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ANALYSIS OF CARBON DIOXIDE DISPOSAL METHODS TO REDUCE GREENHOUSE GASES



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The practice of capturing, storing and utilizing CO2 is becoming key to developing sustainable energy and industrial solutions. The technology promotes the use of fossil fuels, which remain the predominant source of energy worldwide. The effectiveness of the technology is evident in the reduction of CO2 levels in the atmosphere, a significant contribution to the reduction of global greenhouse gas (GHG) emissions and the fight against climate change.

However, a notable concern in the realm of geological storage revolves around the potential leakage of CO2 from storage reservoirs. Carbon dioxide has the capability to migrate from the storage site, reaching both the surface and underground formations. Surface leakage presents health risks to humans, animals, and plants. The solution to this problem requires a detailed approach and should be solved through an inverse problem, in which pressure measurements in monitoring wells will be performed frequently to obtain information about the reservoir and possible leaks. Additionally, there are a number of issues with carbon dioxide leakage during oil and gas extraction, as well as various operations at fields.

Emphasizing the monitoring of CO2 leakage, this paper underscores the importance of developing an algorithm designed to proactively prevent CO2 leakage in aquifers and depleted reservoirs. Such an initiative is pivotal in the broader context of mitigating greenhouse gas emissions. The paper offers an overview of methodologies for effective monitoring, management and modeling of CO2 leakage and practical approaches to calculation and assessment, contributing to a more complete understanding of the challenges associated with CO2 storage.

KEY WORDS: *capturing, storing and utilizing, carbon dioxide, leakage.*

ПАРНИКТІК ГАЗДАРДЫ АЗАЙТУ ҮШІН КӨМІРҚЫШҚЫЛ ГАЗЫН ЖОЮ ӘДІСТЕРІН ТАЛДАУ

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CO2 ұстау, сақтау және пайдалану тәжірибесі тұрақты энергетикалық және өнеркәсіптік шешімдерді әзірлеудің кілтіне айналуда. Технология бүкіл әлемде энергияның басым көзі болып қала беретін қазба отындарын пайдалануға ықпал етеді.Технологияның тиімділігі атмосферадағы CO2 деңгейін төмендетуде айқын көрінеді, жаһандық парниктік газдар (ПГ) шығарындыларын азайтуға және климаттық өзгеріске қарсы күреске елеулі үлес қосады.

Дегенмен, геологиялық сақтауда маңызды алаңдаушылық - резервуарлардан CO2 ықтимал ағуы болып табылады. Көмірқышқыл газы өзінің сақтау орнынан жер бетіне де, жер *асты қабаттарына да көшу мүмкіндігіне ие. Бетке ағып кетулер адамдардың, жануарлар мен өсімдіктердің денсаулығына қауіп төндіреді. Бұл мәселенішешу егжей-тегжейлі зерттеуді қажет етеді және оны бақылау ұңғымаларындағы қысымды өлшеу көбінесе қабат туралы ақпарат алу үшін және мүмкін ағып кету үшін орындалатын кері мәселе арқылы шешу керек.*

CO2 ағуын бақылауға баса назар аудара отырып, бұл құжат сулы горизонттар мен сарқылған су қоймаларында CO2 ағуын болдырмауға арналған алгоритмді әзірлеудің маңыздылығын көрсетеді. Мұндай бастама парниктік газдар шығарындыларын азайтудың кең контекстінде маңызды. Мақалада CO2 ағуын тиімді бақылау, басқару және модельдеу әдістемелеріне шолу және CO2 сақтау мен байланысты қиындықтарды толық түсінуге ықпал ететін есептеу мен бағалаудың практикалық тәсілдері ұсынылады.

ТҮЙІН СӨЗДЕР: *ұстау, сақтаужәнежою, көмірқышқыл газы, ағып кету*

АНАЛИЗ МЕТОДОВ ЗАХОРОНЕНИЯ УГЛЕКИСЛОГО ГАЗА С ЦЕЛЬЮ СНИЖЕНИЯ ПАРНИКОВЫХ ГАЗОВ

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Практика улавливания, хранения и использования CO2 становится ключевой для разработки устойчивых решений в области энергетики и промышленности. Технология способствует использованию ископаемого топлива, которое остается преобладающим источником энергии во всем мире. Эффективность технологии очевидна в снижении уровня CO2 в атмосфере, значительном вкладе в сокращении глобальных выбросов парниковых газов (ПГ) и борьбы с изменением климата.

