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Design of foam-assisted carbon dioxide storage in a North Sea aquifer using streamline-based simulation

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ABSTRACT

Carbon capture and storage (CCS) – the collection of CO_2 from industrial sources and its injection underground – could potentially contribute to the reduction of atmospheric emissions of greenhouse gases. In this paper, we investigate the sequestration of CO_2 in aquifers with the co-injection of surfactants for foam generation. This is equivalent to the use of foam for conformance control in enhanced oil recovery applications. To study foam-assisted sequestration, we extend an in-house streamline-based simulator to model foam flow. We use two foam models that have been previously suggested in the literature. In both models foam hinders gas mobility through increasing its apparent viscosity. The modified simulator is validated by comparison to analytical solutions. We then investigate the performance of CO_2 sequestration with the co-injection of surfactants. We look at CO_2 sequestration in a North Sea aquifer. We study both simultaneous and alternating surfactant-gas injection at different fractional flows (i.e. water:gas ratios). For cases where a seal provides a reliable trapping mechanism, the simulation results suggest that the use of surfactants to generate foam significantly improves the storage efficiency at a marginal increase in water consumption. In this setting, CO_2/surfactant simultaneous injection at a 0.5 CO_2 fractional flow was found to be the optimum injection strategy for the case investigated. To the contrary, if the seal is unreliable or not present at the first place, CO_2/brine simultaneous injection at a 0.85 CO_2 fractional flow was found to be the optimum injection strategy. Although foam-assisted sequestration in this case further improves the storage efficiency, it does that at a significant increase in water consumption. This is since, although foam generation improves the sweep during the sequestration phase, it significantly hinders the sweep during the chase-brine injection phase. Based on that, having a design where the surfactant will degrade just before or during the chase-brine injection phase would provide the optimum sequestration strategy—without reliance on the presence or integrity of the seal.

1. Introduction

Carbon capture and storage (CCS) – the collection of CO_2 from industrial sources and its injection underground – can contribute to the reduction of atmospheric emissions of greenhouse gases (IPCC, 2005). CCS offers an effective and rapid way to reduce atmospheric emissions of CO_2 from large point sources, such as fossil-fueled power plants. Nevertheless, a critical environmental issue is related to the long-term storage of CO_2. The CO_2 needs to remain in the reservoir for hundreds to thousands of years. Typically, a necessary component to assure long-term storage is the presence of an impermeable seal at the top of the formation (Jessen et al., 2005), such as in the Weyburn oilfield (Malik and Islam, 2000) and the Sleipner aquifer (Korbøl and Kaddour, 1995). Yet, the top seal may leak or be penetrated by wells through which CO_2 could migrate to the surface (Bruant et al., 2002). Therefore, it is important to consider sequestration strategies that do not rely on seals.

Three processes can contribute to the safe storage of CO_2 without reliance on the presence and/or integrity of a caprock; those are dissolution in water, reaction with rock surfaces, and capillary entrapment. In the first process, due to dissolution in water, the brine will act as a CO_2-carrier and will move gradually downward because of its higher density. Unfortunately, this natural process needs thousands of years to sequester all the injected CO_2 (Korbøl and Kaddour, 1995; Ennis-King and Paterson, 2005; Hesse et al., 2006). In the second process, due to reaction with rock surfaces, the CO_2 can precipitate as a solid carbonate. Once again this process takes thousands to millions of years or more (Xu et al., 2003). Thus,

