Laboratory-scale Experimental Study of solubility trapping of CO_2 in deep aquifers

Internship Report

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Contents

1 Aim of the Internship

The main aim of my internship is to participate in the 3D scanning setup of the experiment, and perform observations from the experiment along with the post processing of the experimental data. Alongside I will also contribute in analyzing data from the numerical simulations.

2 Abstract

Solubility trapping is one of the trapping mechanisms in which CO2 can be stored in deep aquifers. The carbon dioxide when injected into the ground partially dissolves with the upper layers of the brine in the aquifers and thus the density of the upper layers of brine increases considerably. This triggers a gravitational instability between the upper layers of denser fluid and the lower layers of less dense fluid. This give rise to fingering structures between the upper heavier fluid and the lower denser fluid. In order to find out the onset time and the efficiency of this solubility trapping, we devised a lab experiment in a artificial porous medium consisting of beads of diameter 3mm and using TX100 as the fluid and using a laser sensitive dye Nile Blue to get an idea of the process by laser scanning in 3-dimensional space. Simultaneously, a numerical simulation has also been done on OpenFOAM by coupling the Brinkman-Darcy Equation and the convection-diffusion equation along with introduction of the dispersion term. The porosity and permeability values are defined by a 3D image of a porous media developed on MATLAB.

3 Experimental

3.1 Experimental Setup

The basic geometry of the 3D scanning setup can be seen here. The laser sheet is produced by two simultaneous reflections from two vertically placed mirrors and an optical prism that converts the cylindrical laser ray to a planer sheet. The planer sheet is focused on the experimental cell.

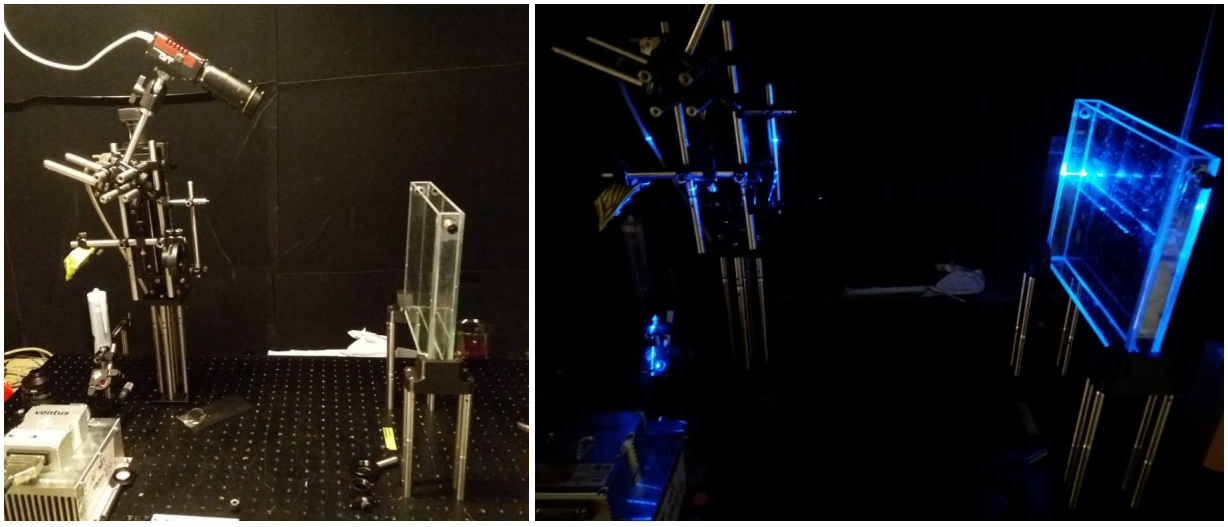
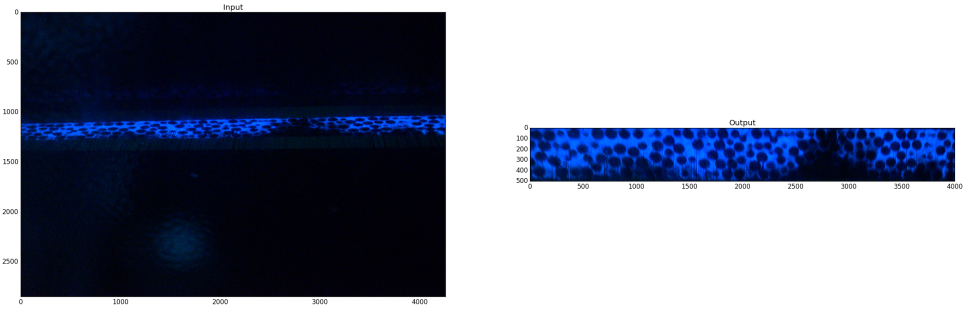