Однако заметное беспокойство в сфере геологического хранения вызывает потенциальная утечка CO2 из резервуаров-хранилищ. Углекислый газ обладает способностью мигрировать из места хранения, достигая как поверхности, так и подземных пластов. Поверхностные утечки представляют опасность для здоровья людей, животных и растений. Решение этой проблемы требует детального подходаиспользование методаобратной задачи, при котором измерения давления в контрольных скважинах будут выполняться чаще для получения информации о пласте и возможных утечках. Кроме того, имеется ряд проблем с утечкой углекислого газа при добыче нефти и газа, а также различных операциях на месторождениях.

Подчеркивая мониторинг утечки CO2, в этой статье подчеркивается важность разработки алгоритма, предназначенного для предотвращения утечки CO2 в водоносных горизонтах и истощенных резервуарах. Такая инициатива имеет важное значение в более широком контексте сокращения выбросов парниковых газов. Статья предлагает обзор методологий эффективного мониторинга, управления и моделирования утечки CO2 и практические подходы к расчетам и оценке, способствуя более полному пониманию проблем, связанных с хранением CO2.

КЛЮЧЕВЫЕ СЛОВА: *улавливание, хранение и утилизация, углекислый газ, утечка.*

Introduction. Carbon Capture, Utilization, and Storage (CCUS) stands as a meticulously crafted process designed to counteract carbon dioxide (CO2) emissions, particularly emanating from industrial sources such as power plants. This intricate procedure involves capturing CO2 emissions at their point of origin, transporting the captured CO2 to a designated storage site, and securely storing it underground to prevent any release into the atmosphere. Despite the explicit aim of ensuring secure CO2 storage, a latent risk of leakage persists at various stages throughout the CCUS process.

To address the challenge of detecting and managing CO2 leakage, a multitude of algorithms has been developed. Zhou et al. (2018) introduced a specialized spatiotemporal convolutional network for precise CO2 leak detection, leveraging seismic data to enhance accuracy. Chen et al. (2018) pioneered a data assimilation approach rooted in machine learning and filtering methodologies, custom-tailored for monitoring CO2 sequestration projects with a primary focus on leakage detection. Gundersen et al. (2018) harnessed the power of Convolutional Neural Networks (CNN) to predict the behavior of CO2 leakage into water formations. Zhong et al. (2019) proposed an innovative spatiotemporal convolutional Long Short-Term Memory (LSTM) model, wherein the LSTM component adeptly learns temporal characteristics, and the convolutional layer acquires spatial information for robust CO2 leak detection. In a more recent study, Chen et al. (2022) developed Reduced Order Models (ROMs) to predict CO2 leakage rates while concurrently exploring the factors influencing the rate of leakage. These diverse algorithmic approaches signify a collective and dedicated effort within the scientific community to advance methodologies for the detection and mitigation of CO2 leakage, contributing significantly to the ongoing refinement of CCUS technologies.

The oil and gas production operations release several types of emissions, including combustion gases (carbon dioxide, carbon monoxide, nitrous oxide, sulfur dioxide, and unburned hydrocarbons like methane and volatile organic compounds). These emissions arise from the combustion of fossil fuels, flaring, well testing, and the use of carbon dioxide for enhanced oil recovery operations. Efforts to reduce emissions include understanding emission inventories, evaluating alternative technologies for emission control, and adhering to environmental regulations.

Materials and methods. Drawing on a meticulous synthesis of available data, peer-reviewed literature, and industry reports, this comprehensive study aims to provide an in-depth overview of the critical issues pertaining to carbon dioxide (CO2) leakage within the context of Carbon Capture, Utilization, and Storage (CCUS) projects. The methodology employed in this research involves a systematic and rigorous review, coupled with a detailed analysis of the existing knowledge base and findings within the field of CCUS. Furthermore, the analysis phase involves the application of rigorous analytical techniques to the synthesized data. This entails scrutinizing the methodologies employed in existing studies, evaluating the reliability of data sources, and identifying gaps or areas requiring further exploration.

