Influence of Intermittent CO_2 Injection on Flow Functions in Chalk Reservoirs

Introduction

Depleted chalk reservoirs in the North Sea are increasingly being considered as promising candidates for geological CO_2 storage due to their large storage capacity, existing infrastructure, and extensive subsurface characterization (Bonto et al., 2021). Several depleted hydrocarbon fields located in the Danish and Norwegian sectors are currently being evaluated for long-term CO_2 storage, making accurate prediction of injectivity, storage efficiency, and trapping mechanisms essential for safe and effective project development. In such systems, multiphase flow behaviour strongly influences pressure propagation, plume migration, residual trapping, and ultimately the amount of CO_2 that can be securely retained within the reservoir.

Accurate prediction of these processes requires representative descriptions of relative permeability and capillary pressure functions, which govern the displacement of formation fluids by injected CO_2 (Besua et al., 2025). Previous studies have demonstrated that hysteresis plays a key role in controlling residual trapping, plume migration, and long-term CO_2 immobilization (Khoramian et al., 2024). Consequently, reliable characterization of hysteretic multiphase flow properties is critical for reservoir-scale simulation and storage performance assessment.

Although significant progress has been made in characterizing CO_2–brine relative permeability and hysteresis effects, limited experimental evidence exists regarding the effective flow functions associated with intermittent injection and repeated drainage–imbibition cycles representative of field-scale storage operations, particularly in low-permeability chalk reservoirs and other fine-grained carbonates. Operational interruptions may occur due to pressure management requirements, infrastructure constraints, or variable CO_2 supply, resulting in cyclic injection conditions that differ substantially from the continuous flooding scenarios commonly employed in laboratory studies. Under such conditions, repeated drainage–imbibition cycles may alter both capillary trapping behaviour and the effective flow functions used in reservoir simulation.

The objective of this study is therefore to investigate the impact of continuous and intermittent CO_2 injection on the relative permeability characteristics of low-permeability North Sea chalk through numerical history matching of laboratory core flooding experiments. Particular emphasis is placed on identifying the role of hysteresis and evaluating how intermittent injection influences the effective flow functions used for predicting injectivity and storage performance.

Method

Two CO_2 flooding experiments conducted on North Sea chalk cores were selected for analysis. The experiments were conducted on two North Sea chalk composite cores with porosities of approximately 28% and permeabilities of 0.55 and 0.64 mD, respectively. The tests were conducted under representative reservoir pressure and temperature conditions. The first experiment represented continuous CO_2 injection, during which approximately 20 pore volumes of CO_2 were injected under reservoir conditions. The second experiment employed an intermittent injection strategy involving multiple injection and shut-in periods designed to mimic cyclic field operations.

A one-dimensional numerical model was developed to reproduce the laboratory observations. Relative permeability and capillary pressure functions were estimated through history matching differential pressure and production data. The experimental data were interpreted using a two-stage numerical history-matching workflow. Initial estimates of relative permeability parameters were obtained through automated history matching using the SENDRA coreflood simulator. The resulting flow functions were subsequently transferred to a compositional ECLIPSE E300 model for refinement and validation under reservoir conditions.

The numerical model consisted of a one-dimensional representation of the core sample and incorporated a three-component system comprising CO_2, H_2O, and NaCl to account for brine composition. Fluid properties were described using the Peng–Robinson equation of state, allowing the model to account for both CO_2 dissolution into brine and water vaporization into the CO_2 phase. The capillary pressure function was obtained from MICP measurements and transformed to equivalent CO_2–brine conditions using the Laplace scaling relationship, assuming constant interfacial tension and contact angle. Relative permeability was represented using LET correlations (Lomeland et al., 2005), while capillary pressure was described using the Brooks–Corey formulation (Brooks and Corey, 1964). The calibrated models were constrained using measured differential pressure and production data, with particular focus on identifying the flow functions required to reproduce the different responses observed during continuous and intermittent injections.

