The Eurasia Proceedings of Science, Technology, Engineering & Mathematics (EPSTEM)
ISSN: 2602-3199

The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 2025

Volume 37, Pages 520-530

ICEAT 2025: International Conference on Engineering and Advanced Technology

Optimization of CO_2-Assisted Gravity Drainage Operational Parameters: Insights from a 2D Hele-Shaw Model

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Abstract: This study investigates the optimization of key operational parameters in the CO_2-Assisted Gravity Drainage (CO_2-AGD) process using a two-dimensional (2D) Hele-Shaw model packed with silica sand to mimic a bottom-water-drive oil reservoir. The experimental work varied two primary parameters—gas injection pressure and oil production rate—to assess their influence on oil recovery and gas breakthrough timing. A total of six experiments were conducted under constant-pressure conditions, and the results were analyzed using Response Surface Methodology (RSM) to develop predictive regression models. To navigate the trade-off between maximizing oil recovery and delaying gas breakthrough, a desirability function-based optimization was applied. The optimal condition was identified at an injection pressure of 1.3 psig and a fully opened production valve, yielding a predicted recovery of 79.3% and a breakthrough time of 157.7 minutes. These findings underscore the role of data-driven optimization in improving CO_2-AGD performance and guiding field-scale operational decisions in enhanced oil recovery (EOR).

Keywords: CO_2-assisted gravity drainage, Hele-shaw model, Enhanced oil recovery, Response surface methodology, Operational optimization

Introduction

Enhanced Oil Recovery (EOR) refers to advanced production techniques designed to increase oil recovery beyond what is achievable through primary and secondary phases, including water flooding and conventional gas injection. Typically, these methods recover less than one-third of the original oil in place (OOIP), with recovery rates often significantly lower in various reservoirs. EOR employs energy and specialized fluids to enhance recovery throughout different stages of reservoir depletion (Green & Willhite, 1998; Alvarado & Manrique, 2010). The implementation of these techniques is critical for prolonging the operational lifespan of mature fields and unlocking previously untapped reserves (Farouq et al., 1996; González-Salazar, 2015). Additionally, using Carbon dioxide (CO_2) as an injection gas in CO_2-EOR methods has attracted considerable interest in the oil and gas industry. This is attributed to the methods' notable recovery potential and their role in promoting environmental sustainability through Carbon Capture and Storage (CCS). This technique not only enhances oil recovery but also mitigates greenhouse gas emissions (GHG) due to the fact that over 95% of anthropogenic CO_2 utilized in EOR operations has the potential to be sequestered permanently in oil reservoirs (Melzer, 2012), making it a sustainable choice for energy extraction (Núñez-López & Moskal, 2019; Gulzar et al., 2020; Karimov & Toktarbay, 2024).

Despite the appeal of CO_2-EOR, conventional gas injection methods such as Water-Alternating-Gas (WAG) and Continuous Gas Injection (CGI) often suffer from early gas breakthrough and inefficient sweep, limiting their effectiveness in oil recovery (Fayers & Lee, 1992; Green &Paul Willhite, 1998; Kulkarni & Rao, 2004; Lake et al., 2014; Kumar & Mandal, 2017; Khan & Mandal, 2020; Koyanbayev et al., 2023). Consequently, and to address these limitations, Gas-Assisted Gravity Drainage (GAGD) has emerged as a novel approach that leverages gravitational forces to stabilize the gas front (Meszaros and Chakma, 1990 Rao et al., 2004; Ren et al.,2005), promoting natural segregation of fluids, leading to improved oil recovery, demonstrating superior performance compared to conventional methods (Ruiz Paidin, 2006; Mahmoud & Rao, 2007; Sharma & Rao, 2008; Rostami et al., 2010; Li et al., 2015; Al-Mudhafar, 2018; Al-Obaidi & Al-Jawad, 2020; Al-Obaidi et al., 2022; Al-Obaidi et al., 2024) Given CO_2 injection's advantages and its escalating significance within both the oil industry and carbon management strategies as a mature, well-commercialized method of secondary and tertiary oil extraction that has the potential to integrate oil production with CCS, CO_2-Assisted Gravity Drainage (CO_2-AGD), utilizes the displacement capabilities of CO_2 to enhance crude oil recovery. (Figure 1) visualizes the principle of the GAGD process mechanism, showing vertical gas injection wells and the horizontal producer positioned above the original oil-water contact (O.W.C). The schematic highlights the reservoir's vertical stratification, including the gas-invaded, oil, and underlying water zones.