Results and discussions. One of the primary obstacles in CO2 sequestration is the potential for leakage. CO2 migration can occur via pathways like faults, fractures, or improperly drilled or abandoned wells. These pathways provide avenues for the injected fluid to escape into overlying formations or to the surface, leading to a reduction in the effectiveness of carbon storage. The movement of CO_2 to shallow aquifers above storage formations poses a significant threat to groundwater quality. To address this issue, it is essential to conduct leakage detection tests, evaluating storage integrity and identifying any CO_2 leakage before it reaches the shallow layers. Overall, preventing and managing CO_2 migration challenges requires proactive measures, including robust detection tests, to ensure the secure and efficient sequestration of carbon dioxide and minimize potential environmental impacts

A leakage detection system is essential for ensuring the secure geological storage of CO_2. While seismic surveys (Alfi et al., 2015) and electrical and acoustic tomography (Carrigan et al., 2013) are currently utilized techniques to monitor CO_2 plumes, their drawbacks, such as high costs, inefficiency, and inaccuracy due to challenges like limited vertical resolution and uncertainties in formation properties, necessitate the exploration of more effective alternatives. Given these limitations, pressure transient analysis has proven to be a viable substitute for monitoring and characterizing CO_2 injection. This method offers cost-effectiveness and improved accuracy, addressing the shortcomings of traditional techniques and presenting a practical solution to enhance the monitoring of CO_2 storage systems for more reliable geological carbon storage practices.

Pressure transient analysis (PTA) is a commonly employed method for reservoir characterization, specifically in the determination of reservoir properties, identification of boundaries, flow regimes, average reservoir pressure, etc. (Bourdet et al., 1989, Horne, 1995, Gringarten, 2008).

Numerous studies have showcased the cost-effectiveness of pressure monitoring techniques. Wang and Small (2014), for instance, utilized pressure measurements in both injection and adjacent zones to detect fluid migration. Hossein and Alfi (2016) applied pressure interference tests to pinpoint CO_2 leakage in zones situated above cap-rock formations. Continuous monitoring of pressure dynamics from various wells, coupled with injection data, proves effective in identifying losses of injected CO_2 (Meckel et al., 2013). Zeidouni et al. employed pressure interference testing and a linear composite reservoir approach to evaluate CO_2 leakage in overlying zones above the cap-rock formation. While this analysis technique allows for assessing the size of the leakage, determining its precise location remains a challenge.

Harmonic pulse testing, characterized by periodic fluctuations in injection and production rates, has been recognized as an effective method to ascertain both the location and volume of the leakage (Tran, 2018). It's important to note that in this analysis, the CO_2 plume is typically considered as gas only, necessitating further conversion of pure gas into a mixture for a more realistic assessment.

Ensuring the effectiveness of CO_2 geological storage necessitates the detection of post-injection leakage to overlying zones. Utilizing pressure measurements from both active and monitoring wells presents a cost-effective alternative to current monitoring techniques.

Concerns surrounding the enduring risk of CO_2 leakage from geological storage, coupled with potential adverse impacts on the environment and water contamination, contribute to a diminished trust in underground CO_2 storage, leading to hesitancy.

Employing continuous leakage detection tests based on pressure responses offers a dependable and economically viable approach.

The application of well testing methods for leakage detection is versatile and can be implemented across various storage locations, providing a comprehensive and secure strategy for CO2 storage. This method not only enhances the overall security of CO2 storage but also addresses apprehensions related to potential environmental consequences, instilling confidence in the reliability of underground storage systems.

The central proposition of this paper posits that the identification of CO2 leakage can be accomplished through pressure measurements in the above-zones, exploiting the marked disparity in mobilities between CO2 and the fluids present in the overlying zones. CO2 is anticipated to undergo a transformation into either a gas or a supercritical fluid, characterized by viscosity values resembling those of a gas, resulting in heightened mobility. Conversely, the fluids in overlying zones are typically liquids with lower mobility. The substantial mobility difference, often exceeding an order of magnitude, facilitates the detection of CO2 intrusion into the fluid in the above-zone.

