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Double diffusive natural convection of CO_2 in a brine saturated geothermal reservoir: Study of non-modal growth of perturbations and heterogeneity effects

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ABSTRACT

In a recent study (Islam et al., 2013) double diffusive natural convection of CO_2 in brine saturated homogeneous permeable geothermal reservoir was investigated. Here we have shown the study of heterogeneous reservoirs. Firstly, we present the non-modal stability theory to analyze time-dependent double diffusive convection. Linear stability analysis is performed and the maximum amplification of perturbations optimized over the entire space of initial perturbations is examined. These provide us onset time of convection (or the critical time) and the structure of the most-amplified perturbations. Secondly, we investigate numerical simulation of an anisotropic and layered reservoir with permeability variations, which is impervious from the sides, and is open to CO_2 at the top. We show the propagation of CO_2 plumes over long period of time by analyzing different combination of problem parameters: solutal Rayleigh number ($100 \leq Ra_s \leq 10{,}000$), the buoyancy ratio ($2 \leq N \leq 100$), Dykstra-Parsons coefficient ($0 \leq V_{dp} \leq 0.85$) and a fixed Lewis number. How permeability variation in vertical (k_z) to horizontal (k_x) direction affects the CO_2 dissolution is discussed for different ratios of k_z/k_x ($0.1 \leq k_z/k_x \leq 0.8$). Results of different cavity aspect ratios ($0.5 \leq A \leq 2$) are also presented. It is found that heterogeneous porous reservoir renders better mass transfer of CO_2 than the homogeneous one. CO_2 dissolution is enhanced with increasing both Ra_s and V_{dp}. N, which represents geothermal effect, has minor impact on overall dissolution process. The results have implications in enhanced oil recovery and CO_2 based geothermal systems.

1. Introduction

Geological CO_2 sequestration (CS) in saline aquifers is currently considered as one of the most promising options to reduce CO_2 accumulation in atmosphere. The CO_2 released in the atmosphere is the principal cause of the green house effect, leading to global warming. CS, also referred to as carbon management, is a complementary approach to the current CO_2 mitigation efforts of improved energy efficiency and increased use of non-carbon energy sources. CS enables the continued use of fossil fuels supplying >80% of the primary power demand by mankind (Hoffert et al., 2002; MIT, 2007). In brief, CS involves capturing CO_2 from the flue gas of power plants, compressing it into supercritical state, and finally injecting into deep saline aquifers for long term storage (IPCC, 2005; Orr, 2009; Szulczewski et al., 2012). Injection into deep saline aquifers provides the highest storage capacity (IPCC, 2005; Piri et al., 2005; Orr, 2009). This type of aquifers can provide storage capacity of up to 11^{13} tons of CO_2 which is enough to store several hundred years of CO_2 emissions (Ormerod, 1994; Orr, 2004; Piri et al., 2005; Orr, 2009). Storage capacity estimates for the United States, for instance, range over almost four orders-of-magnitude from ~5 to 20,000 billion metric tons of CO_2 (Bergman and Winter, 1995; Dooley et al., 2004; DOE-NETL, 2010). CO_2 sequestered dissolves over time in the interstitial solution of the aquifer and in some formations it slowly reacts with minerals to carbonates locking up permanently. That said, among many other mechanisms (Han et al., 2010) CO_2 is eventually trapped by capillary trapping and solubility trapping. In capillary trapping, part of CO_2 rises through porous rock formation above due to buoyancy and capillary forces and gets trapped into the rock pores (Juanes et al., 2006; Ide et al., 2007; Han et al., 2010). On the other hand, at the interface of CO_2 rich phase and brine dissolution starts by molecular diffusion increasing brine density by about 1–3% (Teng et al., 1997; Garcia, 2001; Duan et al., 2008; Islam and Carlson, 2012) on the aquifer top surface and then sinks by natural convection due to solute gradient. Besides this solubility trapping naturally occurring geothermal temperature gradient

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Notations

A	aspect ratio, H/L
c	concentration (mol/m^3)
C_p	heat capacity at constant pressure (J kg^{-1} K^{-1})
D	diffusion coefficient (m^2/s)
g	acceleration due to gravity (m/s^2)
H	porous medium height (m)
k	permeability (m^{-2})
L	porous medium length (m)
n	number of nodes
p	pressure (Pa)
λ	wave number
Le	Lewis number
Pe	Peclet number
Pr	Prandtl number
Ra	Rayleigh number
$\bar{S}$	average dissolution
t	time (s)
u	velocity (m/s)
V	Dykstra-Parsons coefficient
x	distance along x-axis
z	distance along z-axis

Greek letters

α	thermal diffusivity
β_c	coefficient of density increase by concentration (m^3/mol)
β_T	coefficient of thermal expansion (K^{-1})
ϕ	porosity
μ	viscosity (kg m^{-1} s^{-1})
κ	thermal conductivity
ρ	density (kg/m^3)
ψ	stream function (m^3 m^{-1} s^{-1})

Superscript

*	dimensionless quantity

Subscripts

0	initial value
b	base state
c	concentration
dp	Dykstra-Parsons
i	node in x-direction
j	node in z-direction
p	perturbed state
r	reference value
s	solutal
T	temperature
x	x-coordinate
z	z-coordinate

(typically ~3 °C/100 m vertical depth) also induces destabilization (Islam et al., 2013).

