UDC 502/504
CSCSTI 87.17.03

DOI: https://doi.org/10.54859/kjogi108781

Received: 16.09.2024.
Accepted: 28.11.2024.
Published: 31.12.2024.

Original article

The role of Capillary Hysteresis in Enhancing CO_2 Trapping Efficiency and Storage Stability

Reza Khoramian, Peyman Pourafshary, Masoud Riazi
School of Mining and Geosciences, Nazarbayev University, Astana, Kazakhstan

ABSTRACT

Background: The intensifying impact of climate change demands innovative approaches to reduce atmospheric CO_2 levels. Carbon Capture and Storage (CCS) offers a viable solution by sequestering CO_2 in geological reservoirs. However, understanding the role of capillary hysteresis in CO_2 trapping is critical for optimizing CCS performance.

Aim: This study aims to investigate the influence of capillary hysteresis on CO_2 trapping efficiency in saline aquifers using detailed simulation models and varying hysteresis values.

Materials and methods: Advanced CMG simulation software was utilized to model CO_2 injection and migration in saline aquifers spanning depths of 1200–1300 meters. The model, initially saturated with brine, applied water-alternating-gas (WAG) injection at hysteresis values of 0.2, 0.3, 0.4, and 0.5 to evaluate their effect on CO_2 trapping efficiency.

Results: The simulations demonstrated a direct positive correlation between hysteresis values and CO_2 trapping efficiency. At a hysteresis value of 0.5, nearly 100% CO_2 trapping was achieved. This increased efficiency was attributed to stronger capillary forces immobilizing CO_2 more effectively and reducing mobility towards caprock, thereby minimizing leakage risks.

Conclusion: The study highlights the key role of capillary hysteresis in enhancing CO_2 sequestration. Higher hysteresis values improve long-term storage stability, emphasizing the need for optimized WAG injection strategies in CCS applications.

Keywords: *CO_2 storage; capillary hysteresis; saline aquifers; WAG injection; climate change mitigation.*

To cite this article:
Khoramian R, Pourafshary P, Riazi M. The role of Capillary Hysteresis in Enhancing CO_2 Trapping Efficiency and Storage Stability. *Kazakhstan journal for oil & gas industry.* 2025;7(1):90–99. DOI: https://doi.org/10.54859/kjogi108781.

УДК 502/504
МРНТИ 28.11.2024.

DOI: https://doi.org/10.54859/kjogi108781

Получена: 16.09.2024.
Одобрена: 87.17.03
Опубликована: 31.12.2024.

Оригинальное исследование

Роль капиллярного гистерезиса в повышении эффективности улавливания и стабильности хранения CO_2

Р. Хорамиан, П. Пурафшари, М. Риази
Школа горного дела и наук о Земле, Назарбаев Университет, г. Астана, Казахстан

АННОТАЦИЯ

Обоснование. Усиление воздействия изменения климата требует инновационных подходов к снижению уровня CO_2 в атмосфере. Улавливание и хранение углерода обеспечивает действенное решение путём секвестрации CO_2 в геологических коллекторах. Понимание роли капиллярного гистерезиса в улавливании CO_2 имеет решающее значение для оптимизации эффективности улавливания и хранения углерода.

Цель. Цель данного исследования является изучение влияния капиллярного гистерезиса на эффективность улавливания CO_2 в солёных водоносных горизонтах с помощью детальных имитационных моделей и переменных значений гистерезиса.

Материалы и методы. Для моделирования закачки и миграции CO_2 в солёные водоносные горизонты глубиной 1200–1300 м было использовано современное программное обеспечение CMG. В модели, первоначально насыщенной рассолом, применялась поочередная закачка воды и газа при значениях гистерезиса 0,2, 0,3, 0,4 и 0,5 для оценки влияния этих значений на эффективность улавливания CO_2.

Результаты. Моделирование показало прямую положительную корреляцию между величиной гистерезиса и эффективностью улавливания CO_2. При значении гистерезиса 0,5 было достигнуто почти стопроцентное улавливание CO_2. Такое повышение эффективности объясняется тем, что более сильные капиллярные силы эффективнее иммобилизуют CO_2 и снижают его подвижность в сторону покрова продуктивного пласта, тем самым минимизируя риски утечки.

Заключение. Исследование подчеркивает ключевую роль капиллярного гистерезиса в повышении эффективности секвестрации CO_2. Более высокие значения гистерезиса улучшают долгосрочную стабильность хранилища, подчеркивая необходимость оптимизации стратегий поочередной закачки воды и газа в системах улавливания и хранения углерода.

Ключевые слова: *хранение CO_2, капиллярный гистерезис, соленые водоносные горизонты, поочередная закачка воды и газа, смягчение последствий изменения климата.*

Как цитировать:
Хорамиан Р., Пурафшари П., Риази М. Роль капиллярного гистерезиса в повышении эффективности улавливания и стабильности хранения CO_2 // Вестник нефтегазовой отрасли Казахстана. 2025. Том 7, №1. С. 90–99. DOI: https://doi.org/10.54859/kjogi108781.

ӘОЖ 502/504
ҒТАХР 87.17.03

DOI: https://doi.org/10.54859/kjogi108781

Қабылданды: 16.09.2024.
Мақұлданды: 28.11.2024.
Жарияланды: 31.12.2024.