While the fundamental mechanism of gravity drainage is well established, its success depends heavily on operational strategy, particularly regulating gas injection pressure and oil production rate. Improper management of these parameters can lead to unstable displacement fronts, early gas breakthrough, and reduced recovery efficiency. For instance, high injection pressures may induce viscous fingering or gas channeling. At the same time, excessive drawdown could lead to loss of frontal stability, resulting in gas injection failing to enhance oil recovery beyond levels obtained in primary depletion scenarios (Meszaros & Chakma, 1990;Jadhawar & Sarma, 2008). Yet, a visual, lab-scale experimental investigation that quantifies how varying gas injection pressures and oil production rates affect recovery and gas breakthrough within a bottom water-driven reservoir is especially lacking under constant-pressure injection conditions. Furthermore, no previous efforts have been made to identify the optimal range of these parameters through rigorous statistical modeling and multi-objective optimization, focusing on maximizing oil recovery while delaying gas breakthrough.

This research addresses these knowledge gaps through lab-scale experiments, evaluation of the impact of varying gas injection pressures and production rates on oil recovery and gas breakthrough behavior within a two-dimensional (2D) Hele-Shaw model that simulates the immiscible CO_2-AGD process in a bottom-water-drive reservoir. A structured optimization workflow based on RSM and desirability functions was employed to evaluate the trade-offs between maximizing oil recovery and delaying gas breakthrough using the R programming language within the RStudio software.

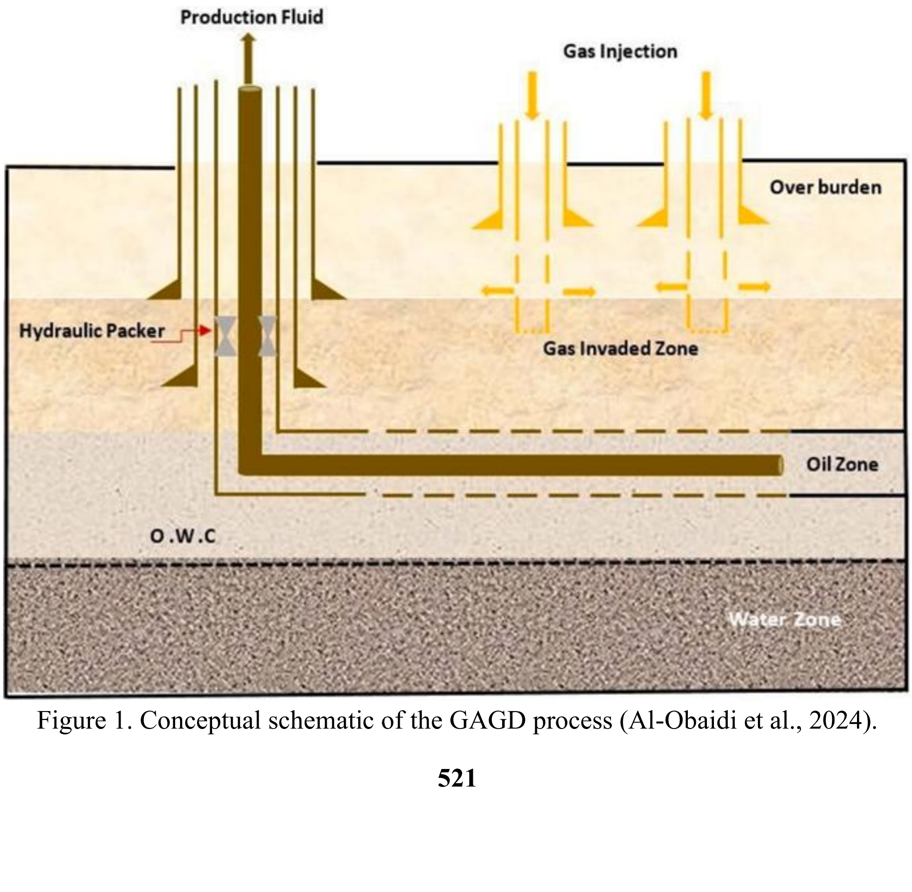

Figure 1. Conceptual schematic of the GAGD process (Al-Obaidi et al., 2024).

