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Advancing CO_2 Huff-and-Puff Simulation in Tight Reservoirs: Critical Gaps and Optimization Strategies

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تطوير محاكاة حقن واسترجاع ثاني أكسيد الكربون (حقن – نقع – إنتاج) في المكامن منخفضة النفاذية: الفجوات الحرجة واستراتيجيات التحسين

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الملخص:
تقدّم هذه الدراسة تقييماً نقدياً لنمذجة طريقة الحقن والاسترداد بثاني أكسيد الكربون (حقن- نقع – إنتاج) لتحسين إنتاج النفط في المكامن منخفضة النفاذية، مع التركيز بشكل خاص على المنهجية المتبعة في دراسة سابقة حول هذا الموضوع. وعلى الرغم من أن نتائج تلك الدراسة — التي أشارت إلى أن مدة النقع المثلى هي 21 يوماً ودورتين من الحقن تحققان معامل استرجاع بنسبة 22.96% — تتماشى مع البيانات التجريبية، إلا أن موثوقية النموذج التنبؤية محدودة بسبب عدة تبسيطات منهجية.
ومن أبرز أوجه القصور: تمثيل مبسط للكسور، ضعف توصيف الخصائص البتروفيزيائية، افتراضات غير مؤكدة حول عدم الامتزاج، ثبات معلمات الحقن، وتحليل محدود للحساسية .وللتغلب على هذه القيود، تقترح الدراسة إطاراً تكاملياً للنمذجة يشمل:
-تمثيل الكسور بشكل صريح باستخدام نماذج**EDFM/DFM** ، - تقييم دقيق للامتزاجية من خلال نمذجة معادلة الحالة **(EOS)**وتجارب الأنبوب الرفيع**(Slim-tube)** ، - بروتوكولات حقن ديناميكية - تحليل متقدم للمعاملات باستخدام تصميم التجارب**(DOE)** ، - وتقييمات تكاملية تقنية اقتصادية وكربونية.
ويُظهر هذا النهج المطوّر كيف أن دمج مبادئ تحسين إنتاج النفط **(EOR)** مع نمذجة المكامن المتشققة يمكن أن يؤدي إلى استراتيجيات تطوير أكثر موثوقية وقابلة للتطبيق ميدانياً.

الكلمات الدالة: منهجية، فجوات، موثوقية، تحسينات، محاكاة.

Abstract
This study provides a critical evaluation of CO_2 Huff-and-Puff (HnP) modeling for enhanced oil recovery in tight reservoirs, with particular attention given to the methodology adopted in a previous study on this topic. Although their findings indicating an optimal 21-day soaking period and two injection cycles yielding a 22.96% recovery factor are consistent with empirical data, the predictive reliability of their model is limited by several methodological simplifications. Notable shortcomings comprise oversimplified fracture representation, insufficient petrophysical characterization, unvalidated immiscibility assumptions, static injection parameters, and limited sensitivity analysis. To overcome these constraints, an integrated modeling framework is proposed, which includes: explicit

fracture modeling using Embedded and Discrete Fracture Models (EDFM/DFM); rigorous miscibility evaluation through Equation of State (EOS) modeling and slim-tube experiments; dynamic injection protocols; advanced parametric analysis employing Design of Experiments (DOE); and integrated techno-economic and carbon intensity assessments. This refined approach illustrates how the integration of established EOR and fractured reservoir modeling principles can lead to more reliable and operationally feasible field development strategies.

Keywords: Methodological, Gaps, Reliability, Enhancements, Simulation.

Introduction

CO_2 EOR mechanisms including oil swelling, viscosity reduction, and interfacial tension reduction are well-established across light to heavy oils. Huff-and-puff has gained attention for tight reservoirs, where single-well cyclic operations enable staged implementation and monitoring (Monger & Coma, 1988; Green & Willhite, 1998; Song & Yang, 2013; Wei-Yu Tang et al., 2023). Advances in compositional simulation and fracture-aware modeling have improved predictive capability in unconventional settings, though results remain sensitive to heterogeneity, fracture connectivity, and operational parameters (Karimi Fard et al.; Moinfar et al., 2014).