Түпнұсқа зерттеу

Капиллярлық гистерезистің CO_2 тұту тиімділігі мен сақтау тұрақтылығын арттырудағы рөлі

Р. Хорамиан, П. Пурафшари, М. Риази
Тау-кен ісі және Жер туралы ғылымдар мектебі, Назарбаев Университеті, Астана қаласы, Қазақстан

АННОТАЦИЯ

Негіздеу. Климаттың өзгеруінің әсерін күшейту атмосферадағы CO_2 деңгейін төмендетудің инновациялық тәсілдерін қажет етеді. Көміртекті ұстау және сақтау геологиялық коллекторларда CO_2 секвестрлеу арқылы тиімді шешімді қамтамасыз етеді. Капиллярлық гистерезистің CO_2 тұтудағы рөлін түсіну көміртекті ұстау және сақтау тиімділігін оңтайландыру үшін өте маңызды.

Мақсаты. Бұл зерттеудің мақсаты – капиллярлық гистерезистің толық имитациялық модельдер мен гистерезис мәндерінің айнымалылары арқылы тұзды сулы горизонттардағы CO_2 тұту тиімділігіне әсерін зерттеу.

Материалдар мен әдістер. Тереңдігі 1200-1300 м тұзды сулы горизонттарға CO_2 айдау және кезуін модельдеу үшін заманауи CMG бағдарламалық жасақтамасы қолданылды. Бастапқыда тұзды ерітіндімен қаныққан модельде бұл мәндердің CO_2 тұту тиімділігіне әсерін бағалау үшін гистерезис 0,2, 0,3, 0,4 және 0,5 мәндерінде кезектесіп су мен газ айдау қолданылды.

Нәтижелері. Модельдеу гистерезис мөлшері мен CO_2 тұту тиімділігі арасындағы тікелей оң корреляцияны көрсетті. Гистерезис мәні 0,5 болған кезде CO_2-ны жүз пайызға жуық тұтуға қол жеткізілді. Бұл тиімділіктің артуы күшті капиллярлық күштер CO_2-ны тиімді иммобилизациялайтындығымен және оның өнімді қабаттың қақпағына қарай қозғалғыштығын төмендететіндігімен түсіндіріледі, осылайша ағып кету қаупін азайтады.

Қорытынды. Зерттеу капиллярлық гистерезистің CO_2 секвестрінің тиімділігін арттырудағы негізгі рөлін көрсетеді. Гистерезистің жоғары мәндері көміртекті тұту және сақтау жүйелерінде су мен газды кезек-кезек айдау стратегияларын оңтайландыру қажеттілігін көрсете отырып, ұзақ мерзімді сақтау тұрақтылығын жақсартады.

Негізгі сөздер: *CO_2 сақтау, капиллярлық гистерезис, тұзды сулы горизонттар, кезектесіп су мен газ айдау, климаттың өзгеруін азайту.*

Дәйексөз келтіру үшін:
Хорамиан Р., Пурафшари П., Риази М. Капиллярлық гистерезистің CO_2 тұту тиімділігі мен сақтау тұрақтылығын арттырудағы рөлі // Қазақстанның мұнай-газ саласының хабаршысы. 2025. 7 том, №1. 90–99 б. DOI: https://doi.org/10.54859/kjogi108781.

Introduction

Industrialization, urban growth, and migration to cities significantly drive up carbon dioxide (CO_2) emissions [1]. CO_2 absorbs heat from the sun and traps it in the atmosphere, leading to ozone layer depletion and alterations in atmospheric circulation patterns [2]. CO_2 geological storage has emerged as an effective approach to reducing carbon footprints and addressing environmental concerns, providing a solution for managing future emissions as part of a comprehensive strategy to combat climate change [3]. Carbon emissions are captured from power plants and permanently stored underground in saline aquifers or abandoned hydrocarbon reservoirs, known for securely storing gases [4]. Four main mechanisms – structural trapping, capillary trapping, solubility trapping, and mineral trapping–hydrodynamically or geochemically immobilize CO_2.

Structural and stratigraphic trapping, prominent in the initial stages of a CO_2 storage project, relies on an overlying caprock to prevent capillary leakage of CO_2 [5]. Capillary trapping occurs when CO_2 becomes immobile, forming isolated ganglia within pore spaces, enclosed by brine in storage aquifer formations [6]. Solubility trapping is considered a secure storage method, where CO_2 bubbles dissolve in the aqueous phase, creating carbonic acid [7]. This acid interacts with metal ions (Ca^{2+}, Fe^{2+}, Mg^{2+}) within the geological structure through geochemical reactions, producing durable solid carbonate minerals known as mineral trapping [8]. However, structural and stratigraphic trapping, which relies on the presence of an overlying caprock, may encounter geological complexities and may not be feasible in all geological formations. Similarly, dissolution trapping requires time for significant storage, and mineral trapping, involving the formation of solid carbonate minerals, is a slow process, further delaying effective CO_2 storage. In contrast, capillary trapping, a rapid process, occurs early in storage, offering an immediate solution and serving as a key element for successful CO_2 storage. This mechanism involves water entering pore spaces, displacing CO_2 and leaving isolated pockets or droplets behind. Residual trapping is crucial for securely storing CO_2 underground over time, significantly enhancing storage efficiency and encapsulation within geological formations.

