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Numerical simulations of pressure buildup and salt precipitation during carbon dioxide storage in saline aquifers

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ABSTRACT

The storage of large amounts of carbon dioxide (CO_2) captured from fossil fuel fired power plants in deep saline aquifers can be an effective and promising measure for reducing the emissions of greenhouse gases. Massive CO_2 injection into saline aquifers may cause multi-scale phenomena such as pressure buildup in a large scale, CO_2 plume evolution in a medium scale and salt precipitation in a small scale. In this study, three-dimensional simulations are performed to investigate the propagation of pressure and the impact of salt precipitation on the process of large scale CO_2 injection into the saline aquifers. Apart from the different scales of the processes, the numerical results show clearly different behaviours of the pressure changes in saline aquifers with different boundaries. Different types of salt precipitation occur adjacent to the injection well, presenting distinct impacts on the fluid flow. Affected by salt precipitation, the porosity and permeability are reduced, leading to declined transportation and degraded injectivity with different boundary conditions. The interplay between pressure buildup and solid saturation is compared in saline aquifers with different boundary conditions.

1. Introduction

Carbon dioxide storage in deep saline aquifers is potentially the most promising method for massively reducing the ever increasing amount of CO_2 in the global atmospheric environment because of combustion utilization of fossil fuels [1–3]. Massive CO_2 injection into the saline aquifers may cause multi-scale spatial phenomena, including pressure buildup occurred in a large scale [4–6], CO_2 plume in a medium size [4,5] and the distribution of precipitation in a small dimension [7]. When large volumes of CO_2 are injected into saline aquifers, pressure buildup may be produced which can quickly propagate in a large space. At the temperature and pressure conditions for CO_2 storage, the injected CO_2 will tend to accumulate at the top of reservoir and spread out along the top caprock, as schematically shown in Fig. 1(a). Meanwhile, the injection of dry supercritical CO_2 will displace the resident brine immiscibly, combined with the evaporation of water, which may eventually cause the aqueous phase dry-out and salt precipitation near the injection well [7–14]. The spatial size of precipitation region is just a small fraction of the plume. These phenomena are of great importance for the safety of CO_2 storage. On the one hand, excessive pressurization may cause a series of problems, involving the caprock fracture, the pollution of shallow groundwater resources, and the seismicity [15–18]. On the other hand, salt precipitation may lead to salt blockage near the injection well, which would obstruct the transportation of CO_2 and the propagation of pressure to the far filed [7,8]. Therefore, predicting the propagation of pressure and the impact of salt precipitation on injectivity is crucial to the security of CO_2 storage in saline aquifers.

The pressure buildup during CO_2 injection into saline aquifers has been the focus of research by a number of theoretical analyses and numerical simulations. In terms of the theoretical analyses, several simple semi-analytical methods using Buckley–Leverett equation are used to study the distribution of pressure, which describe the one-dimensional immiscible flow in the absence of compression of rock pores and brine as well as capillary pressure [19–21]. Mathias et al. [4] improved the Buckley–Leverett method by incorporating the compressibility of rock and brine to study the pressure buildup during CO_2 injection into a closed saline aquifer. Zhou et al. [6] developed a quick assessment method of CO_2 storage capacity due to the formation and fluid compressibility, with assumptions that pressure buildup is spatially uniform and independent of formation permeability. Although these theoretical analyses may efficiently predict the pressure changes in some cases, detailed numerical simulations of carbon storage to calculate the pressure buildup including the spatial and temporal distributions are needed. For numerical studies,

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Nomenclature

Symbols

d	diffusivity
$\mathbf{D}$	distance between meshes m and n
$\mathbf{g}$	gravitational acceleration
$\mathbf{k}$	permeability tensor
k_{rg}	the relative permeability of CO_2
k_{rl}	the relative permeability of brine
$\mathbf{n}$	normal vector
P	pressure
$\mathbf{q}$	Darcy flux
S	saturation
t	time
T	temperature
V	volume
X	mass fraction
x, y, z	Cartesian coordinates

Greek symbols

Γ	area
μ	dynamic viscosity
ρ	density
Σ	summation
τ	tortuosity
ϕ	porosity
∇	gradient operator

Subscripts/superscripts

c	capillary, critical
i, j, m, n	index
s	solid
α, β	fluid phase

the important physical phenomena of pressure buildup are observed. Nonlinear behaviours of pressure change near wellbore during CO_2 injection into saline aquifers are observed [22]. Large-scale CO_2 injection could cause groundwater pressure perturbation and hydrological impact on groundwater resources [5,17,23,24]. If the pressure buildup is above a threshold value, fracturing may occur. There is a stipulation by the U.S. Environment Protection Agency, stating that the maximum pressure must not exceed 90% of the fracture pressure in the injection zone [25]. Coupled reservoir geomechanical analyses are performed to check the fracture pressures by numerical simulations [26,27]. Numerical simulations and optimization schemes are increasingly used to investigate this phenomenon, e.g. [28]. Optimization and parallel algorithms are also available to improve computation performance, e.g. [29–32]. The previous studies indicate that the pressure buildup in the injection zone is crucial to the security of CO_2 storage.

