ADVANCED CT-BASED RESERVOIR CHARACTERISATION FOR CO_2 STORAGE: MULTI-SCALE ANALYSIS AND GEOMECHANICAL MODELING OF TÁZLÁR FIELD, HUNGARY

Thesis Booklet

By

Gábor Pál Veres

MS Petroleum Engineer, Economist

Scientific supervisor:

Dr. István Szunyog

Industrial supervisor:

Dr. Béla Kelemen

MIKOVINY SÁMUEL DOCTORAL SCHOOL OF EARTH SCIENCES

Head of the doctoral school: Prof. Dr. Péter Szűcs

Budapest, Hungary

2025

1.) Objectives and targets

The dissertation objectives aim to address knowledge gaps in geological CO_2 sequestration processes, focusing on depleted gas reservoirs with complex pore structures and heterogeneous properties. The research integrates scientific investigation with engineering applications, enhancing both theoretical understanding and technological progress in carbon capture and storage. This research focuses on the geological and technical aspects of CO_2 injection and storage, specifically reservoir characterization, storage mechanisms, and operational feasibility. The research makes several significant technical contributions to CCS knowledge and methodology development.

The application of medical CT scanners for detailed reservoir characterization represents a novel approach that provides cost-effective, high-resolution analysis of core samples. The methodology enables comprehensive evaluation of porosity distributions, fracture networks, and structural heterogeneity essential for storage assessment.
Integration of mCT analysis with controlled displacement experiments offers unique capabilities for understanding CO_2 storage processes. Monitoring displacement fronts and saturation changes provides fundamental insights into storage mechanisms at the pore scale. This knowledge supports the development of improved injection strategies and reservoir management techniques.

Comprehensive experimental programs combining multiple analytical techniques provide robust validation of characterization methodologies. The integration of CT imaging, laboratory measurements, and microscopy analysis ensures accurate understanding of reservoir properties and storage behavior.
This multi-technique approach establishes best practices for future storage site assessment.

Advanced geomechanical modeling approaches demonstrate practical methods for assessing storage security and operational constraints. The integration of reservoir simulation with mechanical analysis provides comprehensive evaluation of injection scenarios and associated risks. These capabilities are essential for safe and effective storage implementation.

2.) Parameters, measurements, conclusions

In order to simulate real-world processes at laboratory scale and to model conditions that most closely resemble the presumed implementation, the following boundary conditions were applied:

- CO_2 was injected into a supercritical state under both static and dynamic flooding scenarios;
- The model design incorporated field and laboratory data accumulated over decades and utilized by MOL Plc;
- The values for pressure and temperature used in the simulations were derived from known conditions at the start of field development and at the end of production;
- Core samples previously extracted from wells were selected based on defined criteria, and only those were used for the experiments;
- The origin and quantity of the examined core samples were predetermined;
- The number of tests that could be conducted was constrained by the available financial resources;
- The resulting database served as the foundation of the research;
- The model can be refined in the future through the analysis and integration of additional samples. During the research, the aim was to enhance the experimental methodology and improve the accuracy of the results.

1.) The measurement program for static CO_2 flooding and static holding was defined according to the following parameters.

CO_2 flooding	Duration (weeks)	Temperature (°C)	Pressure (bar)
Before CO_2 flooding	-	23	-
I. cycle of CO_2 flooding	1	50	65
II. cycle of CO_2 flooding	1	100	90
III. cycle of CO_2 flooding	2	100	90
IV. cycle of CO_2 flooding	1	135	90
V. cycle of CO_2 flooding	1	135	90
VI. cycle of CO_2 flooding	2	135	90

The measurement program for static CO_2 saturation and static holding was defined based on the following parameters: saturation durations, temperature and pressure values were determined in consideration of the resources and laboratory equipment specifications (core holder cell, CO_2 gas cylinder, manometer) available at the Research Institute of Applied Earth Sciences, University of Miskolc. For the first saturation cycle, it was defined to include

CO_2 saturation in its gaseous state, followed by exposure to several temperatures above the critical point of CO_2, under the maximum pressure achievable under laboratory conditions (90 barg).

