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RESERVOIR PERFORMANCE SIMULATION AND PROCESS-TO-SIMULATOR QUALITY CONTROL TO SUPPORT EOR METHOD SELECTION IN CARBONATE-CONTAINING RESERVOIRS

Abstract

Enhanced oil recovery (EOR) selection requires reservoir performance simulation that reproduces not only production trends but also the physical mechanisms controlling pressure, fluid behavior, multiphase flow, gas mobility, well constraints, and long-term reservoir response. This study presents a reservoir performance simulation and process-to-simulator quality-control workflow for CO_2-based EOR evaluation in anonymized carbonate-containing Field X, Kazakhstan. The field-scale simulation uses a three-dimensional ECLIPSE E300 compositional model with 93 × 88 × 78 grid cells, 194,413 active cells, and a 40-year forecast period. The framework integrates compositional pressure-volume-temperature/equation-of-state (PVT/EOS) behavior, minimum miscibility pressure (MMP), three-phase relative permeability, hysteresis, vertical connectivity and gravity override, injection scheduling, bottomhole-pressure (BHP) control, wellbore thermal response, CO_2 tracking, and mass-balance verification. Each mechanism is linked to a simulator functional block, diagnostic output, sensitivity test, and acceptance criterion. A representative ECLIPSE E300 process-to-code sequence – RUNSPEC, GRID, PROPS, SOLUTION, SCHEDULE, SUMMARY, followed by MATLAB post-processing – provides traceability from reservoir physics to forecast interpretation. Sensitivity analysis identifies vertical connectivity, gas relative permeability, MMP uncertainty, fault transmissibility, hysteresis, and BHP constraints as the principal controls on simulated reservoir performance. Continuous CO_2 injection increases cumulative oil production from 17.96 to 25.37 Mt, yielding 7.41 Mt of incremental oil (+41.3%); at year 40, the CO_2 case maintains 238.6 t/d while the Base case declines to zero. The results demonstrate that reservoir performance simulation provides a rigorous engineering basis for forecasting reservoir behavior, quantifying model sensitivity, validating physical consistency, and supporting defensible EOR method selection.

Keywords: CO_2-EOR; reservoir performance simulation; physical-process coding; EOR method selection; CO_2 mass balance; carbonate-containing reservoir.

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Introduction

Carbon dioxide enhanced oil recovery (CO_2-EOR) differs from waterflooding and simplified gas-pressure-maintenance models because the injected component modifies phase behavior, oil composition, oil volume, viscosity, gas mobility, residual trapping and pressure-temperature response. Compositional modeling of pure and impure CO_2 demonstrates that fluid composition and phase-equilibrium representation directly affect both oil recovery and storage predictions [1, 2]. Consequently, a reliable forecast requires verification of the physical mechanisms represented by the simulator rather than a comparison of production curves alone.

Gas mobility is equally important. Water-alternating-gas (WAG) and related conformance-control strategies are sensitive to miscibility, gravity, heterogeneity, cycle design, relative permeability and hysteresis [3, 4, 5]. Alternative CO_2 delivery concepts, including microbubble injection, further emphasize that gas mobility and interfacial transport must be treated explicitly rather than embedded in a generic gas-injection assumption [14].

Pressure safety and wellbore behavior form a second control layer. CO_2 injection can generate significant pressure redistribution near faults and sealing units, and geomechanical studies therefore require the operating pressure to remain within defined integrity limits [6, 7]. Dense-phase CO_2 also undergoes strong pressure-temperature transients during well start-up; numerical wellbore studies show that the start-up schedule and pressure drop must be evaluated together with the temperature profile [8, 9].

The objective of this paper is to develop and quantitatively demonstrate a process-to-simulator quality-control workflow for CO_2 injection modeling and to show its representative process-to-code implementation at ECLIPSE E300 section level. Field X is the anonymized publication designation of the case study. The workflow requires each relevant physical mechanism to be connected to a simulator functional block, a diagnostic output, a sensitivity test and a pass/fail criterion. Within an EOR method-selection workflow, this framework is used to test whether the CO_2 option remains technically credible under process and implementation uncertainty. This structure separates uncertainty in the reservoir description from uncertainty created by model implementation. Geostatistical uncertainty concepts provide a compatible framework for this separation because multiple realizations and diagnostic statistics can be used to distinguish spatial variability from model-form uncertainty [10].

The scientific contribution is methodological rather than the proposal of a new constitutive law. The workflow makes the model auditable: the predicted incremental oil is considered credible only after thermodynamic behavior, flow functions, vertical segregation, operational controls and CO_2 accounting have passed defined quality-control checks. Reactive transport is not included in the executed calculation set and is not used to support the reported results; it is retained only as a future extension when mineral reactions or brine chemistry control injectivity [11,12].

Materials and methods

Field X numerical model and calculation layers

The publication dataset combines two connected calculation layers for Field X, the anonymized designation of the carbonate-containing complex reservoir interval used in the underlying modeling dataset. The first is the anonymized field-scale ECLIPSE E300 compositional model used for the direct Base-versus-CO_2 comparison. The second is a sector/process-diagnostic layer used to isolate the individual CO_2 mechanisms shown in Figures 3–9. Commercially sensitive coordinates, well identifiers and selected absolute PVT values are normalized for publication, while grid architecture, aggregated field-scale outputs, sensitivity ranges and process relationships are retained. The two layers are reported separately to prevent process-diagnostic pressure or rate values from being misinterpreted as full-field operating constraints.

Only the Base case and the continuous CO_2 case are claimed as explicit field-scale dynamic runs in this manuscript. WAG and surfactant-alternating-gas (SAG) appear as process-control schedule diagnostics and engineering follow-up options; they are not presented as additional full-field production forecasts. This distinction is maintained throughout the Results and Discussion section.

Process-to-simulator quality-control principle

The workflow consists of five sequential checks: (1) identify the physical mechanism; (2) assign the mechanism to a simulator functional block; (3) define the diagnostic output; (4) run a controlled sensitivity test; and (5) accept the forecast only when the diagnostic response is physically and numerically consistent. The sequence prevents the common error of interpreting incremental oil without confirming that the underlying CO_2 mechanism is represented in the model.