The authors (Islam et al., 2013) performed comprehensive investigation of double diffusive convection of the discussed system in homogeneous porous medium. As we know the effect of natural convection boosts with Rayleigh number, which, for a isobaric CO_2-injection scheme, depends mainly on the permeability (Farajzadeh et al., 2009). This denotes that the intensity of mixing caused by natural convection is largely influenced by the aquifer permeability subject to spatial and directional variations occurring naturally. They investigated heterogeneity on the character of single diffusive (density driven) convective flow of CO_2 in aquifers and on the dissolution rate of CO_2–brine. Our interest, in this study, is to examine the CO_2 mass transfer in heterogeneous geothermal reservoir due to both density and temperature differences across the height of the aquifer. Before analyzing the numerical simulation results, non-modal stability theory to compute maximum amplifications possible, optimized over all possible initial perturbations is discussed.

Since initiated in late 50s of last century by Horton and Rogers (1945), Lapwood (1948) and Morrison et al. (1949) development of investigations on the onset of convection in porous media are reviewed in recent studies (Ennis-King et al., 2005; Xu et al., 2006; Hassanzadeh et al., 2006; Javaheri et al., 2010; Riaz et al., 2006; Rapaka et al., 2008, 2009). These recent investigations are concentrated on the application to geological storage of CO_2. Ennis-King et al. (2005) analyzed linear stability analysis (LSA) and global stability analysis (GSA) to provide bounds for the length and time scales of convection in anisotropic porous media. They used single-term approximation of the Galerkin expansion to obtain analytic expressions for the dependence of critical time and wavenumbers. Xu et al. (2006) later extended their work by considering the variation of both the horizontal and vertical permeabilities and found the dependence of critical time and wavenumbers on permeability to be simple power laws. The critical time was defined as the time required for the amplitude of the perturbations to begin amplifying. Hassanzadeh et al. (2006) predicted the onset of convection using LSA based on the amplification of the initial perturbations. They introduced different noises to find the fastest growing noise as initial conditions for the stability analysis. Javaheri et al. (2010) conducted LSA to predict the inception of instabilities and initial wavelength of the convective instabilities. Riaz et al. (2006) also used LSA based on the dominant mode of the self-similar diffusion operator and numerical simulations to find a scaling relationship for the onset of convection. Rapaka et al. (2008, 2009) used the idea of non-modal stability theory to calculate the maximum amplification of perturbations optimized over the entire space of perturbations instigated. This scheme is mathematically rigorous extension of the traditional normal-mode analysis to non-normal and time dependent problems. Non-modal stability analysis (NSA) is used to predict the maximum growth of perturbations along with the optimal wavenumber leading to this growth. LSA provides sufficient condition of instability. Generally for the case of LSA, the PDEs (partial differential equations) for the evolution of the perturbation quantities are converted into one for a suitably defined energy functional. The form of the energy functional used is a linear combination of the kinetic energy of the flow and the mean-squared magnitude of the perturbations. This equation is then finally analyzed to obtain the conditions required for stability.

CO_2 dissolution in heterogeneous media is different than in homogeneous media because the permeability variations results in time-dependent velocity fluctuations, which in turn enhances the mixing process (Farajzadeh et al., 2011). Geologic systems of CO_2 sequestration are commonly characterized by fractured rock environments. Heterogeneity of such systems occur over many spatial scales and variable density flow phenomena may be triggered, grown, and decayed over a very large mix of different spatial and temporal scales (Neild and Simmons, 2007). To list a few, the authors (Waggoner et al., 1992; Chang et al., 1993; Sorbie et al., 1994) also discuss heterogeneity effects. In this paper we consider a quiescent porous medium with initially no CO_2 dissolved in contact with a continuous source of CO_2 at the top of the domain. We assume that the brine lying at the interface with CO_2 is in saturated state. The free-phase CO_2 is expected to remain in the reservoir. Convective mixing increases the rate of dissolution and thus lowers the time scale over which leakage may occur. Once CO_2 is mixed, risk assessments may well ignore the leakage pathways resulting from the very slow movement of CO_2-saturated brine in