Previous studies have employed two methods to examine residual trapping behavior. The first method involves utilizing different ratios of vertical to horizontal permeability [9], as well as varying injection rates, temperatures, and pressures for a specific set of relative permeability curves [10]. The second method isolates the impact of changes in relative permeability curves by measuring the variations in trapped gas saturations. This is done by altering endpoint values such as residual gas saturation, critical gas saturation, irreducible water saturation, and wetting conditions, while maintaining other factors constant [11]. This research employs the second method by using different hysteresis values in relative permeability curves to investigate CO_2 capillary trapping. The commercial CMG simulator is utilized to monitor the distribution of CO_2 after injection into an aquifer, followed by alternating water injections. The influence of four different hysteresis values (0.2, 0.3, 0.4, and 0.5), which reflect differences between drainage and imbibition relative permeability curves, is systematically studied to assess the CO_2 plume shape and trapping efficiency underground.

Model Characteristics

A The aquifer model comprised 2000 blocks: 100 in the i-direction, 1 in the j-direction, and 20 in the k-direction, each block measuring 10 meters in length and width and 5 meters in thickness. Stratified between 1200 and 1300 meters depth, the model had an initial pressure of 1800 psi at 1200 meters (Fig. 1) and maintained a constant temperature of 55°C, characteristic of deep saline aquifers. The aquifer was initially saturated with 6% salinity brine, with water compressibility at 3.102×10^{-6} psi^{-1} and rock compressibility at 3.793×10^{-6} psi^{-1}.

A uniform porosity of 0.13 was applied across all layers to accurately simulate fluid flow, while permeability was set at 60 millidarcies in all directions to model CO_2 plume movement. To represent an infinite reservoir, boundary cell pore volumes were exponentially increased using a volume modifier of 1000, allowing unrestricted fluid flow. Using the CMG-GEM simulator, CO_2 was injected at a rate of 10,000 m³/day to a depth of 1285–1300 meters for one year, followed by a year of water injection at 50 m³/day to 1220–1235 meters after a one-year pause. A 10-year observation period tracked CO_2 migration, focusing on structural and capillary trapping. The simulation revealed that CO_2 displaces water initially but is later trapped as water re-injection lowers CO_2 permeability, achieving residual water saturation. The effectiveness of structural and residual trapping depends on CO_2's mobility through the rock relative to water, controlled by relative permeability curves hysteresis, which is critical for predicting and optimizing CO_2 storage strategies.

Wetting relative permeability (krw) and non-wetting relative permeability (krg) were derived from the experimental study conducted by Edlmann et al. [12]. They injected water into strongly water-wet sandstone cores until reaching steady-state flow, marking the primary imbibition phase, followed by CO_2 injection representing the primary drainage phase. This alternating injection process was repeated for five cycles, each revealing a progressive hysteresis effect on the relative permeability curves

They employed a critical CO_2 saturation (S_{gc}) and irreducible water saturation (S_{wr}) of 0.05 and 0.2, respectively, to determine drainage relative permeability. Initially, S_{gr} was fixed at 0.2 for the first imbibition relative permeability curve and then shifted by 0.1 for the next five cycles of imbibition for the sandstone cores. The relationship between water saturation (Sw) and relative permeability

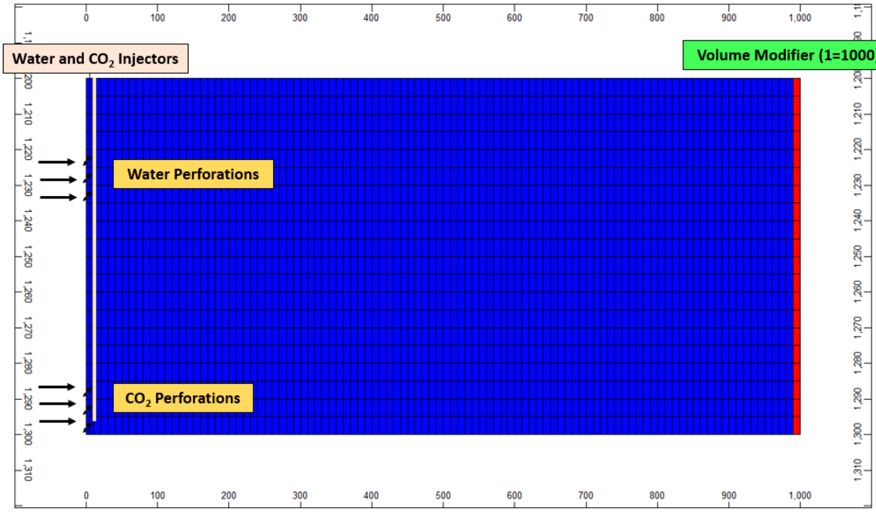

Figure 1. 2D aquifer model with perforations at a depth of 1220–1235 meters for water injection and 1285–1300 meters for CO_2 injection. An infinite boundary was also established by applying a volume modifier of 1000 to the right boundary

