Residual trapping of carbon dioxide during geological storage—Insight gained through a pore-network modeling approach

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ARTICLE INFO

ABSTRACT

To reduce emissions of the greenhouse gas CO_2 to the atmosphere, sequestration in deep saline aquifers is a viable strategy. Residual trapping is a key containment process important to the success of CO_2 storage operations. While residual trapping affects CO_2 migration over large scales, it is inherently a pore-scale process. Pore-network models (PNMs), capturing such processes, are useful for our understanding of residual trapping, and for upscaling trapping parameters for larger scale models. A PNM for simulation of quasi-static two-phase flow; CO_2 intrusion (drainage) followed by water flooding (imbibition) was developed. It accounts for pore-scale displacement mechanisms, and was used to investigate residual CO_2 trapping. The sensitivity of the residual CO_2 saturation to several parameters was studied, to validate a trapping behavior in agreement with earlier studies. Then the PNM was calibrated to core sample data and used to simulate drainage-imbibition scenarios with different turning point saturations. From these the initial-residual saturation curves of CO_2 in Heletz sandstone were estimated, essential for future macroscopic-scale simulations. Further, the occurrence of different pore-scale mechanisms were quantified and the size distribution of the residual clusters was shown to exhibit a bimodal appearance. The findings improve the understanding of residual trapping in Heletz sandstone.

1. Background

1.1. Introduction

Geological storage of carbon dioxide (CO_2) in deep saline aquifers is one approach to mitigate greenhouse gas release from point sources to the atmosphere. The sequestrated CO_2 is held in the subsurface by several trapping mechanisms, including structural and stratigraphical trapping, solubility trapping, geochemical trapping and residual trapping (IPCC, 2005). This study addresses residual trapping, which occurs when the stored CO_2 is displaced by formation fluid, as is the case at the trailing edge of a buoyantly migrating carbon dioxide plume (Ide et al., 2007; Kumar et al., 2005) or if chase-brine is used in the injection-design (Qi et al., 2009). Blobs or ganglia of CO_2 can then be disconnected from the plume and immobilized by capillary forces (Ide et al., 2007). The residual trapping gives rise to hysteresis in the characteristic functions: relative permeability and capillary pressure functions. The effect of hysteresis in relative permeability, on geological CO_2 storage has been evaluated through numerical simulations of storage scenarios (Doughty, 2007; Doughty and Myer, 2009; Flett et al.,

2004; Juanes et al., 2006; Spiteri et al., 2005). These studies indicate that residual trapped CO_2, may comprise a substantial part of the stored CO_2 and provide secure storage. An in-depth understanding of the mechanisms and processes influencing the residual trapping of CO_2 is therefore of great importance.

The CO_2 saturation at which immobilization through capillary trapping occurs is referred to as the residual CO_2 saturation or residual gas saturation (S_{gr}). For brevity the CO_2-rich phase is referred to here as the gas phase, although technically in this case the CO_2 is in its supercritical state. The maximum residual gas saturation (S_{grmax}) is the residual gas saturation obtained after a rock has undergone complete imbibition by water from an initial state where the water saturation is at its irreducible saturation. Residual trapping of supercritical carbon dioxide in sandstone, a common rock found in basins used for CO_2 storage, has been reported in the saturation range of 0.087–0.35 (Andrew et al., 2014; Bennion and Bachu, 2008a; Iglauer et al., 2011; Krevor et al., 2012; Pentland et al., 2011; Rahman et al., 2016; Shi et al., 2011; Suekane et al., 2008; Zuo and Benson, 2014). A study by Hamon et al. (2001) of gas (not only CO_2) trapping in heterogeneous sandstones found that the S_{grmax} ranged from 0.05 to 0.85. For gases in