In their tight light-oil reservoir study using CMG GEM, Abdurahman et al. (2019) identified a 21-day soaking period and two huff-and-puff cycles as optimal, reporting a 22.96% recovery factor consistent with earlier lab and field results (Monger & Coma, 1988; Yu et al., 2014; Li et al., 2016). However, methodological constraints such as a narrow permeability range (1–26.2 mD), a simplified 15×15×2 grid, and static fluid-rock properties limit the generalizability of their findings and obscure the full optimization potential.

1. The primary objectives of this paper are:

- provide a structured, evidence based critique of the modeling assumptions and experimental design in Abdurahman et al. (2019).
- quantify how each limitation could bias predicted performance.
- propose a practical, literature anchored pathway to more credible and field transferable Huff-n-Puff optimization in tight reservoirs.

2. Importance and Impact of this Research:

Tight reservoir Huff-n-Puff results are acutely sensitive to miscibility, fractures, and rate/pressure controls. Clarifying best practice modelling and optimization steps is essential to bridge simulation results with operational decisions and investment grade techno economics (Green & Willhite, 1998; Song & Yang, 2013).

Methodology:

1.Critical appraisal framework

- This work involved a structured appraisal of Abdurahman et al. (2019) across six diagnostic dimensions commonly linked to forecast reliability in cyclic gas EOR:
- Model representativeness: grid scale, heterogeneity, and fracture representation (Karimi Fard et al., 2004; Liyong Li; Seong H. Lee.(2008); Moinfar et al., 2014).
- Geological/petrophysical completeness: stratigraphy, wettability, capillary pressure and relative permeability (Leverett, 1941; Tiab & Donaldson, 2015).
- Phase behaviour and miscibility: EOS fidelity and MMP quantification (Yellig & Metcalfe, 1980; Song & Yang, 2013).
- Operational variability: injection rate/pressure strategies and injectivity diagnostics (Green & Willhite, 1998).
- Design space and uncertainty: soaking time, cycles, and sensitivity/DOE coverage (Li et al., 2016; Yu et al., 2016).
- Economic viability: coupling results to cost and carbon constraints (Yerdaulet et al., 2022).

2. Source scope

Primary target paper: Abdurahman et al. (2019). Supporting literature: peer reviewed articles, SPE papers, and textbooks widely used in EOR and fractured reservoir simulation.

3. Case synopsis: Abdurahman et al. (2019)

- Simulator and model: CMG GEM compositional model on a 15×15×2 grid (~10 acres), described as "simple and heterogeneous."
- Fluid and reservoir: light oil; tight permeability.
- Operational setup: CO_2 Huff-n-Puff with immiscible assumption; constant injection rate of 11.8 MSCF/d. Soaking times: 7, 21, 35 days. Cycle counts: 2 vs 3. Total injection time reportedly held constant across cycle cases.
- Reported outcomes: optimum soak = 21 days; optimum cycles = 2; RF = 22.96% versus baseline RF = 5.82%. The paper also mentions an "initial RF" around 21.69%, which conflicts with the stated 5.82% baseline an inconsistency requiring clarification in any benchmarking or incremental calculations.

Directionally, the 21 day optimum and superiority of fewer, longer cycles comport with published cyclic CO_2 behaviour in light oils (Monger & Coma, 1988; Yu et al., 2014; Li et al., 2016). The core question is how reliably those optima transfer to field conditions given the modelling constraints.

RESULTS:

1.Simplified model and missing fracture physics

- Issue: A 15×15×2 grid over ~10 acres without explicit fracture representation cannot capture multi scale connectivity, anisotropic flow, or sorption diffusion pathways that dominate tight reservoir Huff-n-Puff
-Why it matters: In Huff-n-Puff, fracture geometry and matrix–fracture exchange control CO_2 access, dissolution kinetics, and imbibition/expulsion during cycles. Ignoring these effects biases pressure transient behavior, sweep, and incremental oil forecasts.