Table 1 – Main characteristics of Field X compositional modeling basis

Parameter	Reported value	Role in the study
Dynamic simulator	ECLIPSE E300, compositional mode	Explicit CO_2 component transport and phase behavior
Grid dimensions	93 × 88 × 78	Three-dimensional reservoir representation
Total cells	638,352	Geological discretization
Active cells	194,413	Cells participating in dynamic flow
Nominal cell size	100 × 100 × 1 m	Lateral and vertical numerical resolution
Field-scale forecast	40 years; yearly export	Base-versus-CO_2 long-term comparison
Explicit field-scale cases	Base case and CO_2 injection case	Quantitative production comparison
Process-diagnostic outputs	EOS/MMP, relperm/hysteresis, gravity override, schedule, thermal start-up, CO_2 balance, sensitivity	Mechanism-specific QC
MMP pressure-window reference	13.2 MPa	Regional laboratory reference used for below/near/above-MMP interpretation [13]

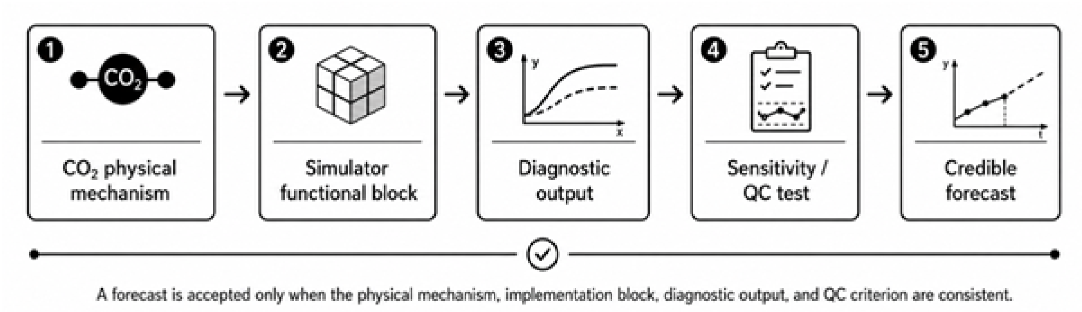

Figure 1 – Process-to-simulator quality-control workflow for CO_2 injection modeling

Table 2 – Physical-process checks used in the Field X process-to-simulator workflow

Physical process	Simulator functional block	Main input	Diagnostic / pass criterion
Phase behavior and miscibility	Compositional PVT / equation of state (EOS)	Components, binary interaction coefficients (BICs), MMP reference, viscosity and swelling response	MMP-pressure response is continuous and consistent with the adopted pressure window
Three-phase flow	Gas-oil-water relative permeability	Sgc, Sorg, krg/kro functions	No unrealistically mobile gas front; drainage endpoint and breakthrough response checked
Hysteresis and trapping	Drainage/imbibition history	Separate gas drainage and imbibition functions	Trapping changes gas mobility and retained CO_2 in the expected direction
Gravity override	Vertical permeability and grid connectivity	PERMZ, kv/kh, layering, density contrast	Vertical plume follows connectivity; grid refinement does not reverse the mechanism
Well operation	Schedule and pressure control	CO_2 composition, rate, BHP cap, WAG/SAG cycle	No rate-only pressure violation; switching logic is explicit

Continuation of Table 2

Physical process	Simulator functional block	Main input	Diagnostic / pass criterion
Thermal start-up	Wellbore thermal QC	Start-up time, rate, wellhead pressure, BHP, BHT	Minimum BHT remains above the internal thermal QC threshold
Pressure integrity screening	Pressure/fault-control layer	BHP cap, fault multiplier	Pressure response stays inside the specified operational envelope
CO_2 accounting	Component mass balance	Injected, produced, dissolved, trapped and mobile CO_2	Absolute mass-balance error <1%; reported cases close at 0%
Sensitivity ranking	Low/base/high sensitivity matrix	MMP, kv/kh, krg, hysteresis, fault, BHP, impurity, grid, ramp-up	Dominant response controls are quantified and traceable

Notation: BHP – bottomhole pressure; BHT – bottomhole temperature; GOR – gas–oil ratio; kv/kh – vertical-to-horizontal permeability ratio; krg and kro – gas and oil relative permeability, respectively; Sgc – critical gas saturation; Sorg – residual oil saturation to gas.

Simulator functional architecture

Generic labels such as MULT or LGR are not treated as universal simulator keywords. Instead, the implementation is organized by ECLIPSE-type deck sections and simulator-agnostic functional descriptions. Exact keyword syntax can vary by simulator version; therefore, Table 3 identifies the required function rather than implying that one abbreviation is universally valid.

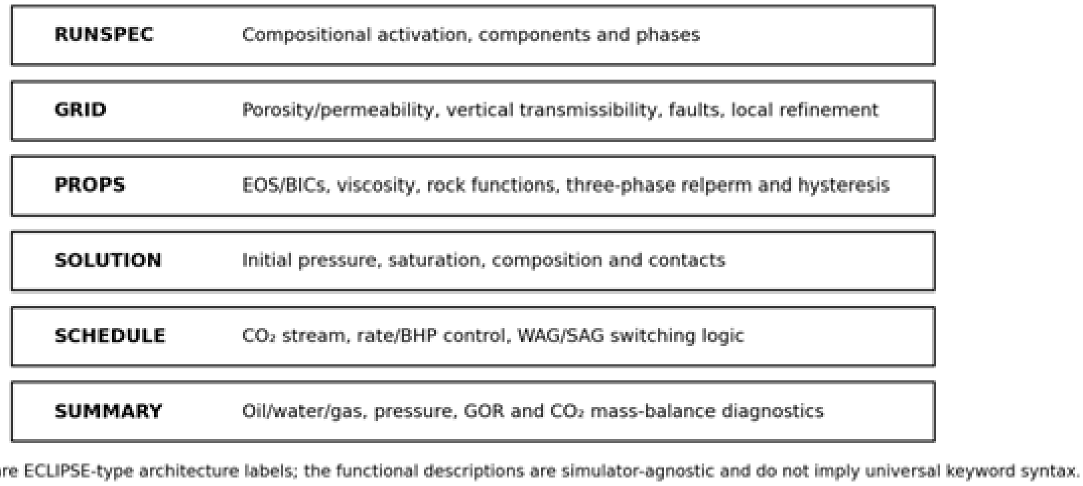

Figure 2 – Functional architecture for compositional CO_2 modeling.
Section names follow an ECLIPSE-type deck structure;
the implementation descriptions are simulator-agnostic