Nomenclature

A	Area
AM	Arc meniscus
Bo	Bond number ($=\Delta\rho g a^2/\sigma$)
CO_2	Carbon dioxide
CCS	Carbon capture and storage
cpb	Cooperative pore body filling
EOR	Enhanced oil recovery
G	Shape factor ($=Area/Perimeter^2$)
g	Gravitational acceleration
$g_{i,IJ}$	Effective hydraulic conductance of phase i
h	Vertical distance from z = 0.0 to the element
I_n	Cooperative pore body filling event n
k	Absolute permeability
k_{rx}	Relative permeability of phase x
l_{ij}	Length of pore throat between pore body i and pore body j
$L_{body\ centers}$	Distance between body centers
M	Viscosity ratio, mobility ratio ($=\mu_{inv}/\mu_{def}$)
MTAM	Main terminal arc meniscus
n	Number of corners
N_c	Capillary number ($=\mu_{inv}q_{inv}/\sigma$ or $=\mu_{nw}u_{nw}/(\sigma \times \cos\theta)$)
P	Pressure
P_c	Capillary pressure
P_c^e	Capillary entry pressure
$P_{c,n}^e$	Threshold capillary pressure for an I_n-cpb-filling event
$P_{c,PISTON}^e$	Threshold capillary pressure for piston-type displacement
$P_{c,so}^e$	Threshold capillary pressure for snap-off
P_c^{max}	Highest capillary pressure during drainage
P_c^{trap}	Capillary pressure at which trapping occurred
PNM	Pore-network model
q	Darcy velocity
$q_{i,IJ}$	Flow rate of phase i between pore body I and pore body J
Q_{tot}	Total flow rate
r	Radius
$\overline{R}_n$	Average radius of curvature for an I_n-cooperative pore body-filling event
REV	Representative elementary volume
S_{xi}	Initial saturation of phase x at the start of imbibition
S_{xr}	Residual saturation of phase x
S_{grmax}	Maximum residual gas saturation
SSORCG	Symmetric successive overrelaxation − preconditioned conjugate gradients
scCO2	Supercritical CO_2
v_s	Velocity
V_g^i	Volume of i:th ganglion
$w^{(x)}$	Parametric weight taking into account the effect of geometry
W	Random number
z	Coordination number
$\overline{z}$	Mean coordination number

Greek letters

β_i	Corner half angle
Δ	Difference
$\Delta\rho$	Density difference between phases
θ	Contact angle
μ	Viscosity
σ	Interfacial tension between the wetting phase and the non-wetting phase
τ	Tortuosity

Superscript

e	Entry
element	Element (throat or body)
pd	Piston-type displacement
so	Snap-off

Subscript

a	Advancing
a,max	Maximum advancing
c	Capillary
def	Defending fluid
g	Gas phase, here scCO2
h	Hinging
inv	Invading fluid
nw	Non-wetting
o	Oil
r	Receding
scCO2	Supercritical CO_2
t	Throat
w	Wetting

general, not limited to CO_2, S_{gr} has been shown to depend on the porosity (/permeability), microporosity and initial gas saturation at the start of imbibition (S_{gi}) (Suzanne et al., 2003). Residual trapping of CO_2 is also dependent on the wettability of the medium and shape of the grains (Chaudhary et al., 2013). It also increases with interfacial tension (σ) (Bennion and Bachu, 2006). The σ is in turn dependent on the temperature, pressure and salinity conditions (Chalbaud et al., 2006; Bennion and Bachu, 2006, 2008b). However, results from laboratory core flooding experiments indicate that pressure, temperature and salinity may have insignificant effect on the trapping curve, S_{gr}-S_{gi} relationship, of CO_2 in sandstone (Niu et al., 2015). The magnitude of S_{gr} also depends on the state of the CO_2; whether the CO_2 is supercritical or gaseous. For the CO_2/brine system, brine is more wetting in contact with gaseous CO_2 than in contact with supercritical CO_2, resulting in less capillary trapping in the latter case (Akbarabadi and Piri, 2013; Prather et al., 2016). Whether the CO_2-rich phase prior to imbibition originates from injected or exsolved phase also affects the residual CO_2 trapping, i.e. a process-dependency exists. The latter case results in greater trapping, explained by that in this case the CO_2 appears in a more uniform distribution in the heterogeneous media (Zuo and Benson, 2014).

Numerical simulations are an important part of the planning and design stage of any storage project. While capillary trapping occurs at the pore-scale, there is a need to quantify residual trapping on the macroscopic scale. Trapping on the macroscopic scale, where Darcy-type flow is assumed, is of interest when simulating field-scale CO_2 storage, and is accounted for by using a trapping model (or an initial-residual saturation curve (IR curve)). Several trapping models, i.e. S_{gr}-S_{gi} relationships, of interest for gas trapping in sandstone were recounted and evaluated by Suzanne et al. (2003). There are multiple ways to obtain a trapping model. One approach is through fitting of a function to direct measurements. Experimentally measured trapping curves, S_{gr}-S_{gi} relationships, for supercritical and/or gaseous CO_2 in sandstone have been presented in several studies (Akbarabadi and Piri, 2013; Li et al., 2015; El-Maghraby et al., 2011; Pentland et al., 2011; Ruprecht et al., 2014). Another approach is to fit a function to data retrieved from pore-network modeling (Spiteri et al., 2005). Spiteri et al. (2005) used pore-network model simulations to derive and validate a hysteretic relative permeability function and trapping model. This approach made it possible to account for wettability conditions