Method

Material Used

A series of physical model experiments were conducted to investigate the CO_2-AGD process using a 2D Hele-Shaw model simulating an oil reservoir under water drive. The model was filled with high-purity water-wet Ottawa silica sand (SiO_2). A specific gravity of 2.65 g/cc characterises this fine sand, and the median particle size (D50) is 0.84 mm. This composition simulates a homogeneous porous medium, effectively minimizing variability and isolating the effects of operational parameters during experimental procedures, ensuring that observed trends are attributable to operational factors rather than rock-specific properties, establishing fundemental understanding of the optimization process.

CO_2 of purity 99% was injected to simulate the gas phase due to its widespread application in EOR and was supplied from a compressed cylinder at 70 bar. The oil phase was simulated with N-Decane, a non-polar hydrocarbon ($C_{10}H_{22}$), because of its water immiscibility and representative behavior of reservoir oils. It was dyed red with Sudan II to enhance visibility during experiments. Deionized water (DIW), dyed blue, was used to simulate aquifer conditions. The fluids had measured densities of 0.0018 g/cm³ for CO_2, 0.73 g/cm³ for n-Decane, and 1.05 g/cm³ for DIW, with respective viscosities of 0.01462 cP, 0.84 cP, and 1.00 cP.

Hele-Shaw Model Fundamentals

The experimental setup included a glass cell, gas injection and aquifer simulation systems, pipe networks, measurement and data acquisition systems, as well as visual monitoring systems. CO_2 was injected from a high-pressure cylinder through a pressure regulator and a mass flow controller (MFC), which maintained a constant pressure during experiments. Water was introduced using a gravity-fed, constant-pressure system with a floating valve to ensure a steady flow, simulating a water aquifer. Key measurements, such as injection parameters and fluid production, were captured in real-time using a pressure transducer, MFC, weight cell, and graduated cylinder. Data were logged via Excel and serial interface software. For visual analysis, two cameras recorded the displacement process—one focused on the Hele-Shaw cell and the other on the production cylinder—to track fluid movement and recovery trends throughout runs. The model and setup used in this study are shown in (Figure 2).