Table 3 – Functional implementation chain for the Field X CO_2 model

E300 section	Functional implementation	Physical process represented	QC output
RUNSPEC	Compositional activation; components and phases	Component tracking and phase behavior	Component/phase consistency
GRID	PORO, PERMX, PERMZ, transmissibility and grid-resolution controls	Heterogeneity and gravity segregation	CO_2 plume geometry

Continuation of Table 3

E300 section	Functional implementation	Physical process represented	QC output
PROPS	EOS/PVT, BIC, viscosity, three-phase relative permeability, hysteresis	Miscibility, swelling, viscosity reduction, gas mobility and trapping	MMP, viscosity, swelling, breakthrough behavior
SOLUTION	Initial pressure, saturation, composition and contacts	Initial thermodynamic state	Initialization consistency
SCHEDULE	CO_2 stream, rate/BHP limits, GOR constraint, WAG/SAG logic	Operational control	BHP, rate and GOR
SUMMARY	Pressure, production and CO_2 inventory outputs	Forecast diagnostics and carbon accounting	Mass-balance closure and retained CO_2

Representative ECLIPSE E300 implementation of the process-to-code workflow

To demonstrate how the proposed process-to-code concept is implemented at simulator level, the principal physical mechanisms are mapped to the corresponding functional sections of an ECLIPSE E300 compositional model. The example below is intentionally abbreviated and omits field-identifying and commercially sensitive parameters. It illustrates the implementation sequence rather than reproducing the complete Field X simulation deck. The essential requirement is that phase behavior, three-phase flow functions, hysteresis, injection composition, well constraints, and diagnostic output vectors are configured consistently before the predicted incremental oil is considered credible.

```
-- Representative ECLIPSE E300 process-to-code implementation
RUNSPEC
   COMPOSITIONAL MODEL
   Components and active phases
   CO2 explicitly represented as an injected component
GRID
   PORO / PERMX / PERMZ
   Vertical-connectivity and fault-transmissibility controls
   Local grid-resolution controls where required
PROPS
   EOS / compositional PVT definition
   Component critical properties and binary interaction coefficients
   Oil-density, viscosity and swelling calibration
   Three-phase gas-oil-water relative-permeability functions
   Drainage / imbibition functions for hysteresis and residual-gas trapping
SOLUTION
   Initial pressure
   Initial water, oil and gas saturations
   Initial fluid composition and fluid contacts
SCHEDULE
   CO2 injection-stream composition
   Injection-rate constraint
   BHP constraint
   Producer GOR constraint
   WAG/SAG switching logic where evaluated
```

SUMMARY
Reservoir pressure
Injector and producer BHP
Oil, water and gas production
GOR
Injected and produced CO2
Dissolved, trapped and mobile CO2 inventories
CO2 retention and mass-balance diagnostics
POST-PROCESSING
E300 diagnostic outputs
↓
MATLAB quality-control module
↓
MMP response / mobility ratio / gravity-override index /
CO2 mass-balance closure / sensitivity ranking

The implementation shown above establishes a direct traceability chain between reservoir physics and numerical representation. The EOS/PVT block controls the pressure-dependent CO_2–oil response around the adopted MMP reference; the three-phase relative-permeability and hysteresis functions control gas mobility and residual trapping; vertical permeability and transmissibility settings govern gravity override and interlayer communication; SCHEDULE controls define physically admissible injection conditions; and SUMMARY outputs provide the quantitative variables required for independent quality control. The MATLAB module therefore operates on simulator-derived diagnostics and does not replace the compositional reservoir model.

MATLAB diagnostic module and dimensional consistency

The MATLAB layer is a quality-control pre/post-processor and does not replace the compositional simulator. The minimum miscibility pressure is explicitly defined as MMP_MPa = 13.2. The logistic parameter transitionWidth_MPa = 0.7 MPa is a numerical transition-width parameter used only to map pressure difference to a continuous diagnostic miscibility index. It does not modify the physical MMP reference and is not used as a simulator calibration parameter. With this definition, the diagnostic index equals 0.269 at MMP – 0.7 MPa, 0.500 at MMP and 0.731 at MMP + 0.7 MPa. Physical MMP uncertainty is tested independently using the ±1 MPa sensitivity cases.

$$MI = 1 / [1 + \exp(-(P - MMP) / \Delta P\_tr)], \quad MMP = 13.2\ \text{MPa}, \quad \Delta P\_tr = 0.7\ \text{MPa}$$

The original overrideIndex combined kv/kh, density difference and gas viscosity and therefore carried dimensions. The algorithm first calculates the raw gravity-segregation proxy and then normalizes it to the Base diagnostic reference. The resulting overrideIndex is dimensionless: values above 1 indicate stronger gravity-segregation tendency than the Base reference, while values below 1 indicate weaker tendency.

$$G\_raw = (kv/kh)\, |\rho\_o - \rho\_CO2| / \mu\_g ; \qquad overrideIndex = G\_raw / G\_raw{,}ref$$

CO_2 balance error is also normalized, so the quality-control criterion is expressed as a percentage of injected CO_2 rather than as an unscaled mass difference.

$$retainedCO2 = injectedCO2 - producedCO2;\ massError\% = 100 \times (retainedCO2 - dissolvedCO2 - trappedCO2 - mobileCO2) / injectedCO2$$

Algorithm 1 – MATLAB diagnostic logic for process-to-simulator quality control of the Field X CO_2 model

```
input = readtable('Xfield_co2_inputs.csv');
MMP_MPa = 13.2;
transitionWidth_MPa = 0.7;  % numerical QC smoothing width, not an MMP correction
dP_MPa = input.pressure_MPa – MMP_MPa;
MI = 1 ./ (1 + exp(-dP_MPa ./ transitionWidth_MPa));
mobilityRatio = (input.krg ./ max(input.kro,1e-6)) .* (input.mu_oil ./ max(input.mu_gas,1e-6));
overrideRaw = input.kvkh .* abs(input.rho_oil – input.rho_co2) ./ max(input.mu_gas,1e-6);
```

```
baseMask = strcmpi(input.caseID,'Base');
overrideRef = median(overrideRaw(baseMask),'omitnan');
overrideIndex = overrideRaw ./ max(overrideRef,1e-12);
retainedCO2_kt = input.injectedCO2_kt – input.producedCO2_kt;
massError_kt = retainedCO2_kt – input.dissolvedCO2_kt – input.trappedCO2_kt – input.mobileCO2_kt;
massError_pct = 100 .* massError_kt ./ max(input.injectedCO2_kt,1e-9);
out = table(MI,mobilityRatio,overrideIndex,retainedCO2_kt,massError_pct);
writetable(out,'Xfield_qc.csv');
```

Quantitative sensitivity design

The analysis reports the numerical low/base/high ranges rather than qualitative sensitivity labels. The tested process-diagnostic ranges are MMP shift -1/0/+1 MPa; kv/kh = 0.02/0.08/0.16; krg endpoint = 0.45/0.65/0.85; hysteresis state = off/base/enhanced; fault multiplier = 0.1/1/5; BHP cap = 13.5/14.5/15.5 MPa; CO_2 impurity = 0/5/10%; grid refinement = coarse/base/refined; and thermal ramp-up = 0.5/2/6 h. These ranges are used to quantify both oil-response and CO_2-retention sensitivity.