Remedy: Adopt fracture aware methods such as DFM (Karimi Fard et al., 2004) or EDFM (Li & Lee, 2008; Moinfar et al., 2014), and calibrate fracture intensity/orientation to geological constraints.

2.Incomplete geological and petrophysical inputs

- Issue: No stratigraphic layering, wettability, capillary pressure, or rel perm data were reported.
- Why it matters: Capillary pressure and wettability govern saturation distributions and counter current flow central to Huff-n-Puff productivity in tight rocks (Leverett, 1941; Dullien, 1992; Tiab & Donaldson, 2015). Missing layering suppresses baffles/barriers that modulate pressure communication and CO_2 residence time.

Remedy: Include Pc and rel perm functions consistent with rock type and wettability; represent vertical/lateral heterogeneity from
depositional architecture; document initial water saturation and contact positions.

3.Immiscible assumption without MMP justification

- Issue: The model assumes immiscible injection despite light oil classification and no reported MMP estimate.
- Why it matters: Light oils frequently achieve miscibility near feasible pressures; miscible/supercritical operation typically increases extraction via swelling and IFT reduction, altering optimal soak and cycle design (Yellig & Metcalfe, 1980; Song & Yang, 2013; Monger & Coma, 1988; Yu et al., 2014).

Remedy: Estimate MMP using EOS and/or slim tube tests; simulate cases at/beyond MMP and compare to immiscible scenarios to quantify incremental value and operational risk.

4.Fixed injection rate across scenarios

- Issue: Constant 11.8 MSCF/d was applied in all cases.
- Why it matters: Rate dependent injectivity and pressure evolution (including near wellbore fracturing or choked flow) are critical in tight formations; holding rate constant masks optimal rate–pressure windows and misrepresents stress sensitive permeability (Green & Willhite, 1998; Kong et al., 2016).

Remedy: Perform multi rate sensitivity and pressure constrained cases; analyze rate pressure response to identify sustainable operating envelopes and cycle time interactions.

5.Narrow soaking time and cycle sweeps

- Issue: Only three soak durations (7/21/35 days) and two cycle counts (2/3) were tested.
- Why it matters: Recovery response is nonlinear; threshold and diminishing return behaviors depend on diffusion, dispersion, pressure depletion/recharge, and fracture–matrix exchange. Sparse design risks local optima (Li et al., 2016; Yu et al., 2016; Kong et al., 2016).

Remedy: Expand to, e.g., 3–60 days soaking and 1–5+ cycles; use DOE to map interactions among soak, rate/pressure, and cycle timing.

6.No uncertainty, sensitivity, or economic analysis

- Issue: No systematic sensitivity or techno economics.
- Why it matters: Decision quality hinges on parameter uncertainty (Pc/rel perm, MMP, fracture intensity) and the cost/benefit of additional CO_2, time, and cycles, particularly under carbon constraints (Saltelli et al., 2008; Abuov et al., 2022).

Remedy: Apply global sensitivity analysis and Monte Carlo on key inputs; couple with NPV and cost per barrel metrics under CO_2 price/tax scenarios.

DISCUSSION:

The authors' central qualitative results existence of an optimal soak length and a preference for fewer, longer cycles under some conditions are consistent with prior lab and field observations in light oil Huff-n-Puff. However, modelling choices likely compress variability and obscure alternative optima:

-Underestimating fracture controlled transport can overstate or understate soak benefits depending on actual connectivity and matrix transfer.

-Ignoring miscible operation may underpredict incremental oil and distort cycle timing if near MMP pressures are feasible.

-Fixed rates miss the interplay between injectivity, reservoir stress state, and cycle design; allowing pressure constrained injection can reposition optima and improve operational feasibility.