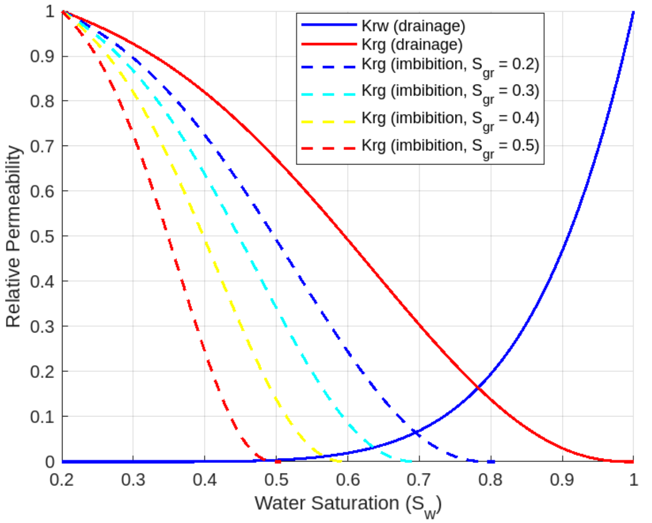

Figure 2. The utilized relative permeability curves for both water and CO_2 in highly water-wet sandstone cores through the primary drainage and imbibition phases, as inferred from the experimental study by Edlmann et al. [12] and mathematically represented using the Brooks-Corey-Moalem model [13]

for both the wetting (water) and non-wetting (CO_2) phases in water-wet sandstone is visually summarized in Fig. 2. This figure includes the observed hysteresis effect, evident throughout successive experimental cycles, which is the shift from drainage to imbibition relative permeability. The relative permeability curves are used in this study to examine the role of hysteresis in the efficacy of CO_2 capillary trapping within geological formations.

Results and Discussions

The study meticulously examines the role of hysteresis in the efficacy of CO_2 trapping within geological formations, an integral component of carbon capture and storage (CCS) initiatives. Using CMG simulation software, a comparative analysis is conducted, contrasting four scenarios with hysteresis values of 0.2, 0.3, 0.4, and 0.5, which mimic drainage and imbibition processes through WAG injection.

Saturation Profiles

Fig. 3 illustrates saturation profiles for the first drainage process in a strongly water-wet aquifer, initially saturated with water and subjected to CO_2 injection. The hysteresis value in this process is assumed to be 0.2, as established in the lab study by Edlmann et al. [1]. Injected CO_2 from the bottom

left corner displaced the water and moved upward due to buoyancy, eventually reaching beneath the caprock, which acts as a no-flow boundary. This upward movement is clearly shown in the total gas saturation profile (Fig. 3a), where the highest gas saturation values are near the bottom left corner. The no-flow boundary at the caprock forces the CO_2 to spread horizontally, resulting in a broad distribution of gas saturation. As the system is strongly water-wet, the displaced water tends to return to pore spaces invaded by CO_2. The returning water moves back from lower layers with lower gas saturation, effectively snapping off and trapping CO_2 in isolated phases. The trapped gas saturation profile (Fig. 3b) shows a high concentration of trapped gas near the injection point and lower layers where the returning water has immobilized the CO_2 in the pore spaces due to capillary forces.
The results of water injection following the first drainage process are illustrated in Fig. 4. This injection, simulating the imbibition phase with a hysteresis of 0.3, pushes CO_2 into areas with high saturation, leading to more gas being trapped within the aquifer. The injected water displaces the CO_2, causing it to become trapped in isolated pockets. This process is driven by capillary forces, which are stronger during the imbibition phase due to hysteresis. During alternating drainage and imbibition cycles, the relative permeability curves shift, reflecting changes in the wetting and non-wetting phase saturations. This shift, known as hysteresis, results in a different saturation path during imbibition compared to drainage. Specifically, the non-wetting phase (CO_2) becomes trapped in the pore spaces during imbibition as the wetting phase (water) re-enters the pores and isolates the CO_2. The presence of this hysteresis-induced trapping reduces the mobility of the CO_2, preventing further migration due to buoyancy.

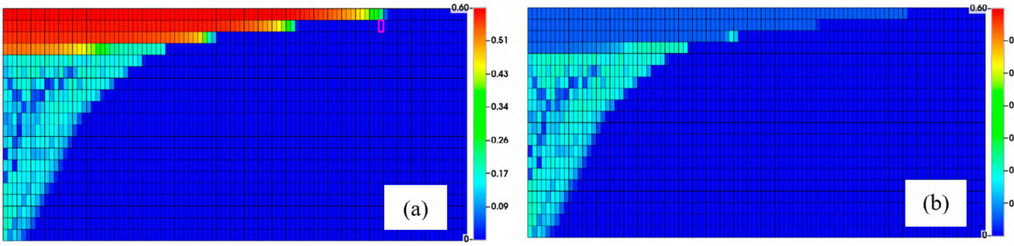

Figure 3. (a) Total gas saturation profile showing CO_2 injected from the bottom left corner spreading upward and horizontally beneath the caprock. (b) Trapped gas saturation profile showing CO_2 immobilized by returning water in lower layers