Scope boundary for reactive transport and geomechanics

Reactive transport is not part of the executed Field X calculation set. It is therefore removed from the Abstract, the list of calculated outputs and the conclusions. It is discussed only as an extension criterion for carbonate-water-rock systems in which dissolution, precipitation or salinity changes control injectivity [11,12]. Likewise, the present study reports pressure-integrity screening through BHP limits, pressure response and fault-transmissibility sensitivity; it does not claim a fully coupled geomechanical solution. Coupled geomechanics remains a separate validation layer when fault slip or caprock stress is a project decision criterion [6,7].

Results and discussion

EOS/MMP diagnostic and oil-property response

The MMP pressure-window diagnostic uses 13.2 MPa as a regional laboratory reference for CO_2-oil interaction [13]. Figure 3 is a diagnostic pressure sweep, not a field pressure-history curve. Across the normalized sweep from 8 to 23 MPa, the miscibility index increases continuously from approximately 0.001 to 1.000. The normalized oil-swelling factor increases from 1.000 to 1.180, while the diagnostic oil viscosity decreases from 4.20 to approximately 2.44 cP. The shaded MMP ±0.7 MPa zone visualizes the numerical transition width used in Algorithm 1; the physically tested MMP uncertainty remains ±1 MPa and is reported independently in the sensitivity matrix.

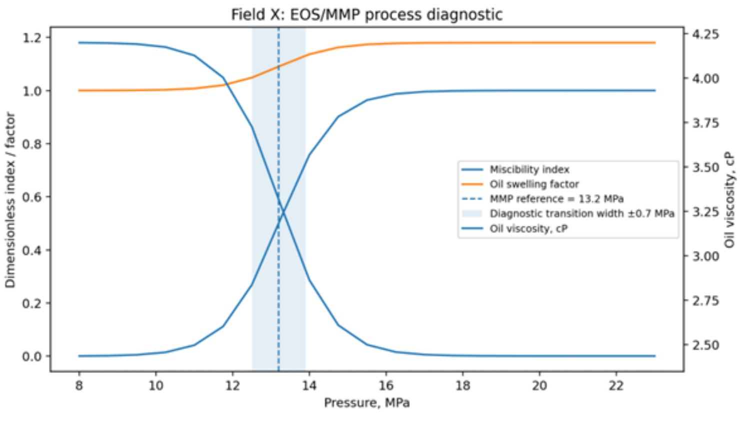

Figure 3 – EOS/MMP process diagnostic for Field X. The 0.7 MPa band is a numerical transition width used for quality-control visualization and does not modify the MMP reference

Three-phase gas relative permeability and hysteresis

The gas-flow input functions are reported explicitly as model-input curves rather than as direct special core analysis (SCAL) measurements. The drainage gas relative-permeability endpoint reaches 0.82, whereas the imbibition endpoint reaches 0.48. The separation between the drainage and imbibition curves creates a trapping envelope that limits gas remobilization during alternating injection. The krg endpoint sensitivity of 0.45/0.65/0.85 changes oil response by -16% and CO_2 retention by -20% relative to the Base diagnostic case, while enhanced hysteresis changes the corresponding responses by +9% and +24%. These values demonstrate that gas mobility and trapping are first-order numerical controls rather than secondary settings [3, 4, 5].

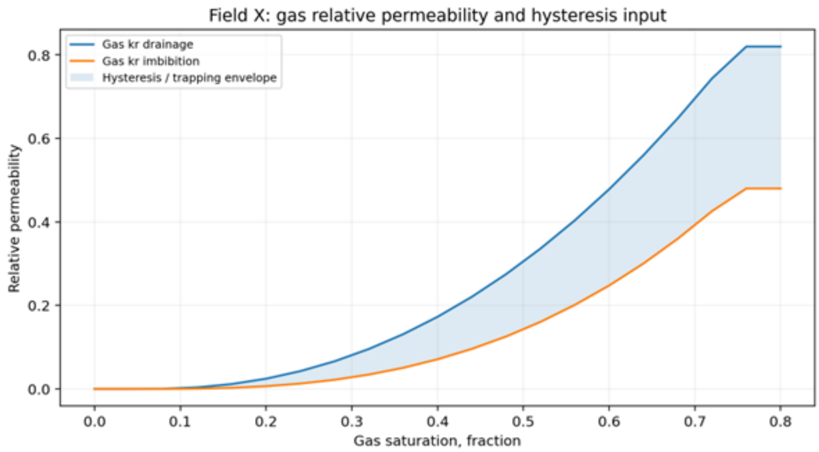

Figure 4 – Gas relative-permeability drainage/imbibition functions used for three-phase gas-oil-water flow and hysteresis diagnostics in Field X

Vertical permeability, grid resolution and gravity override

Figure 5 shows the calculated gas-saturation diagnostic along the injector-producer section. The highest normalized gas concentration occurs in the upper portion of the section, demonstrating the gravity-override tendency. The vertical-to-horizontal permeability ratio kv/kh is tested at 0.02, 0.08 and 0.16. Increasing vertical connectivity produces the largest adverse oil-response shift in the process sensitivity matrix (-18%) and reduces CO_2 retention by 12%. Local grid refinement produces a +5% oil-response shift and +9% retention shift, confirming that numerical dispersion and vertical discretization must be checked together rather than treated as independent post-processing details.