Fig: The 3D laser scanning and image acquisition setup.

We used the GIGE Vision camera and the Hamamatsu for capturing the scanning images. The camera and the prism is mounted on a vertical actuation table. A MATLAB code has been developed for the parallel actuation of the table and the simultaneous capturing of the images. The camera captures each image in TIFF format when the table stops actuating during its vertical motion. And for each round of vertical scanning we take 100 pictures in order to make the number of pixels in the vertical direction equal to 100. We carry on the vertical actuation in a repeated manner and it's kept on until the instability is over. By following this process, we can get the exact position of the slices and also the time it takes for the instability to start.

3.2 Post Processing

The camera captures the images from at an angle to the laser plane. As a result of which the PMMA beads doesn't look round from that angle. Thus, we need to convert those images from the angled look to the vertical view, which is as if the image has been taken from the top. A python code has been developed to convert the images from the angled view to the vertical view using the perspective transform algorithm.



The illuminated part is the Nile-blue concentration and the dark area is the position of the finger in the cell. This script will be run after acquiring all the images from the camera and will make an image stack by placing one image on top of the other in order to give a final 3D visualization of the instability.

4 Governing Equations:

We couple the Brinkman-Darcy equations along with the convection diffusion equations with the introduction to the dispersion term in order to study the effect of dispersion in the experiment.

Assumptions for 3D – Incompressible flow, inertial terms absent in Stokes equations.

4.1 Dimensional equation:

The incompressible density-dependent flow and advective–diffusive–dispersive transport equations, which govern the Raleigh Taylor instability in a porous media are given below:

$$-\nabla p + \mu \nabla^2 u - (\mu/k)u - \rho g \hat{e_z} = 0$$

(classical Brinkman-Darcy equation)

$$\nabla \cdot u = 0$$

(Continuity Equation) and

$$\phi \partial c/\partial t = \nabla \cdot (D \nabla c) - u \cdot c$$

Here

$$\rho = \rho_0 + \Delta \rho c/c_0$$

and z-axis is taken opposite the direction of gravity (g). The anisotropic dispersion coefficient tensor is

$$\bar{D} = (\phi D_m + \alpha_T ||u||)\delta_{ij} + (\alpha_L - \alpha_T)(u_i u_j)/(||u||)$$

$\Delta\rho$ is the difference in density between the two fluids. μ is the viscocity, k is the permeability, $\hat{e_z}$ is the unit vector pointing downwards.D_m is the molecular diffusion coefficient. α_L and α_T are longitudinal and transverse dispersivities accordingly. δ_{ij} is the Kronecker delta, and $||.||$ is the Eucledean norm. u is the Darcy velocity.

4.2 Non-dimensional equation:

For analysis purposes, it is convenient to write governing equations in a dimensionless form. Gravity instability, at least for heat transfer between two prescribed temperature plates separated by a distance H, is classically expressed as a function of the Rayleigh number

$$Ra = u_r H/\theta D_m$$

where the velocity scale

$$u_r \simeq k\delta\rho g/\mu$$

$$-\nabla\bar{p} + Da(\nabla^2\bar{u}) - \bar{u} + \bar{c}\hat{e_z} = 0,$$
$$\nabla \cdot \bar{u} = 0$$

and

$$\partial c/\partial t = (1/Ra)\nabla \cdot (D\nabla c) - u \cdot c$$

The anisotropic diffusion coefficient is

$$\bar{D} = (1 + (\alpha_T u_r/\phi D_m)||u||\delta_{ij} + (\alpha_L - \alpha_T)u_r/\phi D_m(u_i u_j)/(||u||)$$

Here Da is the Darcy number which is in the order of 10^{-6} or lower.

