Study of density driven convection in a Hele-Shaw cell with application to the carbon sequestration in aquifers

Agival Lu¹, Yu Liu¹, Lanlan Jiang¹, Yongchen Song¹, Bohao Wu¹

Key Laboratory of Ocean Energy Utilization and Energy Conservation of Ministry of Education, Dalian University of Technology, 116024 Dalian, China

Abstract

Faster dissolution of CO₂ into the aqueous phase within aquifers plays a crucial role in the optimal storage of carbon dioxide injected into reservoirs. After the injection of CO₂ into such geological structures as saline aquifers, oil fields, and salt marshes, the gas in supercritical state would rise to the top of permeable and porous reservoir zone, forming a buoyant CO₂ plume beneath a layer of cap rock with low-permeability, due to buoyancy forces introduced by the minus density difference between carbon dioxide and brine formations. Only driven by molecular diffusion, mass transfer from the gas phase into the aqueous intervals would take a very long time for the total solution. However, the mixture of CO₂ and brine attributes heavier density to the outcome solution between the free CO₂ phase and the aqueous phase below, which initiates convection currents in the aquifer and creates a remarkable increase of the dissolution rate of carbon dioxide. Thus, larger amounts of free CO₂ gas can be sequestrated in a shorter period of time and the risk of gas leakage through the defects in cap rock would be greatly reduced. It is very vital for the risk assessment of leakage to obtain accurate description of the CO₂ dissolution rate in the aquifers. The longer the dissolution is enduring, the more possibly the sequestration of CO₂ becomes unstable.

In our experiments a series of CO₂ solute-driven convection laboratory tests were performed in transparent vertical Hele-Shaw cells with a 1.2mm gap that contained brine water overlain by gas phase and visualization of convective phenomena was achieved with the help of bromocresol purple completely solved into the brine at first. The phase in rich of CO₂ would have a lighter colour and was transferred into cell bottom in the form of flow fingers in figure 1. A short time after the introduction of CO₂ into the Hele-Shaw cell, a film of CO₂-brine forms at the gas and liquid interface. Subsequently, small phase fingers caused by density contrast would form and they merge, widen, and penetrate deep into the cell. Much series of images (in figure 1) recording the dynamic convection were analysed and the growing properties in timescale of average finger lengths and average wavelengths are encoded into a line chart like figure 2. These results accord with the law demonstrated by T. J. Kneafsey · K. Pruess. The gap in Hele-Shaw cell is not perfectly uniform and the colour of central region is dark purple while other part close to edge has a lighter colour. Binarization process can make up the imperfectness. With the average length and width of fingers on
every time point, it is easily to calculate timescale changes of average/all rich-\(\text{CO}_2\)-area which present mass transfer rate of \(\text{CO}_2\) into the brine.

Effects of such different formation parameters as brine concentration and heterogeneity on the onset and development of convection are investigated in the paper, and two time intervals took most attention, of which the first one is the measurement of starting point of gravitational instability while the second one is recorded to get the velocity of finger growth. Influencing system Rayleigh number, the formation heterogeneity can greatly strengthen the convective mixing and accelerate the growth of \(\text{CO}_2\) solution into the test cell. More heterogeneous porous media make the convection begin earlier. The sodium chloride solution concentration gradient has an obvious influence on the form and development of convection phenomenon in our experiments. It is also confirmed that the presence and strength of convection would count a lot in \(\text{CO}_2\) storage in aquifers.

![Figure 1](image1.png)  
Figure 1  A series of analysed images of convective mixing of \(\text{CO}_2\) into pure water

![Figure 2](image2.png)  
Figure 2  Timescale changes of average finger length and width in convection of \(\text{CO}_2\) solving into pure water