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Incremental CO_2 Immobilization with Ionic Liquid Co-Injection in a Stratigraphically Layered Closed Carbonate System: CMG-GEM Simulation of the Alida Formation, Williston Basin

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Summary

Carbon capture and storage (CCS) in carbonate reservoirs of the Williston Basin has been extensively investigated in the context of long-term containment, particularly in relation to residual and capillary trapping mechanisms operating after injection has ceased. Field-scale projects and numerical studies in the Midale–Weyburn and Alida carbonate systems have demonstrated that storage security in these formations is governed primarily by post-injection immobilization rather than structural trapping alone (Bachu, 2000; Whittaker et al., 2011; Rostron et al., 2014). The Alida Formation, a shallow-marine Mississippian carbonate unit, exhibits pronounced stratigraphic layering and vertical heterogeneity that strongly influence multiphase flow and CO_2 redistribution during long-term storage.

Previous experimental and modeling studies have shown that capillary trapping and relative-permeability hysteresis are dominant controls on residual CO_2 immobilization in carbonate reservoirs under closed or semi-closed boundary conditions (Juanes et al., 2006; Bennion and Bachu, 2008; Krevor et al., 2015). These processes are particularly relevant to the Alida carbonate system, where low vertical permeability contrasts and laterally extensive sealing units limit pressure dissipation and promote long-term trapping.

In parallel, ionic liquids have been widely studied as advanced solvents for post-combustion CO_2 capture due to their strong CO_2 affinity and tunable interfacial properties (Bera and Belhaj, 2016; Zhang et al., 2017). Recent studies have suggested that ionic liquids may also influence subsurface multiphase flow behavior by modifying interfacial tension and wettability, with potential implications for residual trapping efficiency in carbonate formations (Osman et al., 2016; Salama et al., 2025). However, their role in geological CO_2 storage remains poorly constrained at the reservoir scale.

In this study, a compositional CMG-GEM model was developed to represent a fully closed, stratigraphically layered carbonate system of the Alida Formation in the Williston Basin. The modeling framework follows established CCS simulation practices used in Weyburn–Midale and Alida studies, incorporating hysteresis-enabled relative permeability to capture residual trapping behavior. Three scenarios were evaluated under identical geological and operational constraints: pure CO_2 injection, CO_2 with 10% ionic liquid, and CO_2 with 50% ionic liquid. All cases were simulated with five years of injection followed by approximately 995 years of shut-in.