Results & Discussion

The numerical models successfully reproduced the pressure and saturation evolution observed during both the continuous and intermittent CO_2 injection experiments (Figures 1a and 1b). The history-matched relative permeability and capillary pressure functions obtained for the continuous injection case are presented in Figure 1c. The estimated curves exhibit a gradual decline in water relative permeability and a corresponding increase in CO_2 relative permeability during drainage.

A comparison between the continuous injection experiment and the first drainage cycle of the intermittent injection experiment (Figure 1c) reveals a close agreement in the estimated relative permeability functions despite differences in absolute permeability between the two core samples (0.64 and 0.55 mD, respectively). Since porosity remained nearly identical in both experiments, the similarity of the derived flow functions suggests that multiphase flow behaviour in these tight chalk samples is primarily governed by capillary forces. This interpretation is further supported by the comparable pressure and saturation evolution observed during the initial drainage stage (Figures 1a and 1b).

In contrast, the intermittent injection experiment required the introduction of hysteretic flow functions to reproduce the observed response. Repeated injection and shut-in periods promoted drainage–imbibition transitions and progressive fluid redistribution within the pore space. Figure 1d presents the relative permeability functions estimated for the first and second drainage cycles. While only minor variations are observed in the gas relative permeability curves, progressive changes occur in the water relative permeability functions as the injection cycles proceed. These changes reflect the increasing amount of residually trapped CO_2 remaining in the pore space following each imbibition period.

The influence of hysteresis becomes more apparent when comparing the first drainage and final imbibition cycles (Figures 1e and 1f). The gas relative permeability functions remain largely unchanged, whereas the water relative permeability curve shifts systematically towards higher water saturations while preserving a similar overall shape. This behaviour suggests that the accumulated trapped CO_2 progressively reduces the pore volume available for water flow, resulting in increasing residual gas saturation from cycle to cycle. Consequently, the endpoint saturations evolve throughout the intermittent injection process, leading to a systematic rightward shift of the water relative permeability relationship.

A key finding from both the experimental observations and the numerical history matching is that the flow behaviour was primarily controlled by capillary pressure hysteresis rather than changes in gas relative permeability. This is evident from the pronounced separation between drainage and imbibition capillary pressure functions shown in Figure 1f, compared with the relatively small differences observed in the corresponding gas relative permeability curves (Figure 1e). The results therefore suggest that the principal impact of intermittent injection is the progressive accumulation of trapped CO_2 and the associated capillary pressure hysteresis, rather than a fundamental alteration of the flow characteristics of the gas phase.

These findings have important implications for reservoir simulation studies. Flow functions derived solely from conventional continuous injection experiments may not adequately represent cyclic field-scale injection scenarios where repeated drainage–imbibition processes occur. Dedicated characterization of hysteretic relative permeability and capillary pressure relationships may therefore be required to improve predictions of injectivity, plume migration, residual trapping, and long-term storage efficiency in low-permeability chalk reservoirs.

