Contribution ID: **309** Type: **Oral Presentation**

CO_2 Mass Transfer in Porous Media: Implications for Long-Term Carbon Sequestration in Saline Aquifers

Wednesday, 21 May 2025 12:35 (15 minutes)

A critical aspect of carbon sequestration involves understanding the transport and trapping mechanisms that influence the long-term stability of injected CO_2. Among these, solubility trapping, driven by the diffusion and convection of CO_2 in the aqueous phase, plays a pivotal role in enhancing the sequestration security of saline aquifers. This study investigates the dissolution of CO_2 in aqueous solutions within porous media using transmitted light visualization techniques. Experiments were conducted over a period of at least 96 hours in a sealed visualization cell designed to ensure system stability and enable precise monitoring. The porous media consisted of capillary tubes filled with bulk water and water-saturated glass beads of specified grain sizes. These media were saturated with pH-sensitive solutions to enable visualization of chemical changes. To maintain constant system pressure, CO_2 was continuously supplied to the visualization cell, compensating for gas mass transfer into the aqueous phase. The inflow of CO_2 was rigorously monitored in real-time, ensuring accurate control of the process. As CO_2 dissolved into the aqueous phase, it formed an acidic solution, resulting in a measurable change in the color of the pH-sensitive solution. This colour change, indicative of pH variation, was continuously captured and analyzed to provide insights into the dynamics of CO_2 dissolution and its interaction with the porous media. Our experimental methodology enabled a comprehensive analysis of CO_2 mass transfer dynamics under two distinct conditions: (1) diffusive mass transfer supported by natural convection and (2) diffusive mass transfer with density-driven convection suppressed. Key observations were made by measuring the velocity of the gas-liquid interface, which reflects diffusive mass transfer, and by characterizing natural convection through parameters such as the onset time of convection, mass flux, and flow dynamics. The study explored the influence of salinity (NaCl), gas contaminants (N_2), and the grain size of porous media on CO_2 dissolution behavior. Results revealed that as the average grain size of the porous medium decreases, natural convection has a diminishing role in enhancing the dissolution process compared to diffusion alone. Specifically, smaller grain sizes led to a delayed convection onset time, which in turn reduced the convection-driven mass flux. This highlights the critical role of pore-scale interactions in influencing convective dynamics. Salinity was found to significantly impact the onset time of convection, as it directly affects key parameters such as fluid density, effective molecular diffusivity (affected by pore size), and viscosity. Increased salinity delayed the onset of convection, altering the balance between diffusive and convective mass transfer mechanisms. Additionally, the presence of even small concentrations of N_2 as a gas contaminant adversely affected overall CO_2 dissolution rates, underscoring the importance of gas purity in mass transfer processes. This study presents a novel experimental approach based on light transmission techniques to investigate CO_2 mass transfer dynamics in aqueous solutions within porous media. The insights gained from this work are critical for evaluating the efficacy of solubility trapping, a key mechanism for the secure and long-term storage of CO_2 in geological formations.

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References

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Session Classification: MS01

Track Classification: (MS01) Porous Media for a Green World: Energy & Climate