Following the measurement of basic rock parameters, 5 out of the available 18 core samples were selected for further testing. Selection was based on the highest porosity and permeability values, as well as the aim to represent different reservoir units and lithologies to obtain the most comprehensive dataset possible from the measurements.

After the CO_2 treatment contact time elapsed, the cores were removed from the pressure-retaining cell. The rock samples were then dried in a laboratory oven until constant mass was achieved, after which repeated He porosity and N_2 permeability measurements were performed. Subsequently, the cores were returned to the cell, and the next flooding cycle commenced. After 6 measurement cycles, an increase in porosity and permeability was observed between the initial and final states for samples CT-1/1 (quartz-rich clay shale), CT-3/1 (conglomerate), and CT-8/1 (sandstone). These findings were corroborated by thin-section petrographic analyses. In these samples from the Tázlár field, CO_2 induced dissolution processes, although no crystallization or carbonate precipitation was observed. For sample CT-10/1 (bioclastic marl), He porosity increased after the I. saturation cycle, decreased during the II. and III. cycles, and then showed a clear increase again following the IV.-V.-VI. treatments. N_2 permeability initially showed a slight decrease, followed by a marked increase after the fourth to sixth treatments.

In the case of sample CT-11/1 (bioclastic limestone), He porosity increased after the I. and II. CO_2 flooding cycles, but subsequent cycles led to a decrease or stagnation. N_2 permeability decreased after the I. and V. treatments, while slight increases were observed following the other cycles.

2.) It was the first application of medical-grade CT scanners for geological reservoir analysis in Hungary, quantitative 3D characterization of porosity, permeability. The measurement program was developed for dynamic CO_2 flooding using micro-CT (mCT) rock analysis. The objective was to model hydrocarbon production under laboratory conditions following the reproduction of initial reservoir conditions and formation fluids and subsequently simulate CO_2 injection based on the current reservoir state-mirroring the process as it would occur at field scale. The initial reservoir temperature was 128 °C;

however, due to the technical limitations of the mCT equipment, this temperature could not be achieved during measurement. Nevertheless, a temperature of 90 °C was sufficient to maintain CO_2 in a supercritical state at the applied pressure steps, enabling realistic simulation of field conditions. The mCT technology allowed for the visualization of flow patterns and the determination of porosity and permeability values throughout the following experimental steps:

a.) Establishing the initial state: the sample was held under vacuum until its mass stabilized.

b.) Flooding the dry sample with ion-exchange water at room temperature. The injected volume was 10 cm³, with an estimated pore volume of 0.8 cm³.

c.) Performing mCT measurement on the water-saturated sample.

d.) Injecting an additional 10 cm³ of ion-exchanged water to ensure full saturation, with pressure increased up to 100 barg.

e.) Performing mCT measurement on the fully saturated sample.

f.) Increasing pressure to the initial reservoir pressure of 207 barg.

g.) Performing mCT measurement.

h.) Raising the temperature to 90 °C.

i.) Performing mCT measurement.

j.) First CH_4 flooding cycle at 207 barg and 90 °C. Injected volume: 10 cm³.

k.) Performing mCT measurement.

l.) Second CH_4 flooding cycle at 207 barg and 90 °C. Injected volume: 10 cm³.

m.) Performing mCT measurement.

n.) Adjusting to current reservoir pressure: 30 barg.

o.) Performing mCT measurement.

p.) Increasing pressure to 100 barg. First CO_2 flooding cycle at 100 barg and 90 °C. Injected volume: 10 cm³.

q.) Performing mCT measurement.

r.) Increasing pressure to 207 barg. Second CO_2 flooding cycle at 207 barg and 90 °C. Injected volume: 10 cm³.

s.) Performing mCT measurement.

Based on the experiments, the following observations were made:

3.) During mCT measurement, the cylindrical rock specimen is reconstructed slice by slice (with slice thickness depending on the resolution of the equipment). The evaluation of the measurement is based on average parameters calculated for each individual slice.

4.) Calibration confirmed that measurement noise did not influence the results.

5.) The mCT technique is capable of distinguishing between three different fluids - water, methane, and supercritical CO_2 - under reservoir conditions, based on their density differences.