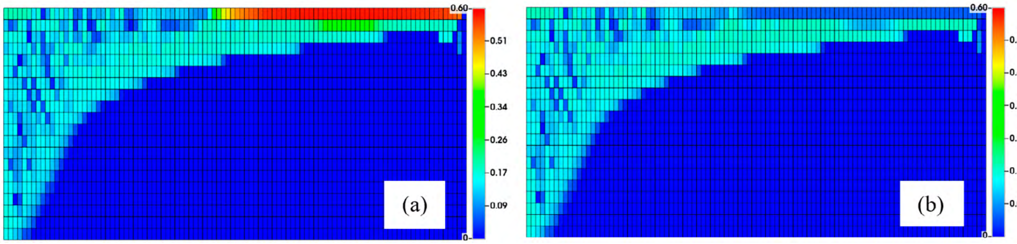

Figure 4. (a) Total gas saturation profile after water injection, showing reduced gas saturation at the top; (b) Trapped gas saturation profile, illustrating the hysteresis effect enhancing CO_2 immobilization during the imbibition phase with a hysteresis of 0.3

Fig. 5 presents the results of a subsequent drainage process where CO_2 is injected again, visualized in the saturation profiles. This time, the hysteresis value was increased to 0.4, up from the previous 0.3, reflecting an additional 0.1 increment. The total gas saturation (Fig. 5a) and trapped gas saturation (Fig. 5b) indicate significant changes compared to the previous drainage cycle. In Fig. 5a, the total gas saturation profile reveals that less CO_2 has moved to the top layers, with only a small section in the top layer exhibiting a light orange color, indicating a gas saturation of around 45%, whereas it was 60% and more extensive in the previous cycle. This reduction in gas saturation at the top layer suggests that CO_2 mobility has decreased due to the increased trapping from the prior cycles. Fig. 5b highlights the trapped gas saturation, showing a significant increase in the amount of CO_2 immobilized by capillary forces. This enhanced trapping results from the hysteresis effect observed during the alternating drainage and imbibition cycles. As the relative permeability curves shift, the wetting phase (water) re-enters the pores, further isolating and trapping the CO_2. The increased trapping efficiency ensures more CO_2 remains securely immobilized within the aquifer, reducing the risk of CO_2 migration and enhancing long-term storage stability.
In the final simulation, water was injected again to simulate the imbibition process,

with the hysteresis in relative permeability set to 0.5. The resulting saturation profiles are shown in Fig. 6, with Fig. 6a representing the total gas saturation profile and Fig. 6b depicting the hysteresis-trapped gas profile. The profiles indicate that all the injected CO_2 has been effectively trapped, leaving no free gas in the system. This complete trapping is due to the increased hysteresis effect, which enhances the capillary forces during the imbibition phase, ensuring that the returning water isolates and immobilizes the CO_2 more effectively. The increased hysteresis value contributes to a stronger trapping mechanism, resulting in the complete immobilization of the CO_2 within the pore spaces. In conclusion, water-alternating-gas injection progressively traps more gas, eventually leading to the absence of mobile gas.

Capillary Trapped Gas Efficiency

Fig. 7 presents the capillary trapped gas percentage as a function of dimensionless time (tD) for varying hysteresis values, with the main plot on the left and an enlarged view on the right to accentuate the initial trapping phase. The data elucidates a positive correlation between hysteresis and CO_2 trapping efficiency, indicating that an increase in hysteresis enhances capillary forces, thereby augmenting CO_2 entrapment within the reservoir's pore network and subsequently reducing post-injection mobility.

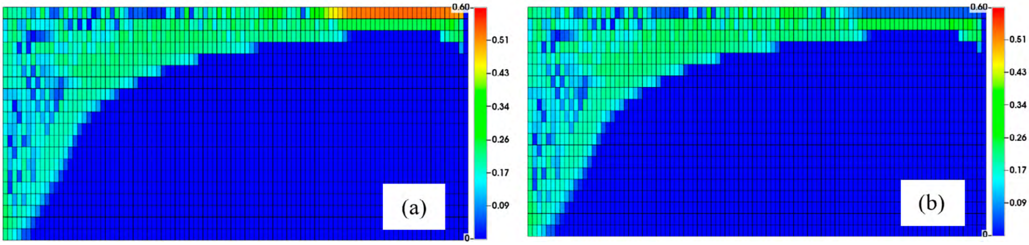

Figure 5. (a) Total gas saturation profile from the drainage process showing less CO_2 movement to the top layers, with a smaller section exhibiting a gas saturation of around 45%; (b) Trapped gas saturation profile indicating increased CO_2 immobilization due to the hysteresis effect during the drainage process

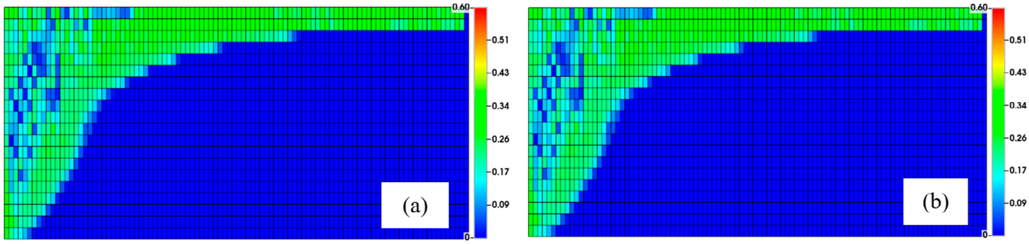

Figure 6. (a) Total gas saturation profile showing complete trapping of injected CO_2 with no free gas remaining; (b) Hysteresis trapped gas profile illustrating the enhanced capillary trapping due to a hysteresis value of 0.5 during the imbibition process

