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ScienceDirect

Energy Conversion and Management 48 (2007) 1768–1781

ENERGY CONVERSION & MANAGEMENT

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Modeling geologic storage of carbon dioxide: Comparison of non-hysteretic and hysteretic characteristic curves

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Received 30 October 2006; accepted 6 January 2007
Available online 6 March 2007

Abstract

Numerical models of geologic storage of carbon dioxide (CO_2) in brine-bearing formations use characteristic curves to represent the interactions of non-wetting-phase CO_2 and wetting-phase brine. When a problem includes both injection of CO_2 (a drainage process) and its subsequent post-injection evolution (a combination of drainage and wetting), hysteretic characteristic curves are required to correctly capture the behavior of the CO_2 plume. In the hysteretic formulation, capillary pressure and relative permeability depend not only on the current grid-block saturation, but also on the history of the saturation in the grid block. For a problem that involves only drainage or only wetting, a non-hysteretic formulation, in which capillary pressure and relative permeability depend only on the current value of the grid-block saturation, is adequate. For the hysteretic formulation to be robust computationally, care must be taken to ensure the differentiability of the characteristic curves both within and beyond the turning-point saturations where transitions between branches of the curves occur. Two example problems involving geologic CO_2 storage are simulated with TOUGH2, a multiphase, multicomponent code for flow and transport through geological media. Both non-hysteretic and hysteretic formulations are used, to illustrate the applicability and limitations of non-hysteretic methods. The first application considers leakage of CO_2 from the storage formation to the ground surface, while the second examines the role of heterogeneity within the storage formation.
Published by Elsevier Ltd.

Keywords: Geologic carbon storage; Two-phase flow; Characteristic curves; Hysteresis

1. Introduction

Numerical modeling has been used extensively in the past few years to study geologic storage of CO_2 in brine-saturated formations. At depths commonly considered for CO_2 storage (>800 m), CO_2 primarily exists as a gas-like supercritical phase, which is the non-wetting phase, while some CO_2 dissolves in the brine, which is the wetting phase. Interactions between the two fluid phases are represented at the grid-block scale by characteristic curves, that is, capillary pressure and relative permeability functions. The simplest characteristic curves are non-hysteretic – the capillary pressure and relative permeabilities depend only on the local saturation at the current time. A more sophisticated approach is a hysteretic formulation, in which capillary pressure and relative permeabilities depend not only on the current value of the local saturation, but on the history of the local saturation and the process that is occurring: drainage (replacement of wetting phase with non-wetting phase) or wetting (replacement of non-wetting phase with wetting phase, also known as imbibition).

Although hysteretic characteristic curves are routinely employed by the petroleum industry, they are less commonly used in studies of the vadose zone, geothermal reservoirs, and geologic isolation of nuclear waste, other areas where two-phase flow through geologic media occurs [1,2]. Because some researchers from these fields are now studying geologic storage of CO_2, and potentially using the non-hysteretic characteristic curves with which they are familiar, it is valuable to investigate the impact of using non-hysteretic characteristic curves for CO_2 geologic

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0196-8904/$ - see front matter Published by Elsevier Ltd.
doi:10.1016/j.enconman.2007.01.022

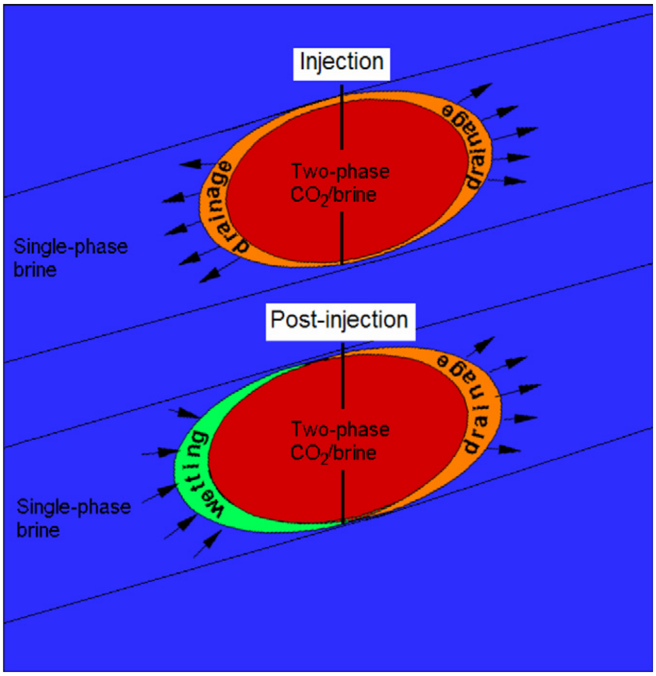

Fig. 1. Schematic of CO_2 injection period (top), in which drainage occurs at all plume boundaries, and post-injection period (bottom), in which drainage occurs at the leading edge of the plume on the right and wetting occurs at the trailing edge of the plume on the left as the plume migrates, e.g. by buoyancy forces.

storage problems. The use of hysteretic characteristic curves is not so critical for the simulation of CO_2 injection periods when the plume is continuously growing (top of Fig. 1), because all locations follow the primary drainage branch of the capillary pressure curve at all times, and this branch can be replicated using a non-hysteretic formulation. However, for post-injection periods (bottom of Fig. 1), when the CO_2 plume moves upward and updip due to buoyancy forces, different locations experience drainage and wetting at different times, necessitating the use of a hysteretic formulation. The purpose of this paper is to illustrate the applicability and limitations of using non-hysteretic formulations, and thereby provide guidance for more accurate modeling of CO_2 geologic storage systems.

