International Journal of Heat and Mass Transfer 121 (2018) 463–476

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

# Enhanced safety of geologic $CO_2$ storage with nanoparticles

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ARTICLE INFO

*Article history:*
Received 10 July 2017
Received in revised form 11 November 2017
Accepted 28 December 2017

*Keywords:*
$CO_2$
Nanoparticles
Convective mixing
Nuclear waste
Safe storage

ABSTRACT

Some methods have been developed to detect leakage of $CO_2$ from its desired storage domain, but that is not sufficient to prevent and mitigate a leak. Two techniques have been proposed to prevent the migration of buoyant $CO_2$ from the storage domain by expediting mixing of $CO_2$ with the brine and mitigate risk of its leakage risk. These two methods are injection of $CO_2$ pre-mixed with brine, and injection of $CO_2$ with nanoparticles (NPs). The former has been studied to some extent, however, understanding of the latter is very limited. Unlike the application of NPs in hydrocarbon recovery, its use to enhance safety of $CO_2$ storage is a fairly unexplored topic that can have important benefits for the safety of the storage process. Also, the use of NPs for subsurface application in general is compromised for its cost. We investigate how NPs produced from low-level nuclear waste can be added with injected $CO_2$ to enhance the mixing of $CO_2$ with brine, which can mitigate leakage risk of $CO_2$.

We numerically investigate the effect of adding NPs from nuclear waste with the $CO_2$ and show that it enhances the mixing of $CO_2$ with in-situ brine in saline aquifers that mitigates the risk related to buoyancy and high mobility of $CO_2$. Additionally, we examine the effect of reservoir heterogeneity on mixing of $CO_2$ in reservoir brine when it is injected with NPs. The results show that: (i) addition of NPs to $CO_2$ leads to higher mixing, (ii) the discrete shape of $CO_2$ concentration in brine tends to diffuse and become smooth as the heterogeneity of the medium increases, and (iii) the impact of heterogeneity is more pronounced than the fraction of NPs on mixing.



## 1. Introduction

Storage of supercritical carbon dioxide ($scCO_2$) into deep geological formations such as saline aquifers is a key step to mitigate greenhouse gas emissions [7] from large industrial emitters, such as coal-fired power plants, cement plants, iron and steel plants. There has been considerable progress in understanding the science of $CO_2$ storage and in demonstrating this technology in the US and around the world. This is evidenced by the fact that, within the span of 10 years since the IPCC Special report [27], 19 small-scale (injection of less than 500 kT/year) validation projects [40], and 8 development phase large-scale (injection of greater than or equal to 1 MT/year) field projects [41] for storage have been demonstrated by the regional partnerships in the United States. As of September 2016, large-scale development phase field projects in the US have injected a total of 13.9 million metric tons of $CO_2$. Over all, >45 projects ranging from small-scale to large-scale projects have been undertaken worldwide [9]. However, one of the most plausible risks to storage of $CO_2$ in geological formations is its leakage through a fractured seal barrier to the ground water resources or through abandoned wellbores to the surface. The leakage of $CO_2$ through such paths is highly probable because of its extremely buoyant nature that lets it rise rapidly soon after it is injected in the reservoir. Even though much work is going on in developing monitoring technologies to detect leakage of $CO_2$ from its desired storage domain [49,6,26,31,46,58,59], that in itself is not sufficient to prevent and mitigate a leak. There has been relatively little work done on devising risk mitigation strategies to prevent the migration of buoyant $CO_2$. A simple search on Google scholar for '$CO_2$ storage' query retrieves 2,100,000 results, whereas the query on '$CO_2$ leakage mitigation strategies' retrieves just 26,700 results or approximately $\sim 1.3\%$ of the total $CO_2$ storage research.

The concern of $CO_2$ leakage can be mitigated through quick mixing of injected $CO_2$ with the underlying brine, however, natural convection through which $CO_2$ mixes with brine in the reservoir is a slow process that could take years to decades depending on rock and fluid properties [20,44]. Two techniques have been proposed to expedite mixing of $CO_2$ with the brine and mitigate risk of its buoyant migration, which are injection of $scCO_2$ pre-mixed with brine [8,13,43,61] and injection of $scCO_2$ with nanoparticles

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https://doi.org/10.1016/j.ijheatmasstransfer.2017.12.152
0017-9310/

**Notations**

| | |
|---|---|
| $c$ | concentration [mol/m$^3$] |
| $D$ | diffusion coefficient [m$^2$/s] |
| $g$ | gravitational acceleration [m/s$^2$] |
| $H$ | reservoir thickness [m] |
| $k$ | permeability [m$^2$] |
| $L$ | reservoir length or characteristic length [m] |
| $n$ | number of nodes [–] |
| $p$ | pressure [Pa] |
| $\lambda$ | wave number [–] |
| $Pe$ | Peclet number [–] |
| $Ra$ | Rayleigh number [–], $Ra = \frac{\Delta\rho gkH}{\phi D\mu}$ |
| $t$ | time [s] |
| $u$ | velocity [m/s] |
| $x$ | distance along x-axis |
| $z$ | distance along z-axis |

