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DERIVATION OF VERTICAL EQUILIBRIUM MODELS FOR CO_2 MIGRATION FROM PORE SCALE EQUATIONS

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This paper is dedicated to Magne Espedal.

Abstract. Equations describing flow in porous media averaged to allow for lateral spatial variability but integrated over the vertical dimension are derived from pore scale equations. Under conditions of vertical equilibrium, the equations are simplified and employed to describe migration of CO_2 injected into an aquifer of variable thickness. The numerical model based on the vertical equilibrium equations is shown to agree well with a fully three-dimensional model. Trapping of CO_2 in undulations at the top of the aquifer is shown to retard CO_2 migration.

Key words. vertical equilibrium, carbon sequestration, multiphase flow, porous media, numerical simulation, ECLIPSE

1. Introduction

Storage of carbon dioxide (CO_2) in saline aquifers has been proposed as an alternative to reduce greenhouse gas emissions [5, 45]. It is expected that injection rates of several million tons per year will be required to capture the emissions from one or several industrial point sources [1]. Detailed modeling and numerical simulations will be required to evaluate the storage capacity of potential sequestration sites, to assess the feasibility of injecting such high volume rates and to predict the long-term fate of the injected CO_2 [6]. In particular, quantitative predictions of migration distances and estimates of time scales associated with different trapping mechanisms will be essential in assessing possible risks associated with CO_2 storage [45].

Supercritical CO_2 injection and subsequent storage in saline aquifers involves physical and chemical trapping mechanisms that occur over several length and time scales. During the injection period, CO_2 quickly rises due to its lower density with respect to the resident brine. Once it reaches an impermeable sealing layer at the top of the aquifer it accumulates beneath it [4, 29]. This structural entrapment of CO_2 is the primary trapping mechanism during the injection time frame. Once injection ceases and the driving pressure dissipates, CO_2 will migrate due to buoyancy forces alone, following the upslope dip of the caprock [4, 31, 48]. During this period, CO_2 will become gradually immobilized due to irregularities in the caprock surface and other primary trapping processes such as residual and solubility trapping [38, 45]. Mineralization occurs on much longer time scales than the primary mechanisms [35, 45], and thus is a secondary process not considered further here. Characterization of the primary post-injection trapping processes is essential for

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understanding the long-term fate of CO_2 in the subsurface over the thousand years time scale. However, because of the large spatial and temporal scales that must be considered, traditional numerical approaches to this problem are impractical in terms of computational requirements. Therefore, efficient mathematical modeling approaches are needed to speed up simulations [6].

With the objective of developing effective models, certain physical characteristics of the CO_2-brine system can be exploited to simplify the governing system of equations. For example, given the strong buoyancy forces, it is reasonable to assume that complete gravity segregation occurs quickly during and after the injection period. In addition, the large horizontal and thin vertical scales result in negligible vertical movement of the fluids. These characteristics lead to implementation of what is known as the vertical equilibrium (VE) assumption. This assumption facilitates vertical integration of the three-dimensional governing flow equations to obtain a set of two-dimensional equations [39, 49, 56]. So called vertically-integrated or VE models have been used extensively in the past to simulate the behavior of petroleum reservoirs where strong vertical fluid segregation occurs [9, 10, 13, 19, 39, 44, 55], or groundwater aquifers with large aspect ratios [2, 20]. VE models have received renewed attention in recent years to model CO_2 injection and migration in saline aquifers [12, 22, 31, 36, 43, 47, 49, 51]. Despite the model simplifications, analytical and numerical solutions to VE models have compared well with solutions using standard simulation tools [12, 49, 51], most notably in two recent benchmark studies [8, 50]. Recently, Nilsen et al. [48] simulated the long-term migration of CO_2 injected at the Utsira formation in the North Sea [7]. Furthermore, because of their infinite vertical resolution, VE models have proven to be particularly advantageous for modeling the long-term movement of thin CO_2 plumes underneath the aquifer caprock [31, 32, 48].

As with any simplified model, the VE model is not appropriate for all systems. The limitations become important when considering small-scale (in the tens of meters) or short-term ($<$10 yrs) processes, particularly when anisotropy and intermediate shale layers retard the vertical migration of the CO_2 plume. For example, it has been shown that the VE model leads to inaccurate results when examining near wellbore flow effects of CO_2 injection [42]. Therefore, we focus on the longer term effects of CO_2 migration over tens of kilometers after injection has ceased, an application for which the VE model is appropriate.

Previous mathematical models based on the VE assumption have been developed from the standard Darcy theory of two-phase flow, e.g.[31, 39]. By this process Darcy scale, or macroscale equations, are integrated over the thickness of the flow domain. The macroscale equations are employed as a starting point for a change in scale to the megascale, the fully integrated scale. Here, we begin with the microscale equations. These equations can be integrated to the macroscale to obtain multiphase flow equations in term of variables that are well-defined functions of their microscale precursors for multiphase flow. This procedure is best carried out when the conservation equations of mass, momentum, and energy, along with the fundamental thermodynamic postulates, are integrated to the macroscale [34]. These constructed equations and closure conditions would then have to be integrated over the vertical to obtain a VE set. An alternative approach to obtaining the VE equation is to start with the microscale equations and, in one step, integrate the conservation and thermodynamic relations to a form that is macroscopic in the lateral direction and megascale in the vertical direction. This is accomplished by using the theorems for mixed megascale/macroscale averaging [25]. We note that the