4.3 Boundary Conditions:

The conditions would be that either at all the lateral walls $u = 0$. At all the lateral walls c has zero flux (no penetration). At the bottom and top wall also, $u = 0$ and flux of c is 0. For the present simulation we have considered an initial condition where dimensionless c varies from 1 at the top part of the channel to 0 at the bottom part of the channel, with an error function where the change is sharp and this sharp change (the interface between the heavier and lighter liquid) is situated at the centre of the simulation box.

5 Numerical Simulations:

All the numerical simulations has been done in OpenFOAM. We program the solver by coupling the Brinkman Darcy Equation with the convection diffusion transport equation.

We modified the icoFoam solver which solves the incompressible laminar Navier-Stokes equations using the PISO algorithm. The code is inherently transient, requiring an initial condition (such as zero velocity) and boundary conditions. The icoFOAM code can take mesh non-orthogonality into account with successive non-orthogonality iterations. The number of PISO corrections and non-orthogonality corrections are controlled through user input. We modified the solver by addidng the advection diffusion equation with dispersivity along with the simple Navier Stokes solver inside the solution loop such that it uses the value of the Darcy velocity and solve the concentration values from the second equation.

5.1 Darcy Scale:

For the Darcy scale system, the coupled equation that we solved here are:

```
UEqn:

 fvm::ddt(U)
     - n * fvm::laplacian(Da,U)
      + U * m
      - g* (c/c0)

    if (piso.momentumPredictor())
    {
        solve(UEqn == -fvc::grad(p));
    }

// --- PISO loop
.
...
cEqn :

fvm::ddt(c)
      + fvm::div(phi, c)
      - Rainv * fvm::laplacian(Dm, c)
```

```
- a * fvm::laplacian(mag(U) ,c)
- a/(pow(sqr(U.component(0))+sqr(U.component(1))+sqr(U.component(2))
+sqr(s),0.5))*fvm::laplacian((U*U), c)
- a/((mag(U)+s))*fvm::laplacian((U*U), c )
```

The initial condition :

The initial condition for the concentration has been modelled in MATLAB. The toppart concentration has been given as 1 and the lower part is 0 and the interface-between the two different concentrations has been defined by an error function.

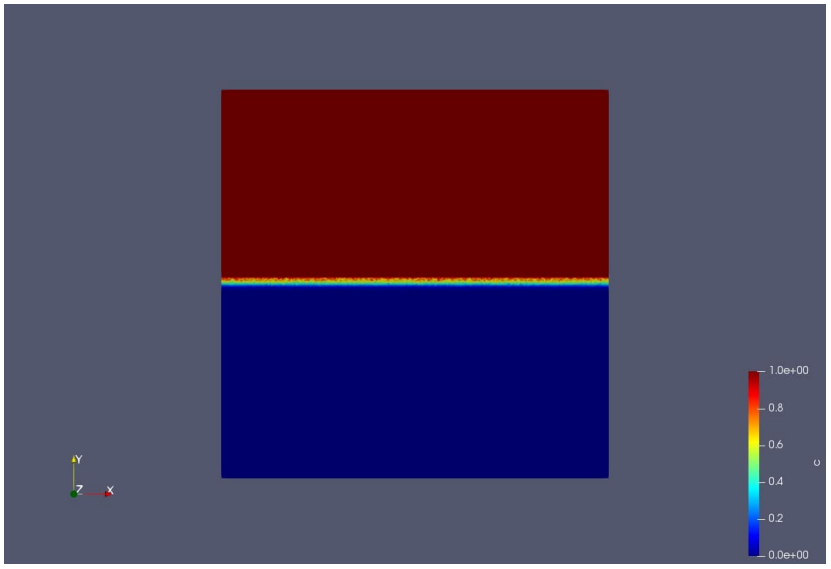


fig: Initial concentration condition

Start of the instability:

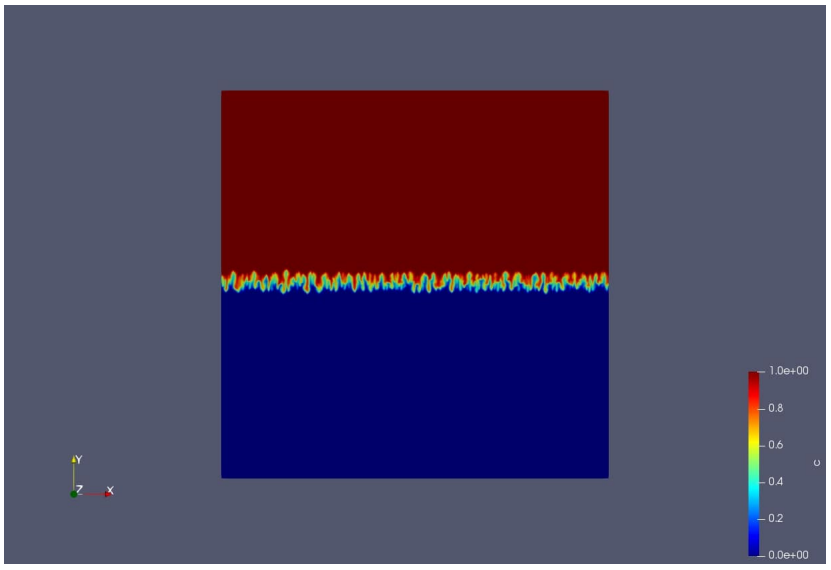


fig: Initial concentration condition

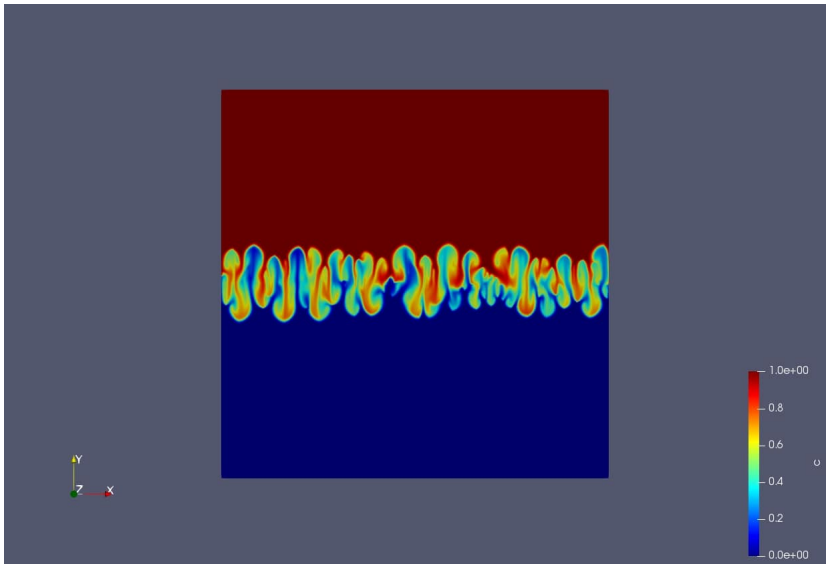


fig: At a later time.