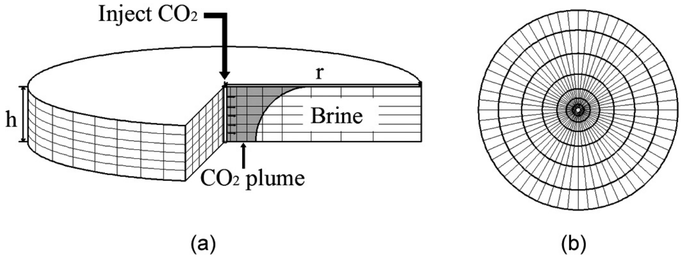

Fig. 1. Schematic representation of (a) CO_2 injection into a closed aquifer via a vertical well and (b) top view.

The process of salt precipitation has also been investigated by several theoretical analyses, experimental studies and numerical simulations. For theoretical analyses, Zeidouni et al. [10] developed a graphical method to determine the location of the front of solid salt. However, their results neglect the effects of the capillary pressure and the gravitational force. In addition their results are only applicable to a very simplified one-dimensional situation. For experimental studies, the reduction of permeability induced by drying of brine in porous media is studied for different rocks and salt contents [33]. A lab-on-a-chip approach is developed to study the pore-scale salt precipitation dynamics during CO_2 injection into saline aquifers [34]. Although experimental studies can provide first-hand results, detailed measurements are always difficult especially when information on flow quantities over a broad range of time and length scales is needed. In numerical studies, several researchers have shown that salt precipitates preferentially near the injection well as resident saline water is evaporated by injected CO_2 [7,8,14,35–37]. For example, Hurter et al. [35] investigated the drying out and salting out phenomena using a commercial code. However, their results ignore the precipitation impact on permeability. Pruess and Müller [7] carried out one- and two-dimensional studies to predict salt precipitation and to understand the influencing factors for this process. Kim et al. [8] pointed out that there are two types of precipitation at different injection rates using two-dimensional simulations, which are characterized by different level of salt precipitation near the well. Their results suggest that great pressure buildup would occur near the lower portion of the injection well in some cases. These previous studies indicate that salt precipitation could cause reduction of aquifer porosity and permeability near the well and thus deterioration of injectivity.

Although some understandings on the impacts of pressure buildup and salt precipitation of CO_2 injection into the saline aquifers have been obtained, more studies are needed to understand the interplay between pressure buildup and salt precipitation. In previous numerical studies of salt precipitation in saline aquifers, the injection period is short and the injection rate was low, which does not meet the requirements of long-term and large-scale CO_2 storage. In the meantime, comparisons of the two phenomena in storage systems with different boundary conditions, namely the closed, open and semi-closed systems, are important but have not been investigated systematically.

In this study, the distributions of pressure buildup and salt precipitation, the specific processes and the impacts of solid precipitation on the long-term injection in the three storage systems are investigated by three-dimensional (3D) simulations. In the following, the governing equations together with the initial and boundary conditions used in the simulations are presented first, followed by numerical results and discussions of the results for the three systems investigated. Finally, some conclusions are drawn.

2. Modelling and mathematical formulation

2.1. Physical problem and computational domain

The physical problem is CO_2 injection and propagation, via a vertical well, into saline aquifers, as indicated in Fig. 1(a). The storage formation, located at a depth of approximate 1200 m below the ground surface, is 100 m thick with a radius of 40 km for the closed and semi-closed systems. The lateral extent of computation model for the open system is 100 km, which ensures that the lateral boundary could have a minimal effect on the simulation results.

2.2. Governing equations

The governing equations for the fluid flows of multiphase and multicomponent fluid mixtures in porous media are used to describe CO_2 geological storage in saline aquifers [3], which are similar to those for oil, water, and gas flows through porous media. For isothermal problems, only the mass conservation equations for CO_2, water