The proposed methodology involves scrutinizing the pressure interference time within a network of observation points, allowing for the determination of the percentage of CO2 leakage volume. The analytical model aims to establish a deterministic connection between the characteristics of the upper zone of the infiltrated jet and the measured pressure. In the initial stages, the physical model of CO2 leakage in the upper zone will be explicated. Following this, by employing fundamental equations and stipulating boundary and initial conditions, an analytical solution will be derived using a combination of Laplace and Fourier integrals. The validity of the analytical solution will be assessed by comparing it against both a limiting analytical solution representing a scenario without leakage and the outcomes derived from numerical simulations. The shape of the CO2 plume migrating from the injection zone into the above-zone aquifer depends on reservoir heterogeneity, gravity, capillary and viscous forces, and the nature of the CO2 migration pathways. Then, it will be necessary to determine the regions to be modeled and set the boundary and initial conditions for each region, respectively. Diffusivity equations, partial differential equations will be used.

The solution presented involves the utilization of dimensionless quantities (such as dimensionless pressure, mobility coefficient, persistence index, gas plume size, and its distance to the active well) along with temporal and spatial coordinates. This analytical approach aims to detect CO2 leakage by developing a pressure analysis methodology. The method considers an interference pressure test with multiple monitoring well locations as an effective means to identify CO2 discharge in the overlying formation. Additionally, the paper will offer suggestions for remediating CO2 migration, proposing tailored methods for leakage control based on the specific location and size of the CO2 plume.

The approach involves implementing pressure transient analysis with periodically fluctuating injection flow rates. In this method, the pressure response obtained in the field, both from the pulsator well and observation wells, undergoes transformation from the time domain to the frequency domain using a Fourier transform. The resulting amplitude and phase spectrum, derived from the pressure response in the frequency domain, are then employed to assess reservoir properties like storage and transmissibility. The high sensitivity of this type of well survey enables the characterization of gas plumes in underground CO2 storage facilities.

Here are key considerations regarding CO2 leakage within CO2 storage:

• **Storage Sites Selection:**

The careful selection of suitable storage sites, such as depleted oil and gas fields, deep saline aquifers, and unmineable coal seams, is crucial to minimizing the risk of leakage.

• **Storage Mechanisms:**

CO2 is typically stored in geological formations through mechanisms like structural trapping, residual trapping, and solubility trapping, reducing the risk of leakage over time.

• **Monitoring and Verification:**

Continuous monitoring using technologies like seismic imaging, pressure measurements, and geochemical analysis is vital for detecting and addressing potential leaks and ensuring storage site integrity.

• **Regulatory Framework:**

A robust regulatory framework is essential, including comprehensive risk assessments, monitoring plans, and contingency measures, to ensure adherence to strict safety standards.

• **Research and Development:**

Ongoing research focuses on improving storage technologies and understanding the long-term behavior of stored CO2, addressing potential impacts of leakage on the environment.

• **Public Perception:**

Building trust and addressing public concerns through open communication and community engagement is crucial for the success of CO2 storage projects.

• **Case Studies:**

Examining existing CO2 storage projects provides insights into the effectiveness of storage methods and the prevention of leakage.

• **Seal Integrity:**

Maintaining the integrity of seals and cap rocks is critical to prevent CO2 leakage, involving detailed geological surveys and continuous monitoring.

• **Risk Assessment:**

Rigorous risk assessments consider geological characteristics, proximity to populated areas, and potential impacts on underground water resources to minimize leakage risks.

• **Leakage Pathways:**

Studying potential pathways for CO2 leakage, including faults, fractures, and abandoned wells, helps implement preventive measures and choose low-risk storage sites.

• **Emergency Response Plans:**

Well-defined emergency response plans are crucial for rapid detection, communication strategies, and mitigating potential environmental and safety impacts in case of a leakage event.

• **Long-Term Monitoring:**

CO2 storage projects require long-term monitoring even after injection, tracking changes in geological formations and detecting signs of leakage over an extended period.

• **International Collaboration:**

Given climate change's global nature, international collaboration through shared research efforts and best practices contributes to a collective understanding of CO2 storage safety.

• Natural Analogues:

Studying natural analogues, like naturally occurring CO2 reservoirs, provides insights into the long-term behavior of stored CO2 and enhances safety knowledge.