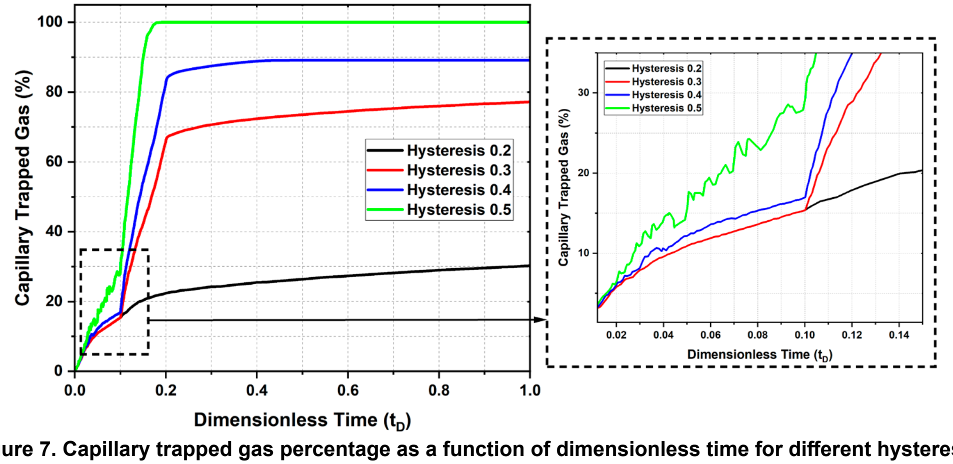

Figure 7. Capillary trapped gas percentage as a function of dimensionless time for different hysteresis values

DOI: 10.54859/kjogi108781

In the primary plot, the capillary trapped gas percentage is depicted for hysteresis values of 0.2, 0.3, 0.4, and 0.5. A hysteresis value of 0.2 reflects the drainage process, wherein CO_2 displaces water from the pore spaces. The trapping efficiency for this value initiates at a low level and increases gradually, achieving a maximum trapped gas percentage of approximately 30% by the end of the simulation period. This gradual increase suggests that lower hysteresis results in less efficient trapping over time. In contrast, the trapping efficiency for a hysteresis value of 0.3, simulating imbibition through the post-injection of water, escalates more rapidly with a plateau around 75%. This indicates improved trapping efficacy through the snap-off of CO_2 by water in pore spaces.

For a hysteresis value of 0.4, the trapped gas percentage increases swiftly, reaching roughly 80%, demonstrating that a higher hysteresis value significantly enhances capillary forces, resulting in more efficient gas trapping. The highest hysteresis value tested, 0.5, exhibits the steepest rise in trapping efficiency, nearly achieving 100%. The rapid increase and elevated plateau imply that the highest hysteresis value results in the most efficient trapping. The zoomed-in plot on the right highlights the initial phase of the trapping process. All curves commence at zero, reflecting the absence of initial trapped gas. The green line (hysteresis 0.5) shows the most rapid increase in trapped gas percentage, followed sequentially by the blue (hysteresis 0.4), red (hysteresis 0.3), and black (hysteresis 0.2) lines. The fluctuations observed in the zoomed-in plot for higher hysteresis values (0.4 and 0.5) can be attributed to the dynamic interplay between capillary and viscous forces during the trapping process. Higher hysteresis engenders stronger capillary forces that effectively trap CO_2 in the pore spaces. However, as CO_2 injection proceeds, the viscous forces associated with the injection can momentarily reconnect trapped CO_2 clusters, causing them to form a stream and be released from the pore spaces, resulting in the observed fluctuations. These fluctuations are absent for lower hysteresis values (0.2 and 0.3) due to weaker capillary forces, leading to more stable and gradual trapping without significant interplay between capillary and viscous forces.

The plots unequivocally demonstrate that increased hysteresis through post-water injection enhances the capillary trapping efficiency of gas within the aquifer. Elevated hysteresis values amplify capillary forces, which trap more gas more rapidly. As hysteresis intensifies, the ability of the wetting phase (water) to isolate and trap the non-wetting phase (CO_2) improves, owing to the increased capillary forces associated with higher hysteresis values, thereby preventing the mobilization of CO_2 and resulting in higher trapped gas percentages. These findings hold significant implications for CO_2 sequestration projects, where maximizing the trapped gas is pivotal for ensuring long-term storage stability. Implementing processes that augment hysteresis, such as WAG injection, can enhance the efficiency and security of CO_2 storage.