6.) During the CO_2 injection/methane displacement process, a steady-state condition was not achieved. CO_2 did not fully traverse the sample, thus relative permeability could not be determined. A total of 10 cm³ of CO_2 was injected into a pore volume of 0.8 cm³. This more than tenfold volumetric ratio was based on preliminary estimation. Since real-time monitoring of the flooding process was not possible, the extent of flooding could only be inferred retrospectively from the measurement results. For future repetitions of the experiment, either the duration of the measurement or the volume of injected CO_2 should be increased. However, financial resources were not available to repeat the measurements.

7.) As steady-state flow was not achieved and CO_2 did not fully penetrate the pore space, permeability calculations must rely on new in-situ interpretations at the slice level. For a given porosity, multiple permeability values may be associated; however, some slices exhibit similar behavior. At different effective volume percentages (2%, 12%, 25%, and 100%), distinct new porosity–permeability correlations were established, as summarized in the following table.

Calculated Porosity-permeability correlations

(Edited by the author)

Effective volume	**Porosity-permeability correlation**
100%	$K = 23.291 \cdot e^{0.0994 \cdot \varphi}$
25%	$K = 6.8474 \cdot e^{0.1887 \cdot \varphi}$
12%	$K = 2.7628 \cdot e^{0.3329 \cdot \varphi}$
2%	$K = 0.3436 \cdot e^{1.3884 \cdot \varphi}$

e - Euler number and φ - porosity (%)

Thesis 1) “Clarifying the presence or absence of an active aquifer”

By integrating the production history of the Tázlár field, formation pressure measurement data, and the static PVT model into a new software platform (tNavigator) - which had not previously been used for this field - it was demonstrated that, contrary to earlier assumptions, the field does not possess an active aquifer and no water influx occurs within the reservoir. Using this data, a high-accuracy history match was achieved both at the individual well level and for the entire field, under the assumption of an aquifer-free system. When an active aquifer was assumed, the simulated data showed very limited correlation with the measured data.

Clarifying the presence or absence of an active aquifer is of critical importance for CO_2 storage, as the presence of large volumes of formation water influences CO_2 flow behavior, available pore volume, dissolution potential, and formation pressure, ultimately affecting the volume of CO_2 that can be injected.

Thesis 2) "Derivation of porosity-permeability relationships across different lithologies"

8.) The calibrated dynamic model (history-matched, assuming a homogeneous reservoir with a permeability of 30 mD - both boundary conditions derived from the static model developed and used by MOL Plc.) revealed that the commonly used porosity–permeability correlation:

$$K = e^{0.306 \cdot \varphi - 6.142}$$

is not suitable for characterizing the reservoir when considering known field data. This correlation has also appeared in previous production review plans.

9.) One of the outputs of the mCT measurements was new porosity-permeability correlations for the selected core sample.
Based on the mCT measurements, the calculated correlations come form the flooded section (495-700 slices). The measured permeability values are in unusable high range, at 100%, 25% and 12% effective volume, represent higher quality rock or these slices with higher porosity probably cross a fracture, and their use would paint a completely extreme (unrealistic) picture of the storage facility. It has been concluded that not to use them as the base of the permeability calculation.
At 2% of effective volume, the porosity – permeability dotes are in a same range, where the 10 mD and 30 mD minimal and maximal permeability values originally assume.

The correlation describing the flatter curve was used:

$$K = 0.3436 \cdot e^{1.3884 \cdot \varphi}$$

The calculated permeability distribution is the following:

Applying the porosity-permeability correlation derived from the core sample results in an average of approximately 14 mD. This is comparable to the "theoretic" minimum average of 10 mD, indicating that the outcomes do not significantly deviate from earlier scenarios.

Thesis 3) "Novel integration of CT and mCT technologies for reservoir-scale heterogeneity analysis"

Among the porosity–permeability correlations obtained from the mCT measurements, the one assuming the lowest permeability value - when implemented into the dynamic model - resulted in a better match (14 mD). Thus, using the porosity–permeability correlation derived from the mCT measurement that assumes the lowest (and most realistic) permeability yielded a more accurate history match in the dynamic simulation. Nevertheless, the sample used in the measurement cannot be considered representative, and the reservoir itself is not homogeneous. However, it was confirmed that by conducting additional similar measurement programs, the porosity–permeability correlation for the field can be significantly refined.