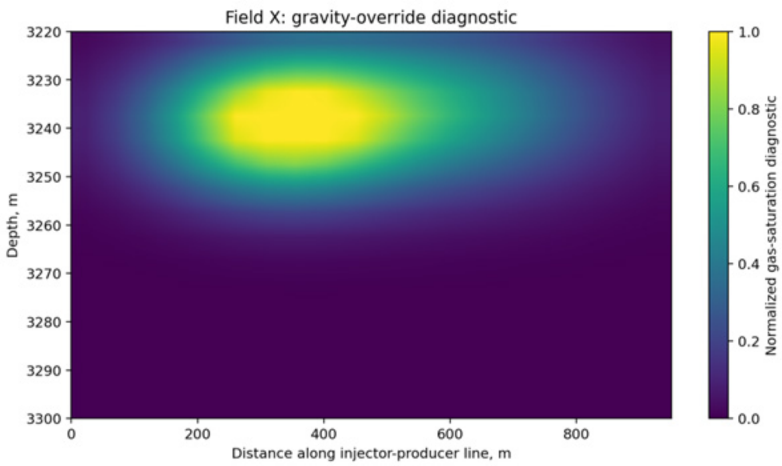

Figure 5 – Field X gravity-override diagnostic controlled by vertical connectivity, density contrast and grid resolution

WAG/SAG schedule logic and operational control

CO_2 injection is not represented solely by a constant gas-rate constraint. The pilot-scale schedule diagnostic alternates 10-day water/surfactant slugs at 2,200 m³/d with 20-day CO_2 slugs at 3,000 t/d over the 120-day screening window. The two streams are plotted on separate axes so that mass rate and volumetric rate are not combined. The schedule block is pressure-limited and is evaluated together with BHP and GOR constraints. The design is a process-control diagnostic; it is not presented as an additional full-field WAG/SAG production forecast. The role of cycle timing, gravity and permeability heterogeneity in WAG performance is consistent with published numerical studies [4, 5].

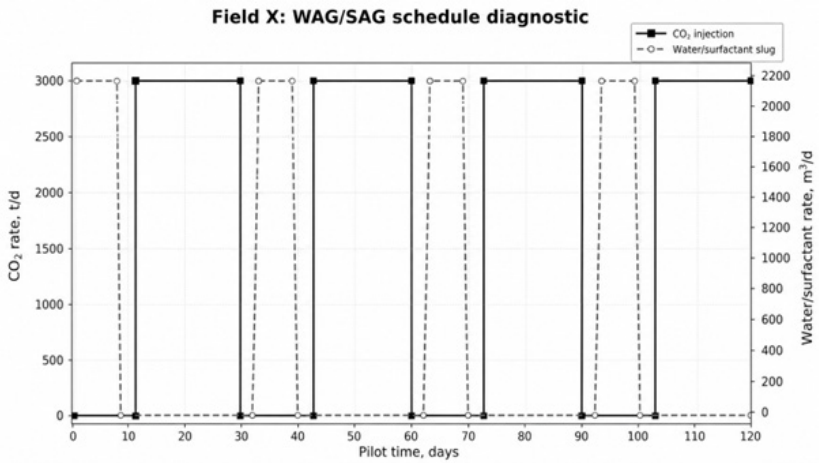

Figure 6 – Field X WAG/SAG schedule diagnostic with CO_2 mass rate and water/surfactant volumetric rate shown on separate axes

Wellbore thermal start-up

The start-up calculation ramps CO_2 rate from 0 to 2,980 t/d over 6 h. BHP rises from 12.5 to 15.2 MPa, while bottomhole temperature decreases from 70.0 °C to a minimum of 62.4 °C at approximately 1.2 h and then recovers to 68.9 °C by 6 h. The figure uses a 10 °C internal thermal QC threshold only as a conservative numerical flag for excessive cooling; it is not presented as a universal hydrate-equilibrium boundary. The calculated minimum BHT remains more than 52 °C above that QC line. This treatment resolves the thermal risk as a quantified start-up diagnostic rather than an undefined hydrate or integrity margin [8, 9].

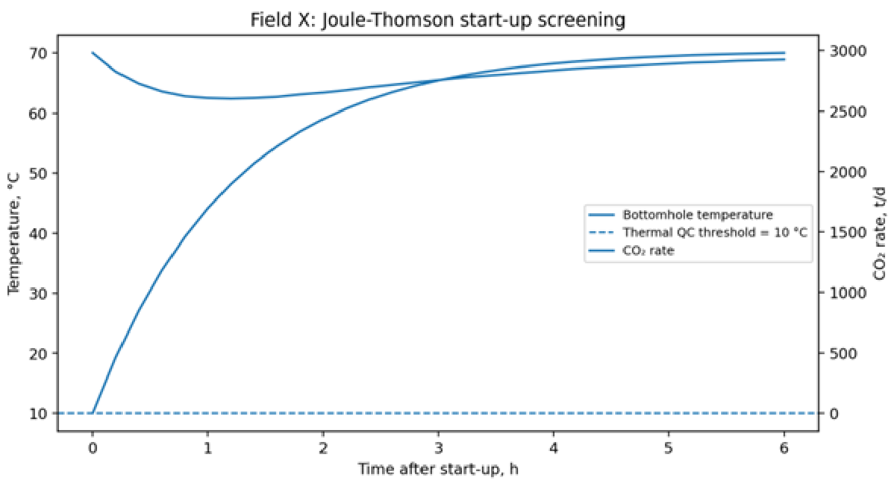

Figure 7 – Joule-Thomson start-up screening for Field X. Temperature is reported in °C and CO_2 rate in t/d on a separate axis

CO_2 retention balance and mass-balance closure

The CO_2 accounting table reconciles injected, produced, dissolved, residual-trapped and mobile CO_2 for every reported year. The retained fraction decreases from 0.875 in 2027 to 0.804 in 2037 as produced CO_2 increases, while the calculated mass-closure error remains exactly 0 kt in all reported cases. The MATLAB module also reports massError_pct and applies a <1% acceptance criterion. This makes carbon accounting a quantitative simulator QC requirement rather than a qualitative carbon capture, utilization and storage (CCUS) statement.