5.2 PoreScale:

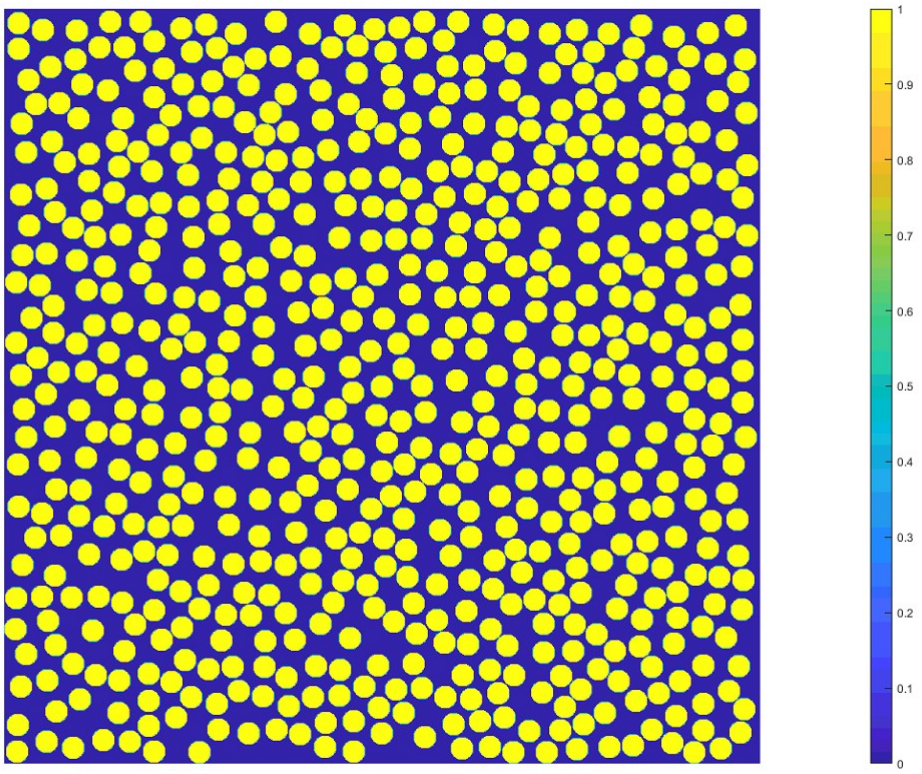


fig: Geometry for the 2D simulation

The geometry is defined as an input image constructed in MATLAB. The image is a collection of random spheres with a constant diameter and random positions of centres of the spheres. We design the image according to the concentration of the mesh we used in our simulation. We use the image such that at the position of the spheres, the permeability and porosity values are incredibly high and at the pore spaces the values are lower in comparison to the spheres. We define the permeability and porosity according to the pixel values from the image. The pixel values inside the spheres is 1 and outside the spheres is 0.

We also proved that such an approach is working when we compared the results of a 2D porous media geometry and one image of the porous media having the same initial and boundary conditions for a flow. It can be seen that both of them were giving similar values of velocity and concentration. We import the image of

the porous media genrated in MATLAB to OpenFOAM by input of the image as a matrix and as a constant value. The image has been written in OpenFOAM as a "$nonuniformList < scalar >$ " in the constant folder. Later for the sake of parallel processing it has been developed in the initial values folder with changes in the fvSchemes as a constant value.

For the equations used in OpenFOAM incorporating the image file,

UEqn:

```
rho0 * fvm::ddt(U)
      +rho0 * fvm::div(phi, U)
      -  fvm::laplacian(nu*epinv, U)
      + (0.01+Im) * U
      - g * c

solve(UEqn == -fvc::grad(p));
//PISO loop
.
...
cEqn :

epinv * fvm::ddt(c)
   + fvm::div(phi, c)
   -  fvm::laplacian(Dm * epinv , c)
   - a * fvm::laplacian(mag(U) ,c)
   - a/(pow(sqr(U.component(0))+sqr(U.component(1))+sqr(U.component(2))+sqr(s),0.5)
   - a/((mag(U)+s))*fvm::laplacian((U*U), c )
```

The initial condition for the concentration has been modelled in MATLAB. The top part concentration has been given as 1 and the lower part is 0 and the interface between the two different concentrations has been defined by an error function.

