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Investigation of CO_2 Geologic Sequestration and the Density-driven Convection Process

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Abstract

In this work, the authors present a simulation study of the convection triggered by gravitational instability due to dissolution. By putting a denser fluid on the top, convection occurred as the upper fluid dissolved into the lighter fluid below. Five kinds of heterogeneous porous media are created with different values of correlation length of permeability. Simulation is conducted with compact finite difference scheme of high accuracy order and spectral method. The results show that flow patterns have a significant difference between heterogeneous porous media and homogeneous one.

Keywords: CO_2 geologic sequestration, density-driven convection, stream-function-vorticity system, pseudo-spectral method, compact finite difference

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1. Introduction

One of CO_2 storage options is its injecting in porous rocks in the deep subsurface [1], such as depleted oil and gas reservoirs. Supercritical CO_2 is lighter than the brine water, so it will stay on top of brine and form a tank [2]. On the interface of supercritical CO_2 and brine, dissolution is going on slowly. In this condition, CO_2 is partially soluble in brine water (typically 3 wt%) and the mixture has a density increase [3]. While the mixture is denser than the brine below it, the convection triggers. The appearance of convection greatly increases the process of dissolution of CO_2 into the brine, compared to the diffusion.

A. Riaz et al. [4] and K. Ghesmat et al. [5] solved Darcy's equation in simulation and got the density-driven miscible flow in porous media. As the upper denser fluid dissolved, clear fingers appeared from the top and induced convection. Actually, the permeability of porous rocks in subsurface varies depending on the rock types and structures. C.Y. Chen et al. [6, 7] conducted numerical study on rotational and injection flow in heterogeneous porous media. The results show a conspicuous difference in fingering patterns between homogeneous porous media and heterogeneous ones.

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In this study, Darcy's equation was solved in porous media with simulation method of high precision order and significant results were obtained.

2. Methods

In porous media, the governing equation of flow is Darcy's equation:

$$u = -\frac{K}{\mu}\nabla p \tag{1}$$

In our numerical study, two fluids are miscible with each other. So, continuity equation and diffusion equation were included:

$$\nabla \cdot u = 0 \tag{2}$$

$$\nabla p = -\frac{\eta}{k}u + \rho g \tag{3}$$

$$\frac{\partial c}{\partial t} + u \cdot \nabla c = D\nabla^2 c, \tag{4}$$

where $\eta = \eta_0 e^{R(1-c)}$, $\rho(c) = \rho_0 + r(c)\Delta\rho$.

The heterogeneous permeability field $k(x,y)$ is assumed as a random function associated with desired statistical features. The permeability can be expressed in terms of a characteristic permeability K and random function, which Gaussian distribution is characterized by the variance s and the spatial correlation length l with a vanishing mean zero:

$$k\,(x) = e^{f\,(x)} \tag{5}$$

$$\langle f, f\rangle = s^2 R_{ff}\,(x) \tag{6}$$

Five different heterogeneous porous media are generated for different values of correlation length l (Fig. 1).

Dimensionless diffusion equation and stream-function-vorticity system are yielded. Difference scheme of high accuracy order, Runge-Kutta of the third order, and spectral method were employed:

$$\nabla^2\varphi = \omega = \frac{1}{\eta}\left(\frac{\partial\eta}{\partial y}u - \frac{\partial\eta}{\partial x}v\right) + \frac{1}{k}\left(\frac{\partial k}{\partial x}v - \frac{\partial k}{\partial y}u\right) - \frac{k}{\eta}\frac{\partial r(c)}{\partial y} \tag{7}$$

$$\frac{\partial c}{\partial t} + u \cdot \nabla c = \frac{1}{Ra}\nabla^2 c, \tag{8}$$

where $Ra = \frac{k_0 H \Delta\rho g}{\eta_0 D}$.

In the simulation, the top of the field was defined as the denser fluid, with a concentration c = 1. In the initial condition, the below field was filled with the lighter fluid, with a concentration c = 0 (Fig. 2).