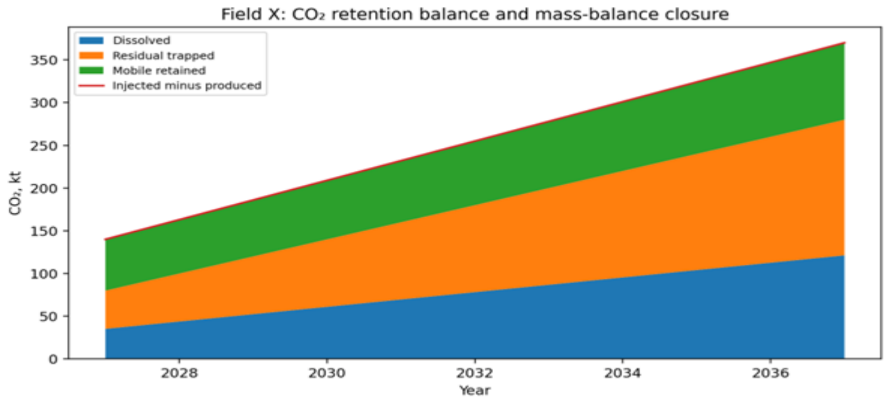

Figure 8 – Field X CO_2 retention balance. Dissolved, residual-trapped and mobile retained CO_2 sum exactly to injected minus produced CO_2 for the reported diagnostic cases

Quantitative sensitivity of process implementation

Figure 9 and Table 4 quantify the response to nine model-implementation assumptions. Across the tested envelope, the oil response ranges from -18% to +12%, and the CO_2-retention response ranges from -20% to +24%. The largest adverse oil changes are associated with kv/kh (-18%), krg endpoint (-16%) and MMP shift (-14%). The strongest positive retention response is produced by enhanced hysteresis trapping (+24%). Increasing the BHP cap produces a +12% oil-response shift but is retained as an operational sensitivity rather than an automatic optimization target because pressure integrity must be evaluated concurrently [6, 7].

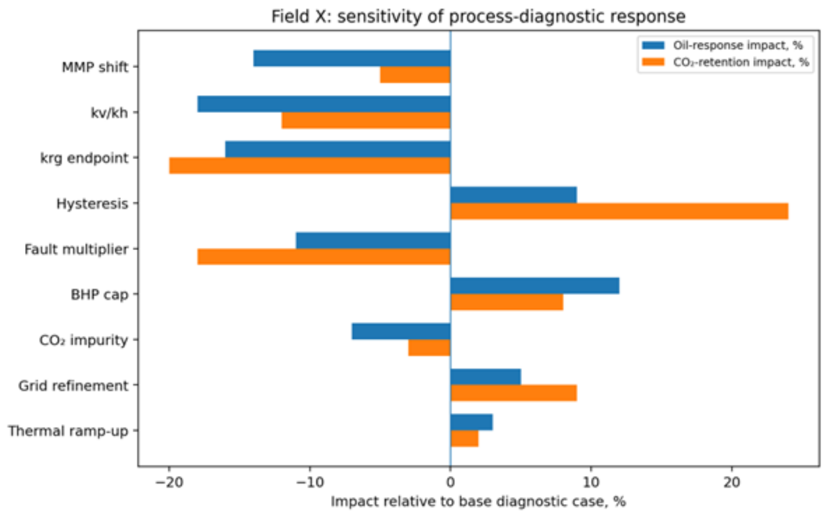

Figure 9 – Quantitative sensitivity of Field X oil response and CO_2 retention to process-diagnostic assumptions

Table 4 – Quantitative sensitivity matrix for Field X process diagnostics

Parameter	Low / Base / High	Oil impact, %	Retention impact, %	Primary block
MMP shift	-1 / 0 / +1 MPa	-14	-5	EOS/PVT
kv/kh	0.02 / 0.08 / 0.16	-18	-12	GRID / vertical flow
krg endpoint	0.45 / 0.65 / 0.85	-16	-20	Three-phase relperm
Hysteresis trapping	off / base / enhanced	+9	+24	Hysteresis
Fault multiplier	0.1 / 1 / 5	-11	-18	Fault connectivity
BHP cap	13.5 / 14.5 / 15.5 MPa	+12	+8	SCHEDULE
CO_2 impurity	0 / 5 / 10%	-7	-3	EOS/PVT
Grid refinement	coarse / base / refined	+5	+9	GRID
Thermal ramp-up	0.5 / 2 / 6 h	+3	+2	Thermal QC

Field-scale production response

The field-scale E300 model provides an independent quantitative check that the process diagnostics correspond to a material production response. Over the 40-year forecast, cumulative oil increases from 17.96 Mt in the Base case to 25.37 Mt in the CO_2 case, giving 7.41 Mt of incremental oil and a 41.3% relative increase. At year 40, the Base oil rate is 0 t/d, while the CO_2 case retains 238.6 t/d. Average reservoir pressure is 22.98 MPa in the Base case and 23.11 MPa in the CO_2 case. Cumulative CO_2 injection reaches 15.67 billion m³, corresponding to approximately 2,115 m³ CO_2 per tonne of incremental oil. These values are the explicit field-scale results; WAG/SAG and foam remain engineering mobility-control options rather than additional full-field forecast claims.

Table 5 – Explicit field-scale Base-versus-CO_2 results for Field X

Indicator	Base case	CO_2 case	Difference / interpretation
Cumulative oil, Mt	17.96	25.37	+7.41 Mt (+41.3%)
Oil rate at year 40, t/d	0.0	238.6	Late-life production sustained by CO_2 case
Average reservoir pressure at year 40, MPa	22.98	23.11	Pressure-support contribution
Cumulative CO_2 injection, billion m³	-	15.67	Field-scale injection volume
Specific CO_2 injection, m³/t incremental oil	-	2,115	Gas-utilization engineering indicator
Cumulative water production, thousand t	55.1	80.0	Higher water handling reflects extended production period

Integrated interpretation

The results establish a two-level acceptance logic. At the process level, the model must pass EOS/MMP, three-phase flow, hysteresis, vertical segregation, operational, thermal and carbon-accounting checks. At the field level, the accepted CO_2 model must produce a material and operationally interpretable response. This separation prevents a positive production curve from being accepted when it is generated by an overly mobile gas function, excessive vertical transmissibility, an undefined MMP transition or incomplete CO_2 accounting. The approach therefore converts the earlier qualitative checklist into a reproducible process-to-simulator quality-control framework with an explicit, auditable process-to-code implementation layer.

Conclusions

1. CO_2-EOR for Field X is represented as a compositional, multiphysics modeling problem rather than a simple additional gas-injection stream. The workflow connects each physical mechanism to a simulator functional block, a diagnostic output, a quantitative sensitivity test and an acceptance

criterion. A representative ECLIPSE E300 implementation chain (RUNSPEC-GRID-PROPS-SOLUTION-SCHEDULE-SUMMARY-MATLAB post-processing) makes the physical-process coding concept explicit without claiming disclosure of the complete confidential Field X deck.