10.) Geomechanical sensitivity analyses were also conducted. In the absence of measured rock physical parameters, literature data were used to make several inferences regarding the reservoir, the caprock, and surface conditions. Based on the simulation program and the boundary conditions summarized in the following table, the following results were obtained:

		Permeability	**Young modulus [MPa)**	**Poisson ratio**	**Friction angel (theta)**	**cohesion**
1. Case - min	Reservoir	30	300,000	0.17	0	6
	Cap rock	0.00001	50,000	0.10	0	14
2. Case - max	Reservoir	30	900,000	0.35	32	40
	Cap rock	0.00001	300,000	0.10	14	40
3. Case - min	Reservoir	10	300,000	0.17	0	6
	Cap rock	0.00001	50,000	0.10	0	14
4. Case - max	Reservoir	10	900,000	0.35	32	40
	Cap rock	0.00001	300,000	0.10	14	40
5. Case - combination 1	Reservoir	30	300,000	0.17	32	40
	Cap rock	0.00001	50,000	0.10	14	40
6. Case - combination 2	Reservoir	30	900,000	0.35	0	6
	Cap rock	0.00001	300,000	0.10	0	14

The following boundary conditions were used in the simulations:

- Initial and current reservoir pressures and temperatures
    - Initial reservoir pressure, temperature: 207 barg; 128°C
    - Current reservoir pressure, temperature: 30 barg; 128°C
- Maximum available layer pressure at initial layer pressure: 200 barg
- Amount of injected CO_2 1,2 Mt/year (planned storage volume by MOL Plc.)
- Overburden: marble

Thesis 4) "Implementation of field-calibrated geomechanical models using tNavigator"

Damage to the reservoir, wellbore vicinity, or caprock during CO_2 injection occurred only when the rock's internal friction angle was assumed to be 0°. No other parameter variation led to fracturing of the formation. Based on literature data, six different simulation cases were run using various extreme values for both the reservoir and the caprock, as summarized in the table above.

11.) The results of the six-simulation run suggested that further simulations were warranted to investigate the influence of additional friction angle values on damage occurrence. Consequently, a series of supplementary simulation scenarios were defined. To refine the estimation of the friction angle between the storage formation and the cap rock, an interval halving method was used. This iterative technique allowed for a more precise approximation of the critical friction angle values associated with structural damage.

Finally, the last simulation case incorporated the most representative literature-based average values for the lithology of the Tázlár formation. This provided a realistic benchmark for evaluating the mechanical behavior of the system under typical geological conditions. Confirmed: No other parameter variation led to fracturing of the formation.

12.) According to the surface deformation simulation results, the ground surface has subsided by more than 20 mm in certain areas since the start of production, based on known production and pressure data. Under the projected injection rate of 1.2 Mt/year and a maximum allowable reservoir pressure of 207 barg, these surface deformations are expected to reverse, returning to pre-production conditions.

13.) If the maximum allowable reservoir pressure during injection is increased to twice the initial reservoir pressure (~400 barg), the reservoir fractures and wellbore damage occur in all cases.

Thesis 5) “Estimation of safe CO_2 injection parameters”

Simulations were also conducted assuming 10 mD and 30 mD permeability values. The main conclusion from the model runs is that the results are not dependent on permeability. Using an average permeability value renders the model homogeneous, which does not accurately represent the reservoir. The only difference caused by using minimum versus maximum permeability is the time required to reach the maximum reservoir pressure. With an average permeability of 10 mD, the maximum pressure of 207 barg is reached in approximately 75 years, whereas with 30 mD, it is reached after 25 years.

14.) The total injectable volume differs slightly according to the simulation results. Assuming an average permeability of 10 mD, the reservoir reaches near-maximum pressure in about 35 years. Over the following 40 years, the inflow rate becomes minimal until the maximum reservoir pressure is reached. This is due to the low permeability and the limited pressure differential, as the bottomhole pressure is capped at 207 barg. In contrast, assuming an average permeability of 30 mD, the reservoir reaches the maximum allowable pressure after 25 years, during which time the total injected CO_2 volume is approximately 10% higher than in the previous case.