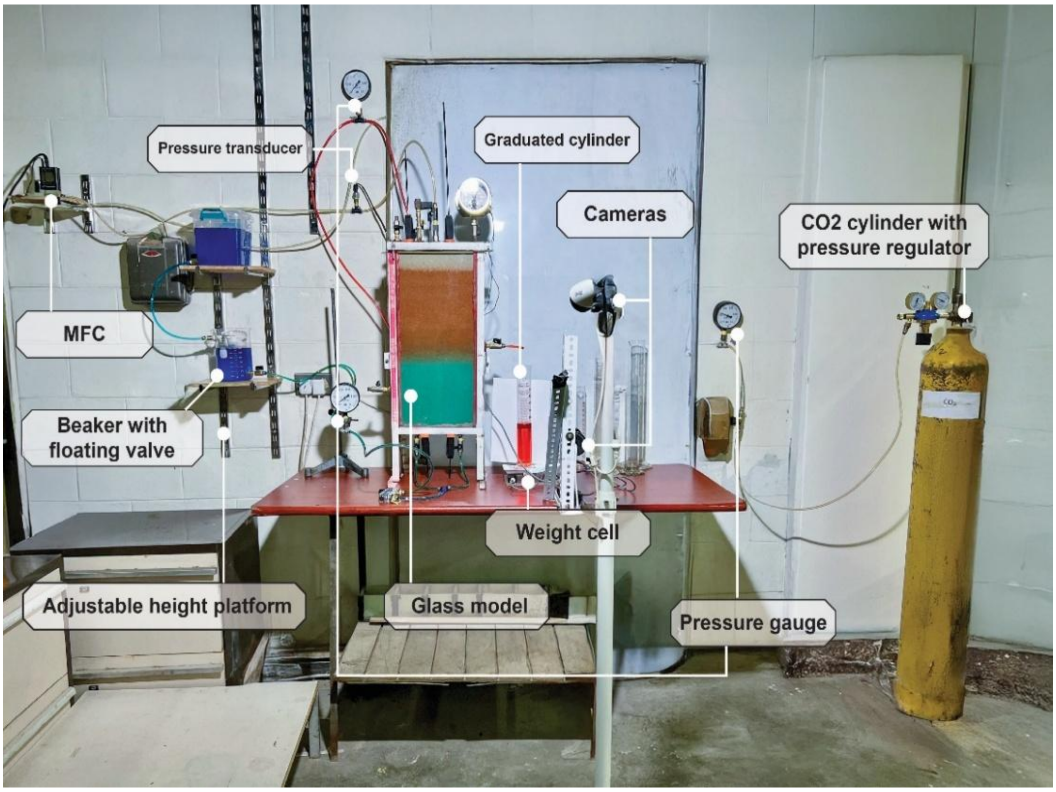

Figure 1. Laboratory set up for CO_2-AGD experiments

Optimization Framework

The work presented in this paper aims to optimize the operational parameters of the CO_2-AGD process. The goal is to find parameter settings that lead to high recovery efficiency in terms of oil recovery and delayed gas breakthrough. The operational parameters under investigation include gas injection pressure and oil production rate. All experiments were performed in a waterdrive oil reservoir configuration, with the aquifer's strength maintained consistent throughout all experiments. This section introduces a systematic optimization workflow using RSM and a desirability function approach.

RSM was selected for its ability to model and explore the complex interactions between multiple operational variables and response outcomes. One of the highlights of RSM is determining the operating conditions (factor settings) to ensure that the response meets the desired specification. RSM explores the relationships between explanatory and response variables in complex settings, where the explanatory variables can be controlled (Srinivasan et al., 2020). It has been defined mathematically as the application of regression analysis to obtain a polynomial approximation of an experiment (Reji & Kumar, 2022).

RSM overall is a statistical technique for designing experiments, building models, evaluating the relative significance of several independent variables, and determining the optimum conditions for a desirable response. However, when multivariate responses needed to be optimized simultaneously, RSM has thus far not been able to fully address the problems of multivariate responses (Srinivasan et al., 2020). The application of the desirability function is implemented at this stage. The process utilizes RSM outputs to determine the optimal balance among various goals. Statistical analyses were conducted using the R programming language. (Figure 3) illustrates the optimization process steps.

The R code was structured to define the model equations using linear regression (lm function), evaluate residuals, and apply the desirability function via a custom-coded loop across a generated grid of parameter combinations. Contour and desirability plots were created using the ggplot2 and fields packages, respectively.