2. The underlying field-scale model is explicitly documented: ECLIPSE E300 compositional mode, 93 × 88 × 78 cells, 638,352 total cells, 194,413 active cells, nominal 100 × 100 × 1 m resolution and a 40-year forecast. Only the Base and continuous CO_2 cases are claimed as explicit field-scale dynamic runs.

3. The MMP reference is 13.2 MPa. The 0.7 MPa term is defined as a numerical logistic transition width used only in the MATLAB QC diagnostic; it does not modify MMP. Physical MMP uncertainty is independently tested at ±1 MPa.

4. The gravity-override indicator is dimensionless because the raw segregation proxy is normalized to the Base diagnostic reference. The CO_2 accounting is also normalized, and the reported diagnostic cases have zero mass-closure error.

5. Quantitative sensitivities identify kv/kh (-18% oil response), krg endpoint (-16%), MMP shift (-14%), fault multiplier (-11%), BHP cap (+12%) and hysteresis (+9% oil; +24% retention) as the principal process controls. The total tested range is -18% to +12% for oil response and -20% to +24% for CO_2 retention.

6. At field scale, continuous CO_2 injection increases cumulative oil from 17.96 to 25.37 Mt, providing 7.41 Mt of incremental oil (+41.3%) and maintaining 238.6 t/d at year 40 compared with zero in the Base case. This field-scale response is supported by the process-level QC workflow rather than interpreted independently of it.

7. Reactive transport is not claimed as an executed result. It is retained only as a future extension when mineral or brine reactions become an injectivity-control mechanism. Pressure-integrity screening is reported without claiming a fully coupled geomechanical solution.

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No external funding was received for this study.

Conflict of interest
The authors declare no conflict of interest.

Data availability
The numerical tables underlying Figures 3–9 and the aggregated Field X results are available from the corresponding author upon reasonable request. Field identifiers, coordinates and commercially sensitive reservoir data are anonymized.

Author Contributions
A.B. Niyazbayeva developed the conceptual framework, process-to-simulator quality-control workflow, Field X sector-case interpretation, MATLAB diagnostic module, quantitative sensitivity analysis, visualization package, and original manuscript.

I.M. Saaid contributed to scientific supervision, validation of the interpretations, and critical review and editing of the manuscript, including scientific revisions and additions made in response to the reviewers' comments. All authors have read and approved the final version of the manuscript.

REFERENCES

1 Lee, H.-S.; Cho, J.; Lee, Y.-W.; Lee, K.-S. Compositional Modeling of Impure CO_2 Injection for Enhanced Oil Recovery and CO_2 Storage. Applied Sciences 2021, 11(17), 7907. https://doi.org/10.3390/app11177907.

2 Song, Y.; Song, Z.; Chen, Z.; Mo, Y.; Zhou, Q.; Tian, S. Simulation of CO_2 enhanced oil recovery and storage in shale oil reservoirs: Unveiling the impacts of nano-confinement and oil composition. Advances in Geo-Energy Research 2024, 13(2), 106–118. https://doi.org/10.46690/ager.2024.08.05.

3 Sharma, M. CO_2 Mobility Control with Foam for Enhanced Oil Recovery and Associated Storage: Multi-scale Approach for Field Application. PhD thesis, University of Stavanger, 2019.

4 Khan, M.Y. Mathematical model and its solution for water-alternating-gas (WAG) injection process incorporating the effect of miscibility, gravity, viscous fingering and permeability heterogeneity. Journal of Petroleum Exploration and Production Technology 2024, 14(12), 3183–3211. https://doi.org/10.1007/s13202-024-01884-7.

5 Luo, Q.; Li, Y.; Sun, H.; Liu, S.; Yu, Y.; Yang, Z. Research on CO_2-WAG in Thick Reservoirs: Geological Influencing Factors and Random Forest Importance Evaluation. ACS Omega 2024, 9(31), 34118–34127. https://doi.org/10.1021/acsomega.4c04901.

6 Chiaramonte, L. Geomechanical Characterization and Reservoir Simulation of a CO_2 Sequestration Project in a Mature Oil Field, Teapot Dome, WY. PhD dissertation, Stanford University, 2008.

7 Ruciński, P. Geomechanical Integrity of Offshore Oil Reservoir During EOR-CO_2 Process: A Case Study. Energies 2025, 18(21), 5751. https://doi.org/10.3390/en18215751.

8 Samuel, R.J. Transient Flow Modelling of Carbon Dioxide Injection into Depleted Gas Fields. PhD thesis, University College London, 2019.

9 Zhang, Y.; Huang, X.; Jiang, L.; Song, Y. Numerical Simulation of Heat Transfer Characteristics of CO_2 Gas Mixture Injection into Wellbores. Energy & Fuels 2024, 38(21), 21065–21078. https://doi.org/10.1021/acs.energyfuels.4c04202.

10 Popova, O.H. Development of Geostatistical Models to Estimate CO_2 Storage Resource in Sedimentary Geologic Formations. PhD thesis, Carnegie Mellon University, 2014.

11 Farshidi, S.F. Compositional Reservoir Simulation-Based Reactive-Transport Formulations, with Application to CO_2 Storage in Sandstone and Ultramafic Formations. PhD thesis, Stanford University, 2016.

12 Niu, B. CO_2 Flooding in Chalk Reservoirs: Experiments with X-Ray Computed Tomography and Reactive Transport Modelling. PhD thesis, Technical University of Denmark, 2010.

13 Niyazbayeva, A.B.; Merbayev, R.B.; Samenov, Y.R.; Zholdybayeva, A.T.; Kozhagulova, A.A.; Shabdirova, A.D. Laboratory Investigation of Miscible CO_2-Induced Enhanced Oil Recovery from the East-Southern Pre-Caspian Region. Processes 2025, 13, 2566. https://doi.org/10.3390/pr13082566.