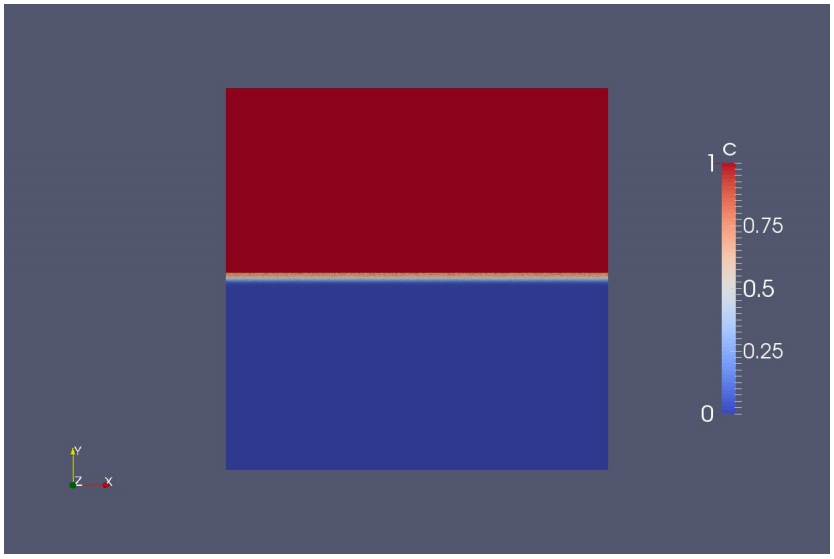


fig: Initial concentration condition

The initiation of the instability in the simulations are given in the following figure.

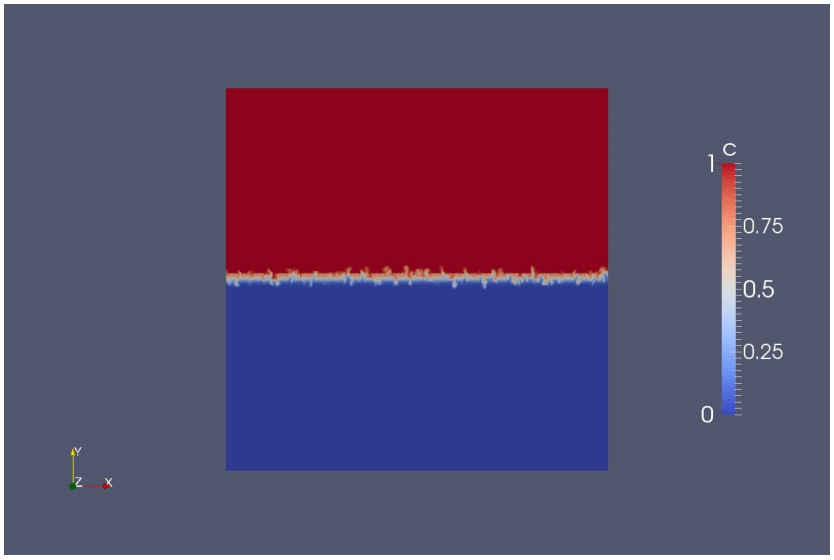


fig: Start of instability.

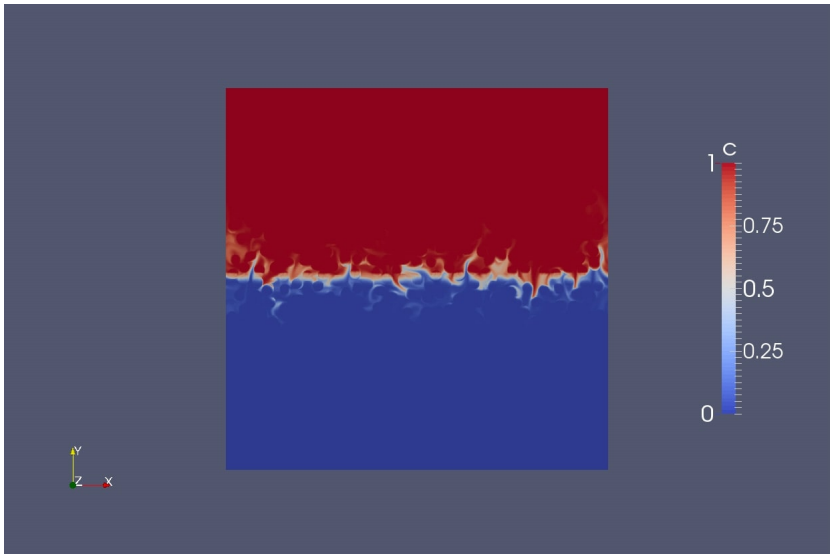


fig: At a later time.

Bibliography

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