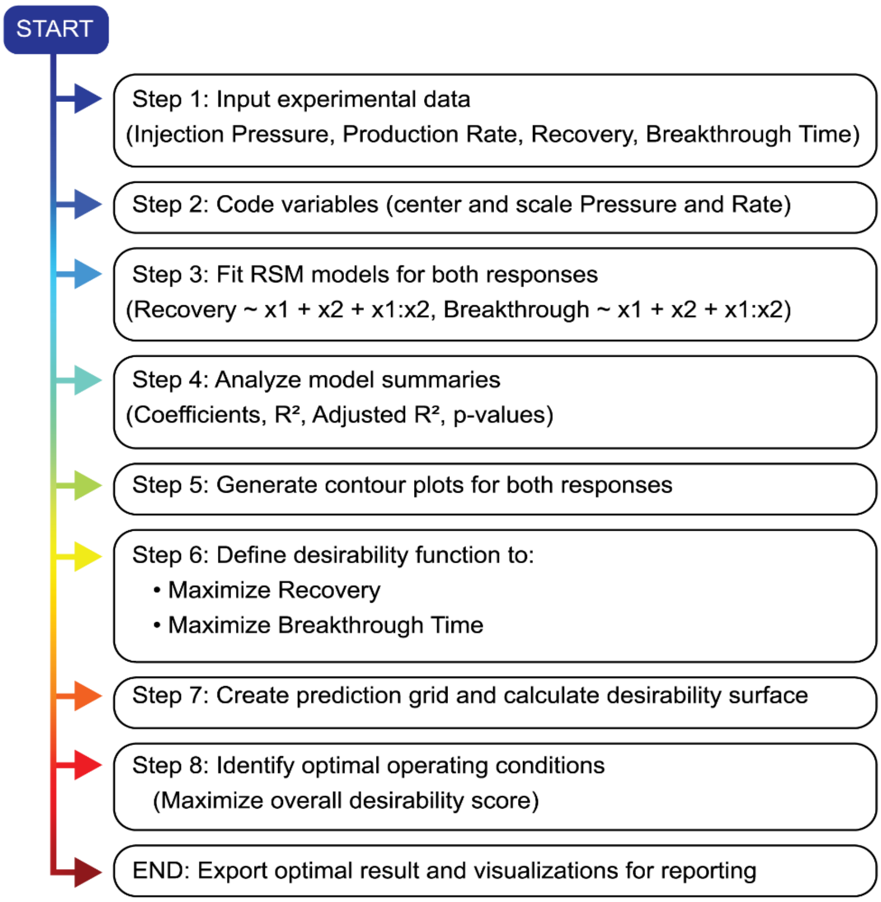

Figure 2. Flowchart of the optimization process

Data Set for Optimization

Six constant-pressure experiments (CP runs) were conducted using the Hele-Shaw model covering a range of injection pressures and production rates (Table 1). Gas was injected at constant pressures of 0.5, 1.0, or 2.0 psig, while production rates were regulated at either 50% or 100% valve opening. Oil recovery and gas breakthrough were monitored over a 270-minute duration. For runs with no observed breakthrough, a breakthrough time of 270 minutes was assigned to standardize comparison. Assigning 270 minutes, corresponding to the maximum experimental time, guarantees a consistent comparison across these runs. The experimental input variables were then coded to a standard scale to enhance interpretability and ensure computational stability. This means injection pressure and production rate were rescaled so that the midpoint of their tested range corresponds to zero, while the extreme values correspond to -1 and +1, respectively.

Table 1. Input data for RSM optimization

Run	Pressure (psig)	Production Rate (% Valve)	Recovery (%)	Breakthrough Time (min)
CP1	0.5	50	71.5	270
CP2	0.5	100	71.8	270
CP3	1.0	50	72.4	270
CP4	1.0	100	73.1	270
CP5	2.0	50	88.4	8
CP6	2.0	100	85.6	5.5

Results and Discussion

Regression Modeling

RSM was used to fit models that characterize the relationship between the response variables and the coded input variables: x_1, Injection pressure, and x_2, Production rate. The responses considered include recovery and breakthrough time. Based on the coded experimental data from the six constant-pressure runs (CP1–CP6), two linear regression models were developed. The models were fitted in *RStudio* using the *rsm* package.

The fitted regression models are as follows:

$$\text{Recovery (\%)} = 75.33 + 8.11x1 + 0.49x2 + 0.65x1\ x2$$

Recovery model summarized in (Table 2):

Table 2. Recovery model summary and factors' contribution

Term	Estimate	Std. Error	p-value	Significance
Intercept	75.33	1.36	0.0003	Base recovery (centered point)
x_1 (Pressure)	+8.11	1.58	0.036	Significant positive effect
x_2 (Rate)	+0.49	1.36	0.754	Not significant
$x_1 \cdot x_2$	+0.65	1.58	0.722	Not significant

The regression model for oil recovery yielded an R^2 value of 0.93, signifying that the model accounts for approximately 93% of the total variation in oil recovery observed across the six CP runs. The adjusted R^2 value of 0.8252 indicates a robust explanatory capability, even with a limited sample size (degrees of freedom = 2). The residual standard error 3.22 indicates a relatively low dispersion around the fitted model.

The regression analysis showed that the base recovery at the centre of the design space-corresponding to 1.0 psig injection pressure and 75% valve opening—was approximately 75.3%. Among the two tested parameters, Injection pressure (x_1) emerged as a statistically significant predictor of oil recovery, exhibiting a positive effect with a p-value of 0.0361. The results indicated that increasing the pressure significantly improved recovery, with a coefficient of about +8.1. This means that for every unit increase in the coded pressure scale (equivalent to a 0.75 psig increase in actual pressure), oil recovery improved by over 8%. The production rate (x_2) and the interaction term x_1:x_2 were statistically insignificant ($p > 0.7$), indicating minimal direct influence in this dataset. Overall, this reinforces the importance of pressure as the primary driver of oil displacement efficiency in the CO_2-AGD process.