14 Nam, L.N.H. Study on Enhanced Oil Recovery by CO_2 Microbubbles Injection. PhD dissertation, Kyushu University, 2022.

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КАРБОНАТҚҰРАМДЫ КОЛЛЕКТОРЛАРДА МҰНАЙ БЕРГІШТІКТІ АРТТЫРУ ӘДІСІН ТАҢДАУДЫ НЕГІЗДЕУ ҮШІН ҚАБАТТЫҢ ИГЕРІЛУ КӨРСЕТКІШТЕРІН МОДЕЛЬДЕУ ЖӘНЕ ТЕХНОЛОГИЯЛЫҚ ПРОЦЕСТІ СИМУЛЯТОРҒА КӨШІРУ САПАСЫН БАҚЫЛАУ

Аңдатпа

Мұнай бергіштікті арттыру әдістерін сенімді таңдау өндіру динамикасымен қатар, қысымның өзгеруін, флюидтердің қасиеттерін, көпфазалы ағынды, газдың қозғалғыштығын, ұңғымаларды пайдалану шектеулерін және қабаттың ұзақ мерзімді реакциясын сипаттайтын кешенді модельдеуді талап етеді. Бұл жұмыста Қазақстандағы анонимдендірілген карбонатты X кен орнының мысалында CO_2 айдауға негізделген мұнай бергіштікті арттыру (МБА) әдістерін бағалау үшін қабаттың пайдалану көрсеткіштерін модельдеу және физикалық процестерді кодтау тәсілі ұсынылған. Толық ауқымды есептеу 93 × 88 × 78 ұяшықтан тұратын, оның ішінде 194 413 белсенді ұяшығы бар үшөлшемді ECLIPSE E300 композициялық моделі негізінде 40 жылдық болжамды кезеңге жүргізілді. Есептеу жүйесі PVT/EOS сипаттамасын, ең төменгі араласу қысымын (MMP), үш фазалы салыстырмалы өткізгіштікті, гистерезисті, тік гидродинамикалық байланыстылық пен гравитациялық сегрегацияны, айдау кестесін, түптік қысым шектеулерін, ұңғымадағы жылулық әсерлерді және CO_2 материалдық балансын біріктіреді. Әрбір физикалық механизм симулятордың тиісті функционалдық блогымен, диагностикалық көрсеткішпен, сезімталдық талдауымен және қабылдау критериймен байланыстырылған. RUNSPEC–GRID–PROPS–SOLUTION–SCHEDULE–SUMMARY тізбегі және MATLAB бағдарламасы арқылы нәтижелерді кейінгі өңдеу қабат физикасынан бастап болжамдық нәтижелерді түсіндіруге дейінгі қадағаланушылықты қамтамасыз етеді. Сезімталдық талдауы нәтижесінде тік байланыстылық, газдың салыстырмалы өткізгіштігі, MMP белгісіздігі, жарықшақтардың өткізгіштігі, гистерезис және түптік қысым шектеулері негізгі факторлар ретінде айқындалды. CO_2-ні үздіксіз айдау жинақталған мұнай өндіру көлемін 17,96 млн тоннадан 25,37 млн тоннаға дейін арттырып, 7,41 млн тонна көлемінде қосымша өндіруді (+41,3%) қамтамасыз етті. 40-жылы мұнай дебиті тәулігіне 238,6 тонна деңгейінде сақталса, базалық нұсқада бұл көрсеткіш нөлге дейін төмендейді. Алынған нәтижелер қабат жұмысын интеграцияланған модельдеу оның мінез-құлқын болжауға, белгісіздіктерді сандық тұрғыдан бағалауға және техникалық негізделген МБА әдісін таңдауға қажетті сенімді инженерлік негіз қалыптастыратынын көрсетеді.

Түйін сөздер: CO_2-МБА, кен орнын игеруді модельдеу, физикалық процестерді кодтау, МБА әдісін таңдау, CO_2 материалдық балансы, карбонатқұрамды коллектор.

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МОДЕЛИРОВАНИЕ ПОКАЗАТЕЛЕЙ РАЗРАБОТКИ ПЛАСТА И КОНТРОЛЬ КАЧЕСТВА ПЕРЕНОСА ТЕХНОЛОГИЧЕСКОГО ПРОЦЕССА В СИМУЛЯТОР ДЛЯ ОБОСНОВАНИЯ ВЫБОРА МЕТОДА УВЕЛИЧЕНИЯ НЕФТЕОТДАЧИ В КАРБОНАТСОДЕРЖАЩИХ КОЛЛЕКТОРАХ

Аннотация

Надежный выбор методов увеличения нефтеотдачи требует гидродинамического моделирования разработки, воспроизводящего не только динамику добычи, но и физические механизмы, определяющие давление, свойства флюидов, многофазное течение, подвижность газа, работу скважин и долгосрочную реакцию пласта. В работе предложен подход к моделированию разработки и кодированию физических процессов для оценки методов увеличения нефтеотдачи (МУН) на основе закачки CO_2 на примере анонимизированного карбонатсодержащего объекта Field X в Казахстане. Полномасштабное моделирование выполнено в ECLIPSE E300 на трехмерной композиционной модели 93×88×78 ячеек, включая 194 413 активных ячеек, с прогнозным периодом 40 лет. Расчетная схема объединяет PVT/EOS, минимальное давление смесимости (MMP), трехфазные относительные проницаемости, гистерезис, вертикальную связанность и гравитационную сегрегацию, график закачки, ограничения по забойному давлению, термический отклик скважины и материальный баланс CO_2. Каждый физический механизм связан с функциональным блоком симулятора, диагностическим показателем, анализом чувствительности и критерием приемлемости. Последовательность RUNSPEC–GRID–PROPS–SOLUTION–SCHEDULE–SUMMARY с последующей обработкой в MATLAB обеспечивает прослеживаемость от пластовой физики до интерпретации прогноза. Анализ чувствительности выделил вертикальную связанность, газовую относительную проницаемость, неопределенность ММР, проводимость разломов, гистерезис и ограничения по забойному давлению как основные факторы. Непрерывная закачка CO_2 увеличивает накопленную добычу нефти с 17,96 до 25,37 млн т, обеспечивая 7,41 млн т дополнительной добычи (+41,3%). На 40-й год дебит нефти сохраняется на уровне 238,6 т/сут против нуля в базовом варианте. Результаты подтверждают, что интегрированное моделирование разработки обеспечивает инженерную основу для прогнозирования поведения пласта, количественной оценки неопределенности и обоснованного выбора метода МУН.

Ключевые слова: CO_2-МУН, гидродинамическое моделирование разработки, кодирование физических процессов, выбор метода МУН, материальный баланс CO_2, карбонатсодержащий коллектор.