Conclusions

This study highlights the crucial role of hysteresis in enhancing CO_2 capillary trapping within a water-wet aquifer. The analysis reveals that lower hysteresis values (e.g., 0.2) lead to gradual and less efficient CO_2 trapping during the drainage process, achieving a maximum trapped gas percentage of around 30%. In contrast, higher hysteresis values, such as 0.3 and beyond, considerably improve trapping efficiency, with imbibition processes reaching up to 75% and subsequent drainage and imbibition cycles approaching nearly 100% trapped gas. The intensified hysteresis enhances capillary forces, ensuring CO_2 remains immobilized within the pore spaces, thereby reducing its mobility and preventing further migration. These findings are essential for CO_2 sequestration projects, suggesting that techniques like WAG injection can substantially improve storage security and long-term stability by amplifying hysteresis effects. Overall, strategic management of hysteresis through appropriate injection methods can maximize CO_2 trapping efficiency, contributing to effective and reliable CO_2 storage solutions.

ADDITIONAL INFORMATION

Funding source. This study was supported by Nazarbayev University through the NU Faculty Development Competitive Research Grants Program (Grant number: 201223FD2608).

Competing interests. The authors declare that they have no competing interests.

Authors' contribution. All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work. The greatest contribution is distributed as follows: Reza Khoramian – conceptualization, methodology, simulation, writing–original draft preparation; Peyman Pourafshary – conceptualization, methodology, validation, writing–review and editing, supervision, project administration, funding acquisition; Masoud Riazi – conceptualization, methodology, validation, writing–review and editing, supervision.

ДОПОЛНИТЕЛЬНО

Источник финансирования. Данное исследование было проведено при поддержке Назарбаев Университета в рамках программы конкурсных грантов на развитие факультета НУ (№ гранта: 201223FD2608).

Конфликт интересов. Авторы декларируют отсутствие явных и потенциальных конфликтов интересов, связанных с публикацией настоящей статьи.

Вклад авторов. Все авторы подтверждают соответствие своего авторства международным

критериям ICMJE (все авторы внесли существенный вклад в разработку концепции, проведение исследования и подготовку статьи, прочли и одобрили финальную версию перед публикацией). Наибольший вклад распределён следующим образом: Хорамиан Р. – концепция, методология, моделирование, подготовка первоначального проекта научной статьи; Пурафшари П. – концептуализация, методология, валидация, написание работы (рецензирование и редактирование), контроль, администрирование проекта, привлечение финансирования; Риази М. – концептуализация, методология, валидация, написание работы (рецензирование и редактирование), надзор за проведением.

REFERENCES

1. Sarkodie SA, Owusu PA, Leirvik T. Global effect of urban sprawl, industrialization, trade, and economic development on carbon dioxide emissions. *Environmental Research Letters.* 2020;15(3):034049. doi: 10.1088/1748-9326/ab7640.
2. Mishra RK, Dubey SC. Solar activity cause and effect of climate variability and their various impacts. *British Journal of Multidisciplinary and Advanced Studies.* 2023;4(2):21–38. doi: 10.37745/bjmas.2022.0133.
3. Kelemen P, Benson SM, Pilorgé H, et al. An overview of the status and challenges of CO_2 storage in minerals and geological formations. *Frontiers in Climate*. 2019;1:482595. doi: 10.3389/fclim.2019.00009.
4. Ilavya A, Patel K, Bera A. *Chapter Two – Underground carbon storage*. In: Rahimpour MR, Makarem MA, Meshksar M, editors. *Advances and Technology Development in Greenhouse Gases: Emission, Capture and Conversion. Greenhouse Gases Storage and Transportation*. Elsevier; 2024. P. 25–44.
5. Iglauer S. Optimum storage depths for structural CO_2 trapping. *International Journal of Greenhouse Gas Control.* 2018;77:82–87. doi: 10.1016/j.ijggc.2018.07.009.
6. Moghadasi R, Goodarzi S, Zhang Y, et al. Pore-scale characterization of residual gas remobilization in CO_2 geological storage. *Advances in Water Resources*. 2023;179:104499. doi: 10.1016/j.advwatres.2023.104499.
7. Bashir A, Ali M, Patil S, et al. Comprehensive review of CO_2 geological storage: Exploring principles, mechanisms, and prospects. *Earth-Science Reviews*. 2024;249:104672. doi: 10.1016/j.earscirev.2023.104672.
8. Sasowsky ID, White WB, Webb JA. *Acid mine drainage in karst terranes: geochemical considerations and field observations*. In: Beck BF, editor. *Karst Geohazards*. London: Routledge; 1995. P. 241–247.
9. Burnside NM, Naylor M. Review, and implications of relative permeability of CO_2/brine systems and residual trapping of CO_2. *International Journal of greenhouse gas control.* 2014;23:1–11. doi: 10.1016/j.ijggc.2014.01.013.
10. Sedaghatinasab R, Kord S, Moghadasi J, Soleymanzadeh A. Relative permeability hysteresis and capillary trapping during CO_2 EOR and sequestration. *International Journal of Greenhouse Gas Control.* 2021;106:103262. doi: 10.1016/j.ijggc.2021.103262.
11. Zapata Y, Kristensen MR, Huerta N, et al. CO_2 geological storage: Critical insights on plume dynamics and storage efficiency during long-term injection and post-injection periods. *Journal of Natural Gas Science and Engineering*. 2020;83:103542. doi: 10.1016/j.jngse.2020.103542.
12. Edlmann K, Hinchliffe S, Heinemann N, et al. Cyclic CO_2–H_2O injection and residual trapping: implications for CO_2 injection efficiency and storage security. *International Journal of Greenhouse Gas Control.* 2019;80:1–9. doi: 10.1016/j.ijggc.2018.11.009.
13. Shaw D, Mostaghimi P, Armstrong RT. The dynamic behavior of coal relative permeability curves. *Fuel.* 2019;253:293–304. doi: 10.1016/j.fuel.2019.04.107.