• Public and Stakeholder Engagement:

Engaging with communities, stakeholders, and the public is crucial for transparency and accountability, fostering support for CO2 storage projects.

• Post-Closure Liabilities:

Planning for post-closure liabilities, including setting aside funds for long-term monitoring and remediation, emphasizes the long-term commitment to storage site safety.

• Site Characterization:

Thorough site characterization involves detailed geological surveys to understand subsurface conditions, including permeability, porosity, and potential CO2 migration pathways.

• Pressure Management:

Controlling pressure within the storage reservoir is critical to prevent over-pressurization, fractures, and potential leakage.

• Injection Techniques:

Employing suitable injection techniques based on geological characteristics helps optimize storage efficiency and reduce the risk of leakage.

• Modeling and Simulation:

Advanced modeling tools simulate CO2 behavior in the reservoir, aiding in understanding migration pathways and optimizing injection strategies.

• Tracer Studies:

Tracer studies involve injecting substances along with CO2 to monitor fluid movement, aiding in tracking CO2 migration and detecting any unexpected movement or leakage.

• Economic and Policy Considerations:

Economic viability is tied to safety, with governments implementing financial mechanisms to ensure operators are financially responsible for potential damages.

• Alternative Storage Methods:

Exploring alternative methods like mineralization and enhanced oil recovery presents different risks and benefits compared to traditional storage.

• Remediation Technologies:

Effective remediation technologies for leaks, including wellbore sealing and chemical methods, are areas of ongoing research.

• Public Awareness and Education:

Increasing public awareness and education about CO2 storage benefits and safety measures enhances community support and participation.

• International Standards and Certification:

Developing international standards and certification processes ensures consistent safety and environmental criteria, building global confidence in the technology.

• Hydro-Mechanical Effects:

Understanding hydro-mechanical effects within the reservoir is crucial to ensure the mechanical stability of geological formations.

• Wellbore Integrity:

Ensuring the integrity of injection and monitoring wells through proper construction and regular inspection is crucial for preventing leaks.

• **Natural Resistance and Trapping Mechanisms:**
Geological formations often have natural resistance and trapping mechanisms that enhance CO2 security.

• **Post-Closure Monitoring and Liability:**
Implementing a robust post-closure monitoring plan is important to detect any delayed or unexpected impacts after the cessation of injection activities. Establishing clear liability frameworks ensures that responsible parties remain accountable for any issues that may arise in the post-closure phase.

• **Public Perception and Social License:**
Beyond simple awareness, obtaining a social license to operate involves building trust and acceptance within the communities where CO2 storage projects are located.

• **Integration with Renewable Energy:**
Integrating CO2 storage with renewable energy projects contributes to a balanced and sustainable energy transition.

• **Regulatory Harmonization:**
Achieving regulatory harmonization at different levels streamlines project development, ensures safety standards, and facilitates cross-border collaboration.

• **Public-Private Partnerships:**
Collaboration between public and private entities is common in the development of CO2 storage projects. Public-private partnerships can leverage the strengths of both sectors to accelerate innovation, enhance safety measures, and share the financial burden of large-scale storage initiatives.

• **Life Cycle Assessment:**
Conducting a comprehensive life cycle assessment of CO2 storage projects considers environmental, economic, and social impacts throughout the entire life cycle. This holistic approach helps identify potential risks and benefits at different stages of the project.

• **Capacity and Scalability:**
Ensuring that CO2 storage has the capacity to accommodate large-scale emissions reduction goals and is scalable to meet future demands is important for its role in climate change mitigation on a global scale.

CO2 emission during oil and gas production and operations

Research conducted by scientists from Stanford University shows that in 2015, oil production at 9,000 oil fields across 90 countries released greenhouse gases equivalent to 1.7 gigatons of carbon dioxide, accounting for approximately 5% of all emissions from fuel combustion that year (PetroWiki, 2022). One of the main problems affecting carbon intensity in production is the burning of associated gas (flaring), especially in countries with high carbon-intensive production practices. Countries with the most carbon-intensive oil production practices emitted nearly twice as much emissions as the average. The study also emphasizes that investments in infrastructure and policies for better natural gas management could bring greater climate benefits than previously thought.