*Greek letters*

| | |
|---|---|
| $\beta$ | coefficient of density increase by concentration [m$^3$/mol] |
| $\phi$ | porosity [–] |
| $\mu$ | viscosity [kg m$^{-1}$ s$^{-1}$] |
| $\rho$ | density [kg/m$^3$] |
| $\psi$ | stream function [m$^3$ m$^{-1}$ s$^{-1}$] |

*Superscript*

| | |
|---|---|
| $*$ | Dimensionless quantity |

*Subscripts*

| | |
|---|---|
| *0* | initial condition |
| *i* | node in x – direction |
| *j* | node in z – direction |
| *x* | x-coordinate |
| *z* | z-coordinate |
| *dp* | Dykstra-Parsons |

*Acronyms/Abbreviations*

| | |
|---|---|
| NPs | nanoparticles |
| DUs | depleted uranium |
| $CO_2$-brine | brine saturated with $CO_2$ |
| nano-$CO_2$ | supercritical $CO_2$ containing NPs |
| nano-$CO_2$-brine | brine saturated with nano-$CO_2$ |
| $UF_6$ | uranium hexafluoride |
| $UO_2$ | uranium dioxide |
| $U_3O_8$ | triuranium octaoxide |

(NPs). Amongst these two proposals, the latter is not well studied with only three preliminary modeling studies [30,53,65] and one laboratory scale experimental study [2] published on this topic. An analogous topic on application of NPs for subsurface oil and gas with an active research community has produced excellent results in the laboratory, specifically for enhanced hydrocarbon recovery through nano-suspensions [12,23,24,64], subsurface mapping through nano-sensors [42,66], hydraulic fracture characterization through nano-magnetization of reservoirs [3], and hydraulic fracturing fluid with better proppant transport ability through nano-foams [38]. However, unlike the application of NPs in hydrocarbon recovery, its use to enhance safety of $CO_2$ storage is a fairly unexplored topic that can have important benefits for the safety of the storage process.

In this study, we numerically investigate the effect of adding NPs from nuclear waste with the $scCO_2$ (henceforth referred to as nano-$CO_2$ in short) and show that it enhances the process of natural convection (also called convective mixing) of $CO_2$ in saline aquifers. Additionally, we explore the effect of reservoir heterogeneity on the behavior of natural convection for the injected nano-$CO_2$. It is assumed that dilute concentration of NPs in $scCO_2$ forms a stable suspension that does not interact with the solid matrix in porous media, and hence it does not affect the porosity and permeability of the reservoir.

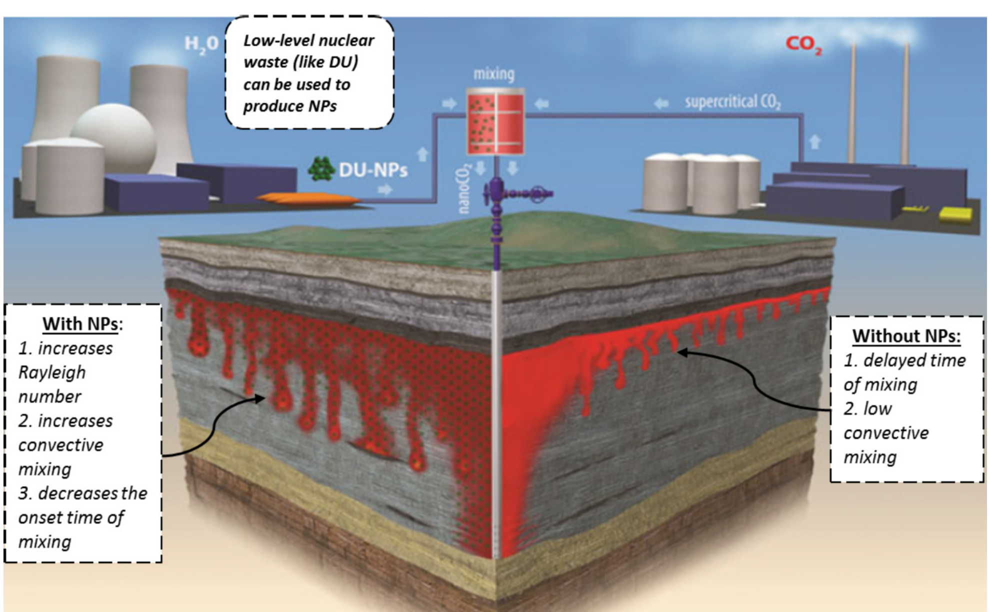


**Fig. 1.** A conceptual schematic illustrating enhanced convective mixing after adding NPs with $CO_2$ (after Singh et al. [53], Javadpour and Nicot [30]).