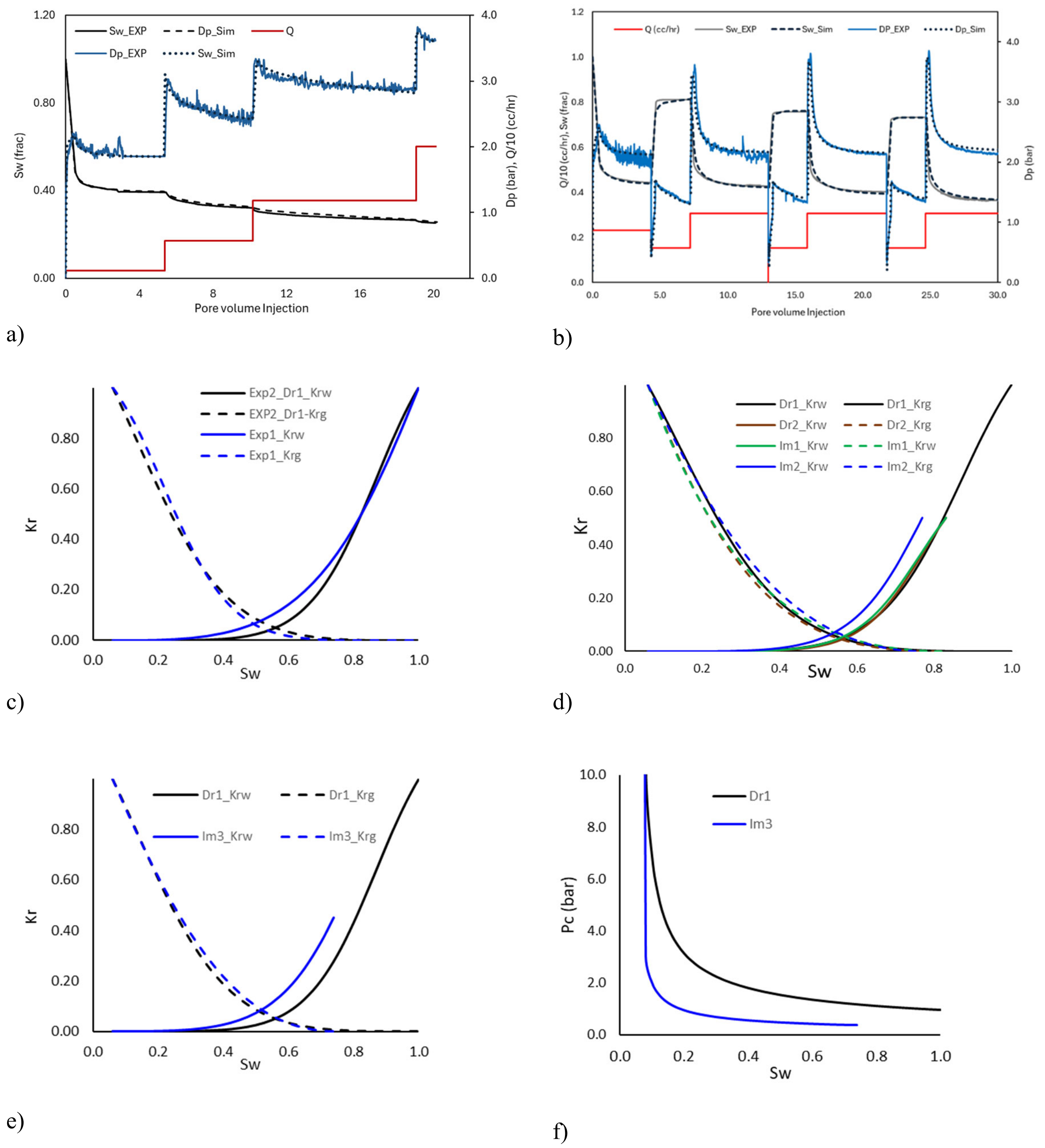

Figure 1 *Numerical history matching and estimated flow functions for continuous and intermittent CO_2 injection in low-permeability chalk. (a–b) Comparison of measured and simulated pressure and saturation profiles. (c) Relative permeability and capillary pressure functions for continuous injection. (d) Evolution of relative permeability during successive drainage cycles. (e) Comparison of relative permeability functions from the first drainage and final imbibition cycles. (f) Corresponding capillary pressure functions illustrating hysteresis effects.*

Conclusions

Numerical history matching of continuous and intermittent CO_2 injection experiments demonstrated that injection strategy influences the effective flow functions governing multiphase flow in chalk formations. Intermittent injection generated pronounced hysteresis effects and progressive accumulation of trapped CO_2, expressed primarily through capillary pressure behaviour and shifts in water relative permeability. The results indicate that flow functions derived from continuous flooding experiments may not be representative of cyclic field-scale injection operations and should be complemented by hysteretic flow-property characterization when assessing CO_2 storage performance in chalk formations.

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