This trend validates the role of gas injection in improving oil recovery (Muskat, 1949) (Rao et al., 2004; Ren et al., 2005) and highlights that a substantial amount of incremental oil recovery can be achieved by increasing gas injection pressure via reservoir pressurization, thereby reducing solution gas liberation and preserving oil viscosity at lower levels, which further supports the gravity drainage mechanism (Rao et al., 2004; Jadhawar, 2010; Al-Mudhafar, 2018;Moghadasi et al., 2018).

Nevertheless, higher injection pressures may enhance oil production by advancing the gas flood front faster, but they also risk inducing viscous fingering. This may result in premature gas breakthrough and diminish total oil recovery. Research conducted by Meszaros & Chakma (1990) indicated that even slight increases in injection pressure could lead to short-term gains followed by long-term inefficiencies. This trade-off was evident in run CP5, where faster recovery was accompanied by premature gas breakthrough, and in the Breakthrough time model summarized in (Table 3):

$$Breakthrough\ (min) = 213.59 - 141.03x1 + 0.27x2 + 0.67x1\ x2$$

Table 3. Breakthrough model summary and factors' contribution

Term	Estimate	Std. Error	p-value	Interpretation
Intercept	213.59	29.73	0.0188	Breakthrough at center point
x_1 (Pressure)	–141.03	34.54	0.0551	Borderline significant; inverse trend
x_2 (Rate)	+0.27	29.73	0.994	No effect
$x_1 \cdot x_2$	+0.67	34.54	0.986	No interaction

The breakthrough time model showed an R^2 of 0.8929, capturing approximately 89% of the variability in gas arrival time. The adjusted R^2 value was recorded at 0.7321, which reflects a decrease attributed to constraints related to degrees of freedom and the variability observed in breakthrough behavior. The regression analysis revealed a clear trend: as the gas injection pressure increased, the time it took for gas to reach the production well decreased sharply.

At the center of the design space (1.0 psig pressure and 75% valve opening), the predicted breakthrough time was roughly 213.6 minutes. The pressure term had a large negative coefficient of –141, indicating that for each unit increase in coded pressure (equal to 0.75 psig), the breakthrough time dropped by around 141 minutes. This strong inverse relationship suggests that higher injection pressure can enhance oil recovery and speed up gas channeling toward the producer. Although the p-value for this term was slightly above the conventional threshold ($p = 0.055$), the trend was physically meaningful and aligned with the experimental observations.

The production rate and the interaction term were statistically insignificant ($p > 0.9$), indicating their minimal direct influence, as pressure is the main predictor of breakthrough timing. However, experimental observations revealed their subtle influence, especially at higher injection pressures where increased drawdown appeared to destabilize the gas-oil interface. At the highest injection pressure tested (2.0 psig), increasing the production rate from 50% to 100% led to an earlier gas breakthrough (from 8.0 to 5.5 minutes) and a decline in recovery (from 88.4% to 85.6%). This suggests that increased drawdown may have destabilized the gas-oil interface and accelerated gas channelling. The model's inability to capture this effect likely stems from the limited degrees of freedom, which restricted the statistical power of interaction terms.

Contour Plot Analysis

Contour plots were generated using the *ggplot2* functioin in *R*. These plots provide visual insight into how recovery and breakthrough responses vary across different combinations of operational space (Figure 4). The axes denote injection pressure and production rate. The contours illustrate the response (Recovery or Breakthrough Time) across various combinations of operational parameters. These plots reveal trends in performance as pressure and production rate change, indicating that the recovery contour increases with higher pressure. In contrast, the Breakthrough contour decreases rapidly with pressure increase, identifies optimal regions, such as areas of high recovery and delayed breakthrough, and assists operational tuning by indicating directional trends (e.g., increasing pressure boosts recovery but may risk front stability).