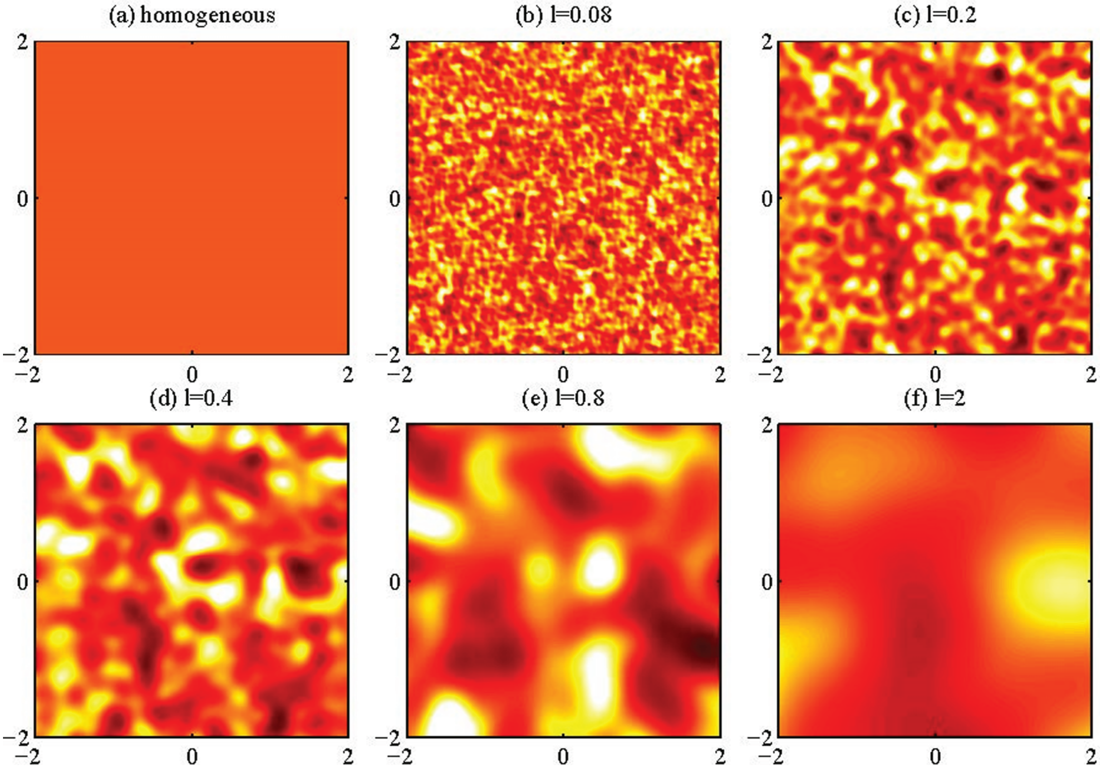

Figure 1: Homogeneous porous medium and five heterogeneous porous media with different values of correlation length *l*: (a) 0.08; (b) 0.2; (c) 0.4; (d) 0.8; and (e) 2. The scale of the simulation field is 4.

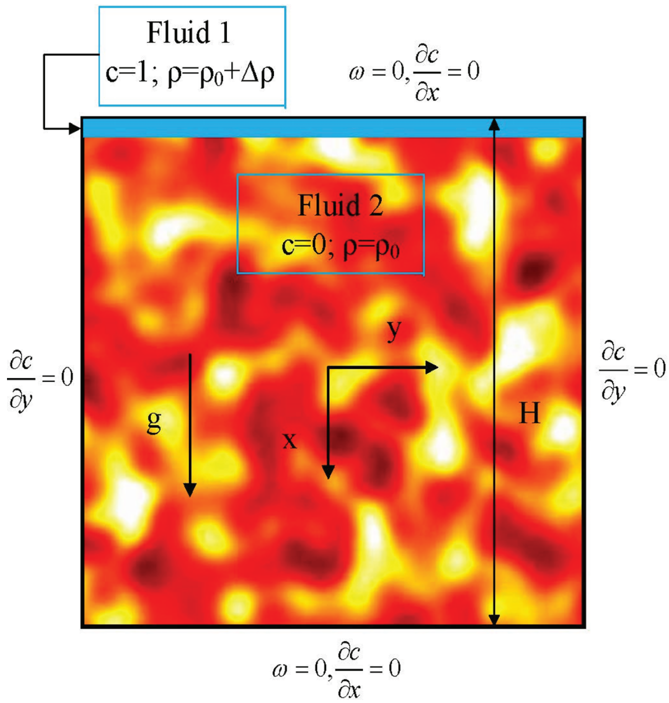

Figure 2: Simulation field and boundary conditions.