СПИСОК ИСПОЛЬЗОВАННОЙ ЛИТЕРАТУРЫ

1. *Sarkodie S.A., Owusu P.A., Leirvik T.* Global effect of urban sprawl, industrialization, trade, and economic development on carbon dioxide emissions // Environmental Research Letters. 2020. Vol. 15, N 3. doi: 10.1088/1748-9326/ab7640.
2. *Mishra R.K., Dubey S.C.* Solar activity cause and effect of climate variability and their various impacts. British Journal of Multidisciplinary and Advanced Studies. 2023. Vol. 4, N 2. P. 21–38. doi: 10.37745/bjmas.2022.0133.
3. *Kelemen P., Benson S.M., Pilorgé H., et al.* An overview of the status and challenges of CO_2 storage in minerals and geological formations // Frontiers in Climate. 2019.Vol. 1. doi: 10.3389/fclim.2019.00009.
4. *Ilavya A., Patel K., Bera, A.* Chapter Two – Underground carbon storage. In: Rahimpour M.R., Makarem M.A., Meshksar M., editors. Advances and Technology Development in Greenhouse Gases: Emission, Capture and Conversion. Greenhouse Gases Storage and Transportation. Elsevier, 2024. P. 25–44.
5. *Iglauer S*. Optimum storage depths for structural CO_2 trapping // International Journal of Greenhouse Gas Control. 2018. Vol. 77. P. 82–87. doi: 10.1016/j.ijggc.2018.07.009.
6. *Moghadasi R, Goodarzi S, Zhang Y., et al.* Pore-scale characterization of residual gas remobilization in CO_2 geological storage // Advances in Water Resources. 2023. Vol. 179. doi: 10.1016/j.advwatres.2023.104499.
7. *Bashir A., Ali M., Patil S., et al.* Comprehensive review of CO_2 geological storage: Exploring principles, mechanisms and prospects // Earth-Science Reviews. 2024. Vol. 249. doi: 10.1016/j.earscirev.2023.104672.
8. *Sasowsky I.D., White W.B., Webb J.A.* Acid mine drainage in karst terranes: geochemical considerations and field observations. In: Beck B.F., editor. Karst Geohazards. London : Routledge, 1995. P. 241–247.
9. *Burnside N.M., Naylor M.* Review, and implications of relative permeability of CO_2/brine systems and residual trapping of CO_2 // International Journal of greenhouse gas control. 2014. Vol. 23. P. 1–11. doi: 10.1016/j.ijggc.2014.01.013.
10. *Sedaghatinasab R., Kord Sh., Moghadasi J., Soleymanzadeh A*. Relative permeability hysteresis and capillary trapping during CO_2 EOR and sequestration // International Journal of Greenhouse Gas Control. 2021. Vol. 106. doi: 10.1016/j.ijggc.2021.103262.
11. *Zapata Y., Kristensen M.R., Huerta N., et al.* CO_2 geological storage: Critical insights on plume dynamics and storage efficiency during long-term injection and post-injection periods // Journal of Natural Gas Science and Engineering. 2020. Vol. 83. doi: 10.1016/j.jngse.2020.103542.

12. *Edlmann K., Hinchliffe S., Heinemann N., et al.* Cyclic CO_2–H_2O injection and residual trapping: implications for CO_2 injection efficiency and storage security // International Journal of Greenhouse Gas Control. 2019. Vol. 80. P. 1–9. doi: 10.1016/j.ijggc.2018.11.009.
13. *Shaw D., Mostaghimi P., Armstrong R.T.* The dynamic behavior of coal relative permeability curves // Fuel. 2019. Vol. 253. P. 293–304. doi: 10.1016/j.fuel.2019.04.107.

AUTHORS' INFO

Reza Khoramian
ORCID 0009-0008-7775-3816
e-mail: *reza.khoramian@nu.edu.kz.*
***Peyman Pourafshary**
Professor
ORCID 0000-0003-4600-6670
e-mail: *peyman.pourafshary@nu.edu.kz.*
Masoud Riazi
Associate Professor
ORCID 0000-0002-6843-621X
e-mail: *masoud.riazi@nu.edu.kz.*

ИНФОРМАЦИЯ ОБ АВТОРАХ

Хорамиан Р.
ORCID 0009-0008-7775-3816
e-mail: *reza.khoramian@nu.edu.kz.*
***Пурафшари П.**
профессор
ORCID 0000-0003-4600-6670
e-mail: *peyman.pourafshary@nu.edu.kz.*
Риази М.
ассоциированный профессор
ORCID 0000-0002-6843-621X
e-mail: *masoud.riazi@nu.edu.kz.*

*Corresponding Author/Автор, ответственный за переписку