In the sections below, we outline the mathematical formulation of the hysteretic characteristic curves used for modeling CO_2 storage, then briefly describe some of the key numerical issues involved in implementing hysteretic functions into the numerical simulator TOUGH2. Two example problems are presented to compare results obtained using non-hysteretic and hysteretic characteristic curves, followed by some concluding remarks.

2. Hysteretic characteristic curves

Together, capillary pressure P_c and relative permeabilities k_{rl} and k_{rg} are known as characteristic curves; they control the way the liquid (wetting) phase and gas (non-wetting) phases interact. In a non-hysteretic model, the characteristic curves are single-valued functions of the current grid-block saturation (Fig. 2). Different grid blocks

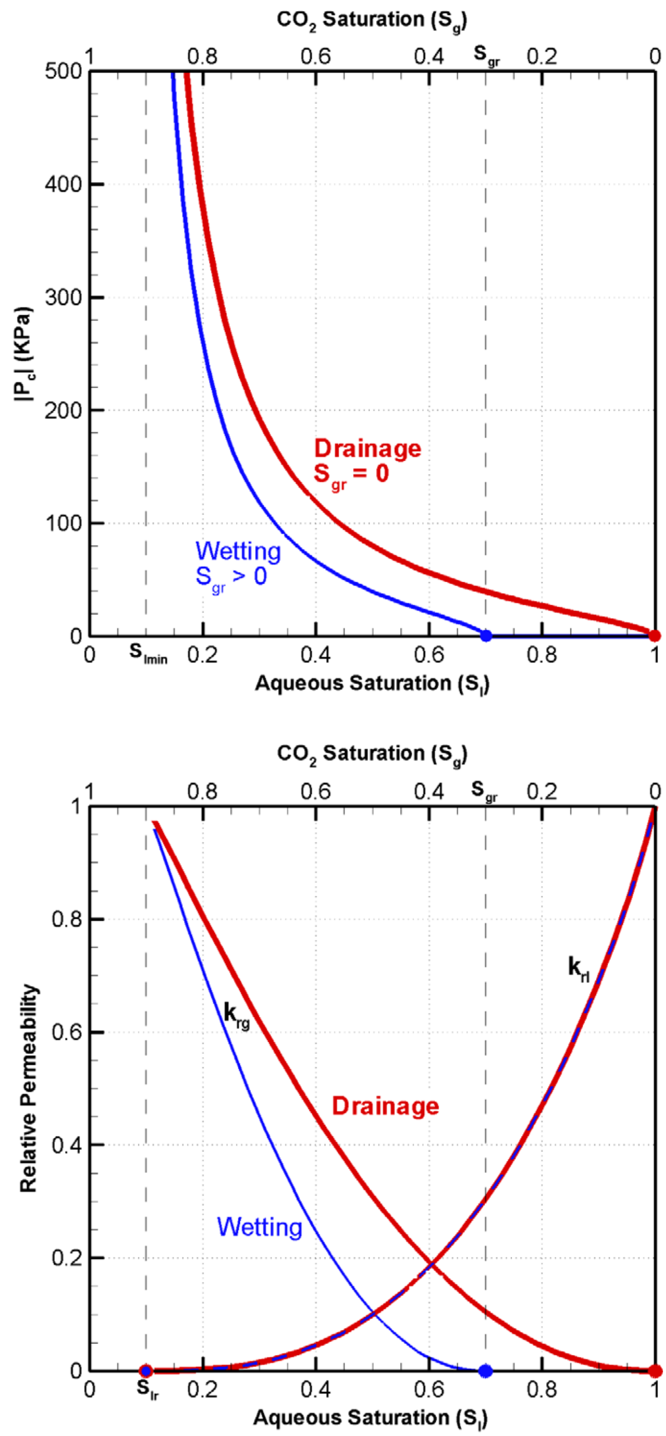

Fig. 2. Typical non-hysteretic characteristic curves. The dots show values of residual saturation for each curve. Typically, drainage is associated with a zero value of residual gas saturation whereas wetting is associated with a large value. Characteristic curves may differ between grid blocks, but each grid block uses the same characteristic curves (and hence the same values of residual saturation) at all times.