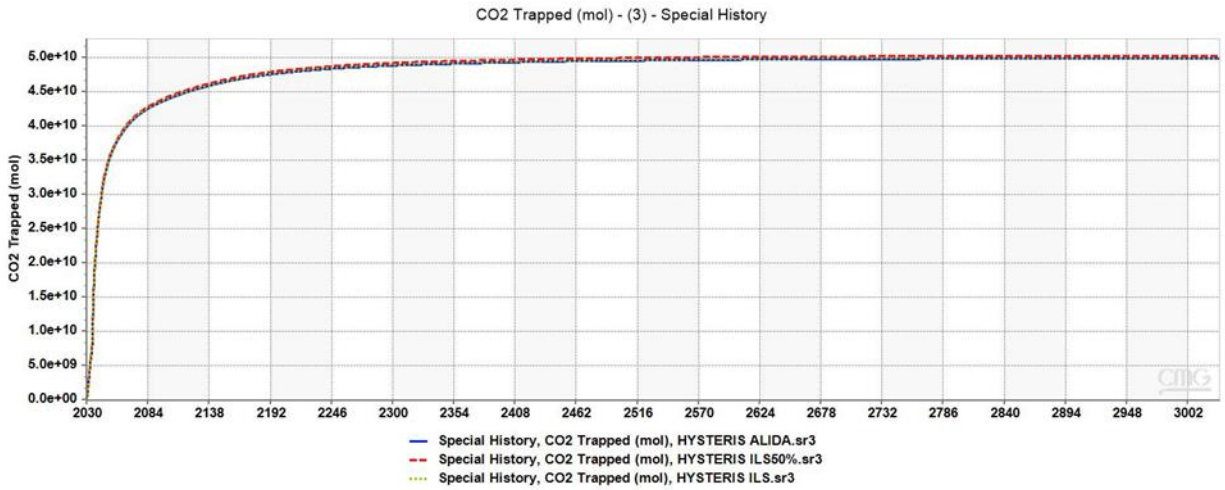


Fig 1: Long-Term CO_2 Trapping Evolution with Ionic-Liquid Co-Injection

As shown in Fig. 1, trapped CO_2 increases rapidly during injection and continues to grow throughout the post-injection period, confirming that immobilization is dominated by capillary trapping and hysteresis effects. Ionic-liquid co-injection produces a small but systematic increase in long-term trapped CO_2 relative to the base case, with the magnitude of enhancement scaling with ionic-liquid fraction. These results are consistent with prior CCS studies in the Williston Basin that emphasize the dominant role of post-injection redistribution processes in closed carbonate systems and demonstrate that ionic-liquid co-injection may provide an incremental enhancement to storage security in the Alida Formation.

Theory / Method / Workflow

Geological CO_2 storage in carbonate reservoirs is controlled primarily by post-injection immobilization mechanisms, including capillary trapping and relative-permeability hysteresis, rather than structural trapping alone (Bachu, 2000; Bennion and Bachu, 2008; Juanes et al., 2006). Field-scale experience from the Weyburn–Midale CO_2 storage project in the Williston Basin demonstrates that long-term storage security is governed by redistribution and trapping after injection has ceased (Whittaker et al., 2011; Rostron et al., 2014).

A compositional reservoir simulation was conducted using CMG-GEM to represent a fully closed, stratigraphically layered carbonate system of the Alida Formation. Stratigraphic layering and vertical heterogeneity were included to reflect carbonate flow-unit partitioning. Relative-permeability hysteresis was enabled to capture residual CO_2 trapping during post-injection imbibition, consistent with established CCS modeling practice (Juanes et al., 2006; Krevor et al., 2015).

Three injection scenarios were evaluated under identical geological and operational conditions: pure CO_2 injection (base case), CO_2 with 10% ionic liquid, and CO_2 with 50% ionic liquid. The inclusion of ionic liquids was motivated by prior studies demonstrating their strong CO_2 affinity and potential influence on interfacial behavior in carbonate systems (Bera and Belhaj, 2016; Zhang et al., 2017; Osman et al., 2016; Salama et al., 2025). All cases were simulated with five years of injection followed by approximately 995 years of shut-in, and analysis focused on the temporal evolution of trapped CO_2 mass.

Results, Observations, and Conclusions

Simulation results indicate that CO_2 immobilization in the Alida carbonate system is dominated by residual and capillary trapping during the post-injection period. As shown in Fig. 1, trapped CO_2 increases rapidly during the five-year injection phase and continues to grow after injection ceases, reflecting hysteresis-controlled immobilization under closed-system conditions.

At approximately 1,000 years, the base-case simulation (pure CO_2) yields a trapped CO_2 inventory of 4.982×10^{10} mol. Co-injection with ionic liquids produces a small but systematic increase in long-term trapping, with trapped CO_2 reaching 4.988×10^{10} mol (+0.11%) for the 10% ionic-liquid case and 5.021×10^{10} mol (+0.78%) for the 50% ionic-liquid case. Across all scenarios, approximately 80–85% of the final trapped CO_2 forms during the post-injection period, highlighting the dominant role of redistribution and imbibition-driven trapping rather than injection-phase processes.

The similarity in trapping trajectories among the three cases indicates that carbonate storage performance is primarily controlled by reservoir architecture, stratigraphic layering, and hysteresis effects. Ionic-liquid addition does not alter the fundamental trapping mechanism but provides an incremental enhancement that scales with ionic-liquid fraction. These results suggest that ionic-liquid co-injection may offer a modest additive improvement to long-term storage security in closed carbonate systems, while overall containment remains governed by established multiphase flow and trapping processes.

Novel/Additive Information

This work applies established carbonate CO_2 trapping theory to evaluate whether ionic-liquid co-injection enhances long-term CO_2 immobilization, building directly on prior studies of hysteresis-controlled trapping in carbonate reservoirs (Bachu, 2000; Bennion and Bachu, 2008; Juanes et al., 2006; Krevor et al., 2015) and recent investigations into the role of ionic liquids in modifying CO_2–brine–rock interactions in carbonate systems (Osman et al., 2016; Bera and Belhaj, 2016; Zhang et al., 2017; Salama et al., 2025).

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