large-scale model involving large-scale averages denoted by a starred variable. For illustration, the large-scale mass balance equation is given by

$$\frac{\partial}{\partial t} \left( \{\varepsilon_T\} (1 - S^*) C_T^* \right) + \nabla \cdot \left( \{\varepsilon_T\} (1 - S^*) U_T^* C_T^* \right) = -\alpha^* (C_T^* - C_{eq})$$

(5)

where the large-scale coefficient $\alpha^*$ is obtained from the resolution of a special closure problem. The theory is tested over different types of heterogeneous media. An example of the application to a stratified porous system is shown (a) which represent the direct Darcy-scale numerical results and the large-scale prediction. One sees that the large-scale prediction works very well, even for very sharp fronts, i.e., larger Damkhler numbers that one would expect from the constraint Eq. 4.

(a) Stratified system

(b) Case of local equilibrium dissolution,
(c) Case of local non-equilibrium dissolution, low Da

Figure 2: Dissolution of a partially soluble stratified porous medium

References