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Nomenclature

A	adsorption level (dimensionless)
C_a	adsored surfactant concentration, dimensionless (wt.%)
C_m	critical micelle concentration
C_s	surfactant concentration, dimensionless (wt.%)
C_s^*	critical surfactant concentration
E	effeciency (fraction)
f_{gi}	injection gas fractional flow (fraction)
f_w	water fractional flow (fraction)
g	gravity acceleration (m/s^2)
H^*	viscosity multiplier in Hirasaki and Lawson (dimensionless)
k	permeability (m^2) [Darcy]
k_{rg}^f	relative permeability of gas in presence of foam (dimensionless)
k_{rg}^o	relative permeability of gas in absence of foam (dimensionless)
k_{rw}	relative permeability of water (dimensionless)
L_B	length of liquid film (m)
L_s	length of liquid slugs (m)
M	shear multiplier (dimensionless)
m	Corey gas exponent (dimensionless)
n	Corey water exponent (dimensionless)
N_L	dimensionless length of the thin film portion of bubble (dimensionless)
N_s	dimensionless number for surface tension gradient effect (dimensionless)
n_L	number of equivalent lamellae per unit length (m^{-1})
p_w	water pressure (Pa)
p_c^*	limiting gas–water capillary pressure (Pa)
Q	injection rate (m^3/d)
Q_w	water production rate (m^3/d)
R	capillary radius (m)
R'	gas mobility reduction factor (dimensionless)
r_B	bubbles radius (m)
r_c	radius of curvature of gas–liquid interface (m)
S_g	gas saturation (fraction)
S_{gr}	residual gas saturation (fraction)
S_w	water saturation (fraction)
S_{wc}	connate water saturation (fraction)
S_{wi}	initial water saturation (fraction)
S_w^*	critical water saturation at limiting capillary pressure (fraction)
t	time (s)
u_g	interstitial velocity of gas bubbles (m/s)
V	volume (m^3)
ε	foam transition window (dimensionless)
Γ	foam quality (fraction)
μ_{app}	apparent viscosity of foam (Pa s) [cp]
μ_g	viscosity of gas (Pa s) [cp]
μ_w	viscosity of water (Pa s) [cp]
ξ	viscosity multiplier (dimensionless)
τ	time of flight (s)
ρ_w	water density (kg/m^3)
σ_{wg}	water-gas interfacial tension (N/m)
ϕ	porosity (fraction)

Superscripts

i	cell identifier in the discretization along a stream line
n	time level

Acronyms

CCS	carbon capture and storage
EOR	enhanced oil recovery
PV	pore volume
SAG	surfactant-alternating-gas
WAG	water-alternating-gas

the third process, capillary trapping, offers the most secure and rapid prospect for CO_2 storage. Recent simulation studies suggest that – through a combination of aquifer flow, chase brine injection, and buoyancy-driven upwards migration – much of the CO_2 could be trapped before it reaches the top seal (Ennis-King and Paterson, 2002; Kumar et al., 2005; Obi and Blunt, 2006; Juanes et al., 2006). With chase brine injection, at least 90% of the CO_2 residing in the reservoir is trapped at abandonment (Qi et al., 2009). Unfortunately, this fraction representing the ratio of immobile CO_2 to the total CO_2 residing in the reservoir, *trapping efficiency*, portrays only part of the picture.

Another important factor is the *storage efficiency*, which represents the fraction of the reservoir pore volume filled with CO_2. In CO_2 sequestration, storage efficiency is hampered by the CO_2 high mobility. This high mobility results in low sweep efficiencies as CO_2 naturally channels extensively through the formation due to its extremely low viscosity. Due to which, much of the injected CO_2 is recycled before it contacts the bulk of the reservoir. Consequently, although much of the CO_2 left underground is rendered immobile—safely stored, the CO_2 occupies only a minute fraction of the total pore volume available for safe storage. In other words, the geologic container used for storage ends up underutilized. To address this issue, Qi et al. (2009) have proposed the co-injection of CO_2 with brine to improve CO_2 sweep efficiency, hence its storage efficiency. Streamline-based simulation results suggest that co-injection of water at a volumetric injection ratio of 15% increases the storage efficiency to around 9% compared to only 3% when no water is co-injected (Qi et al., 2009). Note that in both cases CO_2 injection is followed by chase brine injection. While this is a significant improvement, storage efficiency is still low. Therefore, in this work we further study the coupling of CO_2 sequestration with foam flooding.

Foam flooding is an enhanced oil recovery technique, where surfactants are dissolved in the injected water such that the brine-gas system generates foam. As gas flows through the surfactant solution it generates a dispersion of gas bubbles across the liquid phase (Schlumberger, 2009). In this process, the apparent gas viscosity is increased. This subsequently improves the mobility ratio leading to more uniform sweep and less viscous fingering (Lake, 1989). Therefore, foam-assisted sequestration can provide a viable injection strategy to attain high storage efficiencies. To investigate this prospect, we extend an in-house streamline-based simulator to model foam flooding. The simulator is then used to investigate and propose an optimum CO_2 storage strategy, which maximizes the storage efficiency, minimizes the total amount of brine injected while at the same time maintaining a trapping efficiency of at least 90%. This optimum strategy is determined by comparing numerical simulation results of different possible injection schemes in a realistic heterogeneous reservoir model.

2. Modeling foam flow

Foams have various applications in geosystems: acid diversion in acid stimulation (Gdanski, 1993), mobility improvement in environmental remediation (Hirasaki et al., 2000), and sweep