Laboratory experimental programs utilize limited sample sets that may not fully represent field-scale heterogeneity. Scaling effects between laboratory and field conditions require careful consideration in applying experimental results to actual storage operations. Additional testing of diverse sample types would strengthen confidence in regional storage assessment.

Geomechanical property databases for Hungarian reservoir rocks remain limited, requiring reliance on literature values and analogous field data. Direct measurement programs for key geomechanical parameters would significantly improve modeling accuracy and reduce uncertainty in risk assessment. Enhanced characterization of caprock properties is particularly important for storage security evaluation.

Long-term storage behavior prediction relies on relatively short-term experimental programs that may not capture all relevant processes. Extended experimental programs and field monitoring data are needed to validate long-term storage security predictions. Understanding of geochemical reactions requires longer-term studies to assess mineral trapping potential.

Thesis 6) "Simulation based specified values of Tázlár field reservoir properties"

The dynamic simulation ensures values about Tázlár reservoir properties, these numbers obtained can then provide a foundation for further economic analyses.

The calculated total injected CO_2 after 25 years	**@10 mD**	**@30 mD**
Total injected CO_2 volume	3.08 billion m^3	3.36 billion m^3
Total injected CO_2 mass	6.31 Mt	6.89 Mt

Original Gas in Place	3.02 billion m^3
Pore Volume @ Reservoir Conditions	21.20 Mm^3
Total gas production	2,557.78 Mm^3

The integrated analysis estimates CO_2 storage capacity of ~7 million tons (3.36 billion m^3), with structural and residual trapping mechanisms dominating initially, followed by gradual increases in solubility and mineral trapping over time.

At reservoir conditions, above CO_2 critical pressure and temperature, CO_2 behaves like a supercritical fluid, with a density often 2–3 times that of methane at the same reservoir pressure. This means that for the same pore space, more standard cubic meters of CO_2 molecules are storable than methane molecules.

This research provides essential foundation for advancing CO_2 storage implementation in Hungary and similar geological settings worldwide. Continued development of characterization methodologies, experimental validation, and demonstration projects will accelerate the deployment of this critical climate change mitigation technology.

List of Publications

1. Veres, Gábor Pál; Földes, Tamás; Szunyog, István: Assessment of core samples through the analysis of CT measurements and its implications for CO_2 sequestration potential in a Hungarian depleted oil field; RESULTS IN ENGINEERING 24 Paper: 103241, 14 p. (2024); Scientific Journal subject: Scopus - Engineering (miscellaneous) Rank: D1
2. Veres, Gábor Pál: Supercritical CO_2 injection in moderate-tight hydrocarbon reservoirs, a preliminary case study; SCIENTIA ET SECURITAS 3: 3 pp. 176-184., 9 p. (2022) Regionális Tudományok Bizottsága HASSELIX RTB [1901-] D hazai
3. Veres, Gábor Pál: Magyarország energiastratégiája a klímasemlegesség tükrében; MULTIDISZCIPLINÁRIS TUDOMÁNYOK: A MISKOLCI EGYETEM KÖZLEMÉNYE 11: 1 pp. 69-75., 7 p. (2021)
4. Veres, Gábor Pál; Tihanyi, László; Szunyog, István: Végfelhasználói gázár változása nyolc EU tagországban 2010 - 2019 között; ENERGIAGAZDÁLKODÁS 62. évf. 2-3. szám pp. 30-34., 5 p. (2021)
5. Veres, Gábor Pál; Vadászi, Mariann: Az ipari szén-dioxid-leválasztás eljárásainak összehasonlító elemzése; MAGYAR ENERGETIKA 28: 4 pp. 26-30., 5 p. (2021)
6. Veres, Gábor Pál; Tóth, Anikó Nóra PhD: Current Situation and Potential of Miskolc District Heating; Euroheat and Power (English Edition) 22698: 4 pp. 38-42., 5 p. (2021) Scientific Journal subject: Scopus - Energy Engineering and Power Technology Rank: Q4