Convective dissolution in porous media: experimental investigation in Hele-Shaw cell

Mobin Alipour1,2 and Marco De Paoli1,∗

1 TU Wien, Institut für Strömungsmechanik und Wärmetübertragung, Getreidemarkt 9, 1060 Wien, Austria
2 Università degli Studi di Udine, Dipartimento Politecnico di Ingegneria e Architettura, Via delle Scienze 206, 33100 Udine, Italy

The process of solutal convection in porous media is here studied experimentally in a Hele-Shaw cell. Motivated by the carbon sequestration process, potassium permanganate and water are used to mimic the dissolution of carbon dioxide in brine in underground geological formations. An optical method is used to accurately reconstruct the solute concentration. In this work, we examine the influence of different calibration conditions on the measurement of the solute dissolution rate and we provide indications to improve the accuracy of the technique.

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1 Introduction

The problem of convection in porous media received renovated attention due to its possible application to carbon dioxide (CO2) sequestration [1]. First, CO2 is made liquid and injected in underground geological formations. Afterwards, it eventually dissolves into the fluid that naturally fills the porous rocks (brine) and remains trapped. This system can be modelled as a rectangular Rayleigh-Bénard like configuration: The solute concentration is kept constant on top of the domain and all the other boundaries are close with respect to in- and out-going fluxes [2]. In the frame of carbon sequestration, the time taken to dissolved a certain amount of the CO2 injected is used as a safety indicator for the injection site. Therefore, this time is of crucial importance and it is estimated by computing the dissolution rate of CO2 in brine along the upper boundary.

In this work, we investigate experimentally the process of dissolution of CO2 in brine by means of Hele-Shaw apparatus. With the aid of an optical method, we reconstruct the solute concentration field and estimate the dissolution rate. Finally, we analyse the impact of different calibration strategies on the dissolution rate measurement.

2 Methodology

The experiments are performed in a Hele-Shaw cell (Fig. 1a), consisting of two transparent glasses (thickness 30 mm, width \(L = 160\) mm, height \(H = 350\) mm) divided by a thin gap \(b\) where the fluid is injected, with \(0.3 \text{ mm} < b < 1.0 \text{ mm}\). The cell is illuminated with a tailor-made LED-based panel that provides uniform light intensity over the entire surface. We used an aqueous solution of potassium permanganate (KMnO4) and water as analogues fluids for CO2+brine solution and brine respectively. These fluids, which have already been chosen for previous investigations in the same configuration [3], are characterised by the same viscosity \(\mu\) and have the advantage of a linear dependency of density with respect to concentration, which reflects the behaviour of a CO2+brine mixture. Grains of KMnO4 are distributed along the upper boundary of the cell, where a stainless steel grid is placed (grid size \(< 200 \mu\text{m}\)). With the aid of a syringe pump, water is injected from two channels located at the bottom of the cell. When the water level is increased up to the top of the cell, the dissolution process of KMnO4 in water takes places and finger-like structures form. The evolution of the system is recorded with a high-resolution camera (3456×5184 px) at 1 frame per second. The frames (Fig. 1b) are then processed with an in-house code and the concentration field \(C\) is finally reconstructed (Fig. 1c).

After reconstruction, which is based on the results of the calibration process (see [3] and references therein for a detailed description of the reconstruction algorithm), the solute dissolution flux \(F^*\) is finally computed as

\[
F^* = \frac{1}{bL} \frac{\partial M}{\partial t} \quad \text{where} \quad M = b \int_C CS \quad \text{and} \quad S \text{ is the surface of the cell.} \quad (1)
\]

3 Results

The illumination system has been designed to achieve different light intensities by tuning the voltage applied to the LEDs. The light intensity is indeed of crucial importance for the accuracy of the calibration process. An example of different calibration curves obtained in correspondence of three values of the voltage applied is shown in Fig. 2a). The value of light intensity has been chosen to optimise the sensitivity of the measurement setup over the entire range of light intensities (Fig. 2b).
The governing parameter of the system is the Rayleigh number $Ra$, which represents a measure of the relative importance of buoyancy compared to diffusion, and is defined as $Ra = g\Delta \rho Hb^2/(12\mu D)$, being $\Delta \rho$ the maximum density difference between the fluids, $D$ the solute diffusivity and $g$ the acceleration due to gravity. We performed experiments at $5 \times 10^4 < Ra < 6 \times 10^6$. For $Ra > 10^7$, the evolution of the system can be divided in three main regimes [2]: Diffusion-dominated, convection-dominated and saturation. In this work, we focus on the convection-dominated part, which is characterised by a constant flux and occurs approximately when the finger size is smaller than the cell height. The flux, computed has in Eq. (1) and averaged in time, is reported in Fig. 2c) for four different values of the gap thickness $b$, repeating the calibration for each gap thickness. Therefore, we assume this value $F^*$ as a reference value for each thickness $b$. If the flux is estimated without repeating the calibration, the error is up to 400% (Fig. 2d). For instance, the flux $F$ computed for $b = 1.0$ mm with the calibration obtained for $b = 0.3$ mm is approximately 4 times larger than the correspondent $F^*$ obtained with the calibration curve found for $b = 1.0$ mm.

4 Conclusions

We investigated experimentally the convective dissolution process in a Hele-Shaw cell. From the analysis of different calibration conditions, we observe that both light intensity and gap thickness have a strong influence and may lead to a significant under/overestimation of the convective dissolution rate.

References

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