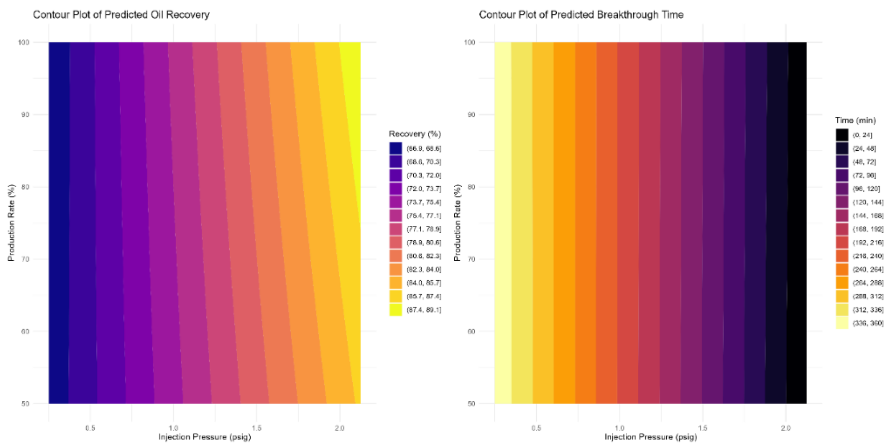

Figure 3. Contour plots of oil recovery and breakthrough time

Optimization via Desirability Function

Following the modeling of oil recovery and breakthrough time as functions of injection pressure and production rate, the next step involved identifying the operating condition that provides the optimal trade-off between the two responses. This was achieved using the *desirability function* approach, a commonly utilized multi-response optimization technique in RSM. Each response variable was transformed into a desirability score (d) ranging between 0 (undesirable) and 1 (ideal). Scaling each response according to the defined range. In this study, Recovery (y_1) was scaled within a range of 70% as the minimum acceptable threshold and 90% as the ideal target. The breakthrough time (y_2) was scaled within a range of 5 minutes, representing the scenario of early gas breakthrough (worst case), to 270 minutes, indicating no breakthrough observed (best scenario). Then, the Geometric mean combined those scaled values into a single overall desirability score (D) calculated using:

$$D = \sqrt{(d1 \times d2\ )}$$

Where:
d_1 is the desirability for oil recovery, scaled to increase with higher recovery values, and
d_2 is the desirability for breakthrough time, scaled to increase with later (delayed) gas breakthrough.

A design space was generated covering all possible coded injection pressure and production rate levels, ranging from -1 to +1, with a resolution of 0.05. A total of 1,681 combinations were generated, and the predicted recovery and breakthrough times were calculated using the fitted regression models. The desirability function was applied to each case, and the optimal condition was determined by selecting the maximum D score. The maximum desirability was identified using a *sorting function* in R to extract the top-ranked configuration, which was then verified by visually checking its location on the response plots. The optimal operational conditions predicted by the model are summarized in (Table 4). At an injection pressure of 1.3 psig and a production rate of 100% valve opening, the estimated recovery was approximately 79.3%, with a breakthrough time recorded at 157.7 minutes. The scenario attained a desirability score of 0.518, reflecting an effective balance between the two objectives.

A 2D desirability surface plot was generated using the *fields package* in *R* to visualize how the overall performance of the CO_2-AGD process varies across different operational conditions. In this plot, warmer colors (red to dark red) indicate higher desirability scores, while cooler colors (blue) denote lower scores. The most desirable conditions—represented by the darkest red region-occurred at an injection pressure of approximately 1.3 psig and 100% production rate, where a favorable trade-off between maximizing oil recovery and delaying gas breakthrough was achieved. In contrast, low injection pressures (below ~0.6 psig) consistently yielded low desirability scores, regardless of production rate, reflecting their poor performance in meeting both objectives.

The predicted optimum falls within the tested range (between 1.0 and 2.0 psig), not extrapolated beyond it.

- CP5 and CP6 showed higher recovery but very early breakthrough.
- CP3 and CP4 had no breakthrough but lower recovery.

Thus, the prediction logically interpolates between actual results and is supported by the observed physical behavior. Future validation is planned as part of extended work and resource availability.