Another study asserts that exploring and reducing emissions associated with oil production techniques globally is a step towards developing policies that could reduce these emissions. Eliminating routine flaring and cutting methane leaks and venting to levels already achieved in Norway could reduce about 700 megatons of emissions from the oil sector's annual carbon footprint, a reduction of approximately 43% (PetroWiki, 2022).

As for emission reduction measures, proactive efforts to reduce emissions include a good knowledge of emission inventories, emission sources, and the parameters controlling individual emissions; evaluating alternative technologies that can control and reduce emissions; and gaining knowledge about the economic impact of introducing alternative emission control technology. For example, in 2012, the Abu Dhabi Marine Operating Company successfully eliminated gas flaring in offshore operations at the Zakum field using a Vapor Recovery Unit (VRU), which allowed the recovery of 3,924 tons of CO2 per year (PetroWiki, 2022). Developing new pipeline infrastructure is key to reducing methane and other carbon emissions in the oil and gas sector.

These studies highlight the importance of reducing emissions in the process of extraction, transportation, and use of oil and gas, and propose ways to solve this problem through improved natural gas management and research conducted by scientists from Stanford University have identified significant CO2 emissions associated with oil production, particularly noting the impact of flaring associated gas during extraction. It is indicated that avoiding the most carbon-intensive reservoirs and improving natural gas management could significantly reduce emissions.

Conclusion. In summary, while CCUS endeavors to securely capture and store CO2 emissions, the persistent risk of leakage necessitates careful attention at various stages. The key to success lies in the implementation of robust preventive measures, meticulous monitoring procedures, well-defined emergency response plans, and ongoing research initiatives. Effectively addressing these challenges is paramount for ensuring the responsible and safe execution of CCUS, playing a pivotal role in advancing global efforts to combat climate change.

Additionally, it is indicated that avoiding the most carbon-intensive petroleum reservoirs and improving natural gas management could significantly reduce emissions.

The significance of the paper lies in its emphasis on monitoring CO2 leakage and the development of an algorithm to proactively prevent such incidents in aquifers and depleted reservoirs. The initiation of CCUS projects in Kazakhstan not only aligns with the objectives of the Paris Agreement but also underscores a commitment to reducing CO2 emissions and actively contributing to the overarching goal of achieving carbon neutrality.

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REFERENCES

1 Hosseini, Seyyed A., Alfi, M., Time-lapse application of pressure transient analysis for monitoring compressible fluid leakage // Greenhouse Gases: Science and Technology. – 2016. – Vol. 6 (3). – P. 352-369.

2 Bourdet, D., Ayoub, J.A., Pirard, Y.M.,Use of pressure derivative in well test interpretation // Society of Petroleum Engineers Formation Evaluation. – 1989. – N 4 (2). – P. 293–302.

3 Gringarten, A.C.,From straight lines to deconvolution: the evolution of the state of the art in well test analysis // SPE Reservoir Evaluation and Engineering. – 2008. – N 11 (1). – P. 41–62.

4 Wang Zan, Mitchell J. Small, A Bayesian approach to CO 2 leakage detection at saline sequestration sites using pressure measurements // International Journal of Greenhouse Gas Control. – 2014. – Vol.30. – P. 188-196.

5 Zeidouni Mehdi, Nam H Tran, Muhammad D. Munawar, Interpretation of above-zone pressure influence time to characterize CO2 leakage // Greenhouse Gases: Science and Technology. – 2017. – N 7 (23). – P. 1050-1064.

6 Alfi Masoud, Seyyed A. Hosseini, Mehrdad Alfi, Mahmood Shakiba, Effectiveness of 4D Seismic Data to Monitor CO2 Plume in Cranfield CO2-EOR Project // Carbon Management Technology Conference. – 2015.

7 Caesary Desy, Seo Young Song, Huieun Yu, Bitnarae Kim,A review on CO2 leakage detection in shallow subsurface using geophysical surveys // International Journal of Greenhouse Gas Control. – 2020. – Vol. 102 (103165).

8 Roland N. Horne, Modern Well Test Analysis. A Computer-Aided Approach, 2nd ed. – California, USA. Palo Alto. Petroway Inc. – 1995. – P. 79-81.