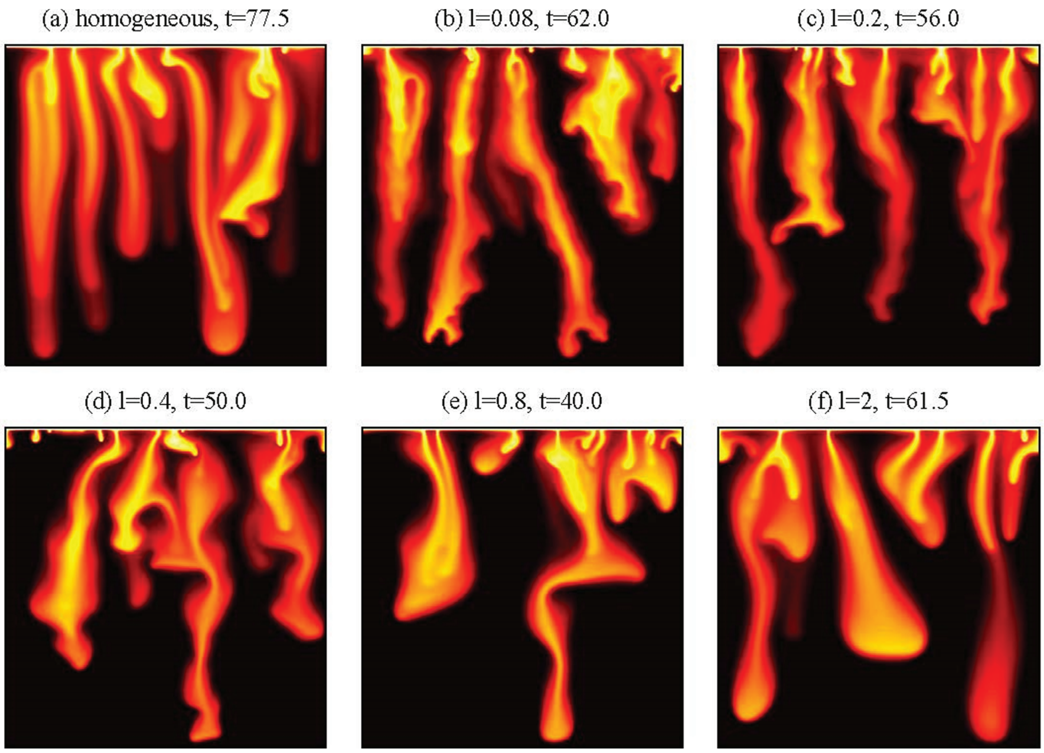

Figure 3: Finger patterns of homogeneous porous medium and five heterogeneous porous media at the breakthrough time.

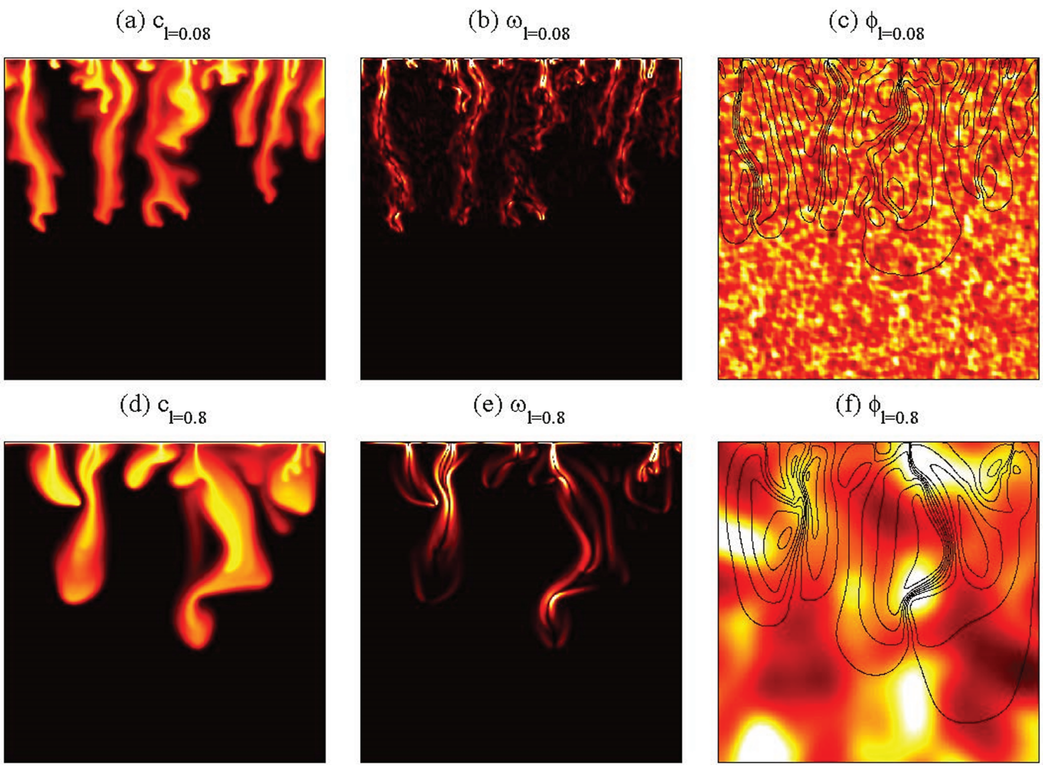

Figure 4: Finger patterns, vorticity, and stream line of the case *l* = 0.08 and 0.8 at time 30.

3. Results

In the simulation, when fingers reached the bottom of the field, the simulation stopped. Figure 3 shows the finger patterns of each porous medium at the breakthrough time. In homogeneous porous medium, fingers have smoother interface and have a longer breakthrough time. For the case with small correlation length l = 0.08 and 0.2, the finger's interface gets rough and the breakthrough time becomes shorter. For the medium correlation length cases l = 0.4 and 0.8, the breakthrough time reaches its minimum value and the interface turns smooth. In these cases, few fingers are formed demonstrating a prominent finger competition, since the width of fingers coincides with the correlation length. While the correlation length gets much larger than the width of the fingers, the breakthrough time rises again.

Figure 4 shows the finger patterns, vorticity, and stream line of the two cases with correlation length l = 0.08 and 0.8 at time 30. In the case of l = 0.8, vorticity and stream line are more concentrated at the position of fingers, so the fingers grow faster and lead to a shorter breakthrough time.

4. Conclusion

As shown in the results, finger patterns are obviously affected by the permeability heterogeneity. When the correlation length of the permeability and the width of fingers are resonant, a prominent finger competition occurs leading to an outstanding breakthrough time and finger pattern.

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