Table 4. Optimal operational conditions

Injection Pressure (psig)	Production Rate (%)	Predicted Recovery (%)	Predicted Breakthrough (min)	Desirability Score
1.3	100	79.3	157.7	0.518

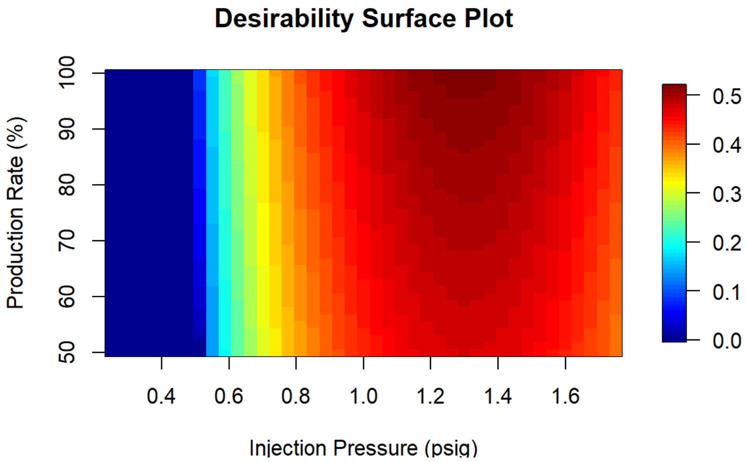

Figure 4. Desirability surface plot.

Conclusion

The main objective of this work was to evaluate the performance of the CO_2-AGD process under varying operational conditions and to identify optimal settings through experimental observation and statistical analysis. Rather than relying on trial-and-error experimentation, a structured approach was followed, using RSM and desirability-based optimization, to explore how gas injection pressure and production rate influence both oil recovery and gas breakthrough behavior. In this study, the primary depletion phase was assumed to have been completed, and the secondary recovery process was designated as the CO_2-AGD process. The main conclusions drawn from this research are presented as follows:

1. Regression models provided strong predictive power for oil recovery ($R^2 = 93\%$) and breakthrough time ($R^2 = 89\%$), with injection pressure as the dominant factor.
2. The optimal operational conditions predicted by desirability function optimization combine oil recovery and breakthrough timing. 1.3 psig injection pressure and 100% production rate offered the best trade-off, predicting a 79.3% recovery and 157.7 minutes breakthrough, achieving a desirability score of 0.518.
3. Blindly increasing injection pressure may improve short-term recovery but risks premature gas breakthrough. The desirability function allows for navigating this trade-off, offering a data-supported guide for operational decision-making.
4. The desirability surface plot demonstrated that increased injection pressure consistently enhances oil recovery; however, optimal performance is achieved within a moderate pressure range of approximately 1.3 psig to mitigate early breakthrough risks.

Recommendations

In light of the findings presented in this work, the following recommendations and directions for future research are outlined as follows:

1. Future work should aim to include more intermediate points in both pressure and production rate to refine the response surface models and reduce statistical uncertainty.
2. Additional experimental runs near the predicted optimum to confirm the robustness of the model and improve confidence in the desirability-based optimization approach should be considered in light of resource availability and time constraints.
3. Assess economic feasibility by incorporating injection costs, gas utilization efficiency, and oil recovery rates into a techno-economic model based on lab-scale findings.

Scientific Ethics Declaration

* The authors declare that the scientific, ethical, and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Conflict of Interest

* The authors declare that they have no conflicts of interest

Funding

* This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Acknowledgements or Notes

* This article was presented as a/an oral/poster presentation at the International Conference on Engineering and Advanced Technology (ICEAT) held in Selangor, Malaysia on July 23-24, 2025.

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To cite this article:

Ibrahim, R. T., Al-Obaidi, D. A., & Al-Mudhafar, W. J. (2025). Optimization of CO_2-assisted gravity drainage operational parameters: Insights from a 2D hele-shaw model. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics (EPSTEM), 37,* 520-530.

Appendix 1. List of Abbreviations

Abbreviation	Full Term
CCS	Carbon Capture and Storage
CGI	Continuous Gas Injection
CO_2	Carbon Dioxide
CO_2-AGD	Carbon Dioxide-Assisted Gravity Drainage
CP	Constant Pressure
DIW	Deionized Water
EOR	Enhanced Oil Recovery
GAGD	Gas-Assisted Gravity Drainage
GHG	Greenhouse Gas
MFC	Mass Flow Controller
OOIP	Original Oil In Place
OWC	Oil-Water Contact
RSM	Response Surface Methodology
R^2	Coefficient of Determination
WAG	Water-Alternating-Gas