-Sparse sweeps can misidentify local optima; DOE based exploration commonly reveals interactions among soak, rate, and cycles not visible in one factor at a time designs.

Conclusion:

The study by Abdurahman et al. (2019) provides a useful compositional simulation exploration of soak time and cycle count for CO_2 Huff-and-Puff in a light-oil tight reservoir, identifying a 21-day soak and two cycles as operationally favorable. However, the model's simplicity including the absence of fracture physics, essential petrophysical inputs, an unexamined immiscibility assumption, a fixed-rate design, narrow parameter sweeps, and a lack of uncertainty and economic analysis limits its predictive strength and field transferability.

The scientific impact of this critical review is manifold:

1. Identification of Critical Methodological Gaps: This analysis provides a structured, diagnostic framework for critically evaluating Huff-and-Puff simulation studies, systematically highlighting specific limitations that undermine the reliability and generalizability of their predictions.

2. A Practical Pathway for Enhanced Fidelity: Beyond critique, this work proposes an integrated and practical suite of remedies such as explicit fracture modelling (EDFM/DFM), rigorous miscibility evaluation via EOS and MMP, dynamic operational protocols, Design of Experiments (DOE), and integrated techno-economic assessment to significantly improve the predictive credibility of simulation models.

3. Bridging the Simulation-Field Application Gap: By addressing these constraints, this framework paves the way for more robust and reliable field development strategies. It enhances the confidence of industry practitioners in simulation results, thereby supporting better-informed operational and investment decisions.

4. Enriching Analytical Tools for the Field: This research advocates for the adoption of more sophisticated and comprehensive modelling practices in unconventional EOR studies. It contributes to the advancement of research and development methodologies in this critical domain by synthesizing established principles from fractured reservoir modelling, EOR, and uncertainty analysis into a coherent optimization strategy.

By embedding fracture-aware simulation, MMP-informed phase behaviour, dynamic rate/pressure design, DOE-driven exploration, and techno-economic screening, future studies can generate defensible, investment-grade guidance. The literature offers mature tools to implement these upgrades; the path to credible, field-ready CO_2 Huff-and-Puff optimization is both practical and clear.

Recommendations:

1. Modelling and Data:

- Represent fractures using EDFM/DFM and calibrate with geological, pressure, and historical production data.
- Incorporate capillary pressure (Pc), relative permeability, and wettability consistent with core/SCAL measurements or reliable analogs.

- Develop and validate a tuned Equation of State (EOS) and estimate the Minimum Miscibility Pressure (MMP).

2. Experiment Design and Optimization:

-Extend the range of soaking times (3–60 days) and cycles (1–5+), while jointly varying injection rate, injection pressure, and production drawdown.

- Apply Design of Experiments (DOE), response surface methods, and global sensitivity analysis to identify robust optimal conditions and quantify uncertainty.
- Benchmark results against published data and performance ranges to ensure reliability.

3. Operations and Economics:

- Evaluate pressure-constrained injections near or above MMP, defining safe and repeatable operational windows.
- Link simulation outputs to Net Present Value (NPV), cost per incremental barrel, and carbon price sensitivity.
- Consider using foam or chemical additives to enhance mobility control, especially in fracture-dominated systems.

4. Key Gaps, Remedies, and Expected Impact:

- Fracture representation: Use calibrated EDFM/DFM → More realistic pressure and soaking behavior.
- Pc/rel perm/wettability omission: Incorporate SCAL-based functions → Improved saturation and interfacial tension dynamics.
- Immiscible assumption: Tune EOS and estimate MMP → Better modelling of miscibility effects and higher recovery potential.
- Fixed injection rate: Employ variable rate/pressure design → More stable and feasible operations.
- Limited soaking/cycle tests: Apply DOE across parameters → Reveal nonlinear effects and avoid local optima.
- No sensitivity/economic analysis: Integrate global sensitivity and NPV coupling → More robust and decision-ready insights.

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