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Recent advances and challenges in gas injection techniques for enhanced oil recovery

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Abstract

Gas injection techniques have emerged as a pivotal method in Enhanced Oil Recovery (EOR), aimed at maximizing the extraction of oil from mature reservoirs. Recent advances in this domain have significantly improved the efficiency and effectiveness of gas injection methods, contributing to increased recovery rates and extended reservoir lifespans. This reviews the latest technological innovations and persistent challenges associated with gas injection techniques in EOR. One of the primary advancements in gas injection is the development of more sophisticated gas compositions, including the use of CO_2, nitrogen, and hydrocarbon gases. These gases have been optimized to improve miscibility with crude oil, thereby enhancing displacement efficiency and increasing oil recovery. Moreover, advancements in monitoring and modeling technologies, such as real-time reservoir simulation and 4D seismic monitoring, have enabled more precise control and assessment of gas injection processes, ensuring optimal gas utilization and minimizing environmental impact. Innovations in smart well technologies and downhole monitoring systems have further enhanced the ability to manage and optimize gas injection operations. These technologies provide continuous data on reservoir conditions, enabling dynamic adjustment of injection parameters to maximize recovery. Additionally, the integration of machine learning and artificial intelligence in EOR processes has facilitated predictive analytics, improving decision-making and operational efficiency. Despite these advancements, several challenges persist. The primary challenge lies in the high operational costs and economic feasibility of gas injection projects, particularly in volatile oil markets. Ensuring the long-term stability and effectiveness of injected gases in heterogeneous reservoirs also presents significant technical hurdles. Moreover, environmental concerns related to the use of CO_2 and other gases necessitate the development of more sustainable and eco-friendly injection methods. Addressing these challenges requires ongoing research and development, as well as collaboration between industry stakeholders, to refine gas injection techniques and mitigate associated risks. The future of gas injection in EOR looks promising, with continued innovation poised to overcome existing barriers and drive more efficient and sustainable oil recovery methods. In conclusion, while recent advances in gas injection techniques for EOR have demonstrated considerable potential, overcoming the economic, technical, and environmental challenges remains crucial for the widespread adoption and success of these methods.

Keywords: Recent Advances; Challenges; Oil Recovery; Enhanced; Gas Injection Technique

1. Introduction

Enhanced Oil Recovery (EOR) techniques are pivotal in maximizing the extraction of oil from mature and declining reservoirs, playing a crucial role in meeting global energy demands (Karimov & Toktarbay, 2023, Malozyomov, et. al., 2023). Primary and secondary recovery methods typically leave a substantial portion of the oil in the reservoir, often up to 60-80%, making EOR methods essential for maximizing production. EOR techniques, including gas injection, thermal recovery, and chemical injection, are implemented to improve the efficiency of oil extraction, thereby extending the productive life of oil fields. This not only boosts the economic viability of existing wells but also reduces the need

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for new exploratory drilling, which can have significant environmental impacts. EOR is becoming increasingly important as the industry shifts towards more sustainable and efficient resource management practices.

Gas injection for EOR has a long history, with its origins in the early 20th century. The initial methods involved simple gas flooding to maintain reservoir pressure and displace oil. Over the years, these techniques have evolved significantly (Liu, et. al., 2020, Xu, et. al., 2020). In the 1970s, the concept of miscible gas injection emerged, where gases like CO_2 or hydrocarbon gases are injected to mix with the oil, reducing its viscosity and improving flow. The 1990s and early 2000s saw advancements in simulation technologies, allowing for better prediction and optimization of gas injection processes. More recently, the integration of digital technologies such as smart well technology, real-time monitoring, and AI-driven analytics has revolutionized gas injection methods, making them more efficient and adaptive to changing reservoir conditions.

This paper aims to provide a comprehensive review of the latest technological advancements in gas injection techniques for EOR. Key areas of focus include the development of more effective gas compositions, such as the use of enriched gases and innovative gas mixtures, and the application of advanced simulation models to predict and optimize gas injection performance. The paper also explores the integration of digital technologies, including the use of AI and machine learning algorithms to enhance real-time decision-making and improve the overall efficiency of gas injection operations. By examining these technological advancements, the paper highlights how they contribute to increased oil recovery rates, operational efficiency, and sustainability in EOR practices.

In addition to highlighting technological advancements, the paper addresses the ongoing challenges associated with gas injection EOR. These challenges include technical issues such as the long-term stability of injected gases, reservoir heterogeneity, and gas breakthrough problems. Economic challenges, including the high costs of gas procurement and injection infrastructure, are also discussed. Environmental concerns, particularly the management of CO_2 emissions in CO_2 injection EOR, are examined in the context of regulatory requirements and sustainability goals (Clark & Santiso, 2018, Núñez-López & Moskal, 2019). The paper aims to provide potential solutions to these challenges, such as improved gas recycling techniques, enhanced monitoring and control systems, and the development of more cost-effective injection methods. By presenting both the advancements and challenges, the paper offers a balanced perspective on the current state and future prospects of gas injection techniques in EOR.

Addressing both the technological advancements and the persistent challenges is crucial for providing a holistic understanding of gas injection techniques in EOR. While technological innovations hold the promise of significantly enhancing oil recovery rates and operational efficiency, the challenges must be overcome to fully realize this potential (Koroteev & Tekic, 2021, Panchal, et. al., 2021). By analyzing both aspects, the paper aims to offer valuable insights for industry professionals, researchers, and policymakers, encouraging continued innovation and addressing the barriers that may impede the widespread adoption of advanced gas injection techniques. This balanced approach ensures that the discussion is grounded in the practical realities of EOR operations while also highlighting the transformative potential of emerging technologies.

2. Advances in Gas Injection Techniques

One of the most significant advancements in gas injection techniques for Enhanced Oil Recovery (EOR) is the use of carbon dioxide (CO_2) for miscible gas injection (Al-Shargabi, et. al., 2022, Kumar, et. al., 2022). CO_2 is particularly effective because it can mix with crude oil under certain pressure and temperature conditions, reducing the oil's viscosity and interfacial tension, thus enhancing its flow towards the production wells. This process, known as miscible displacement, allows for a more efficient sweep of the oil reservoir. The adoption of CO_2 injection not only improves oil recovery rates but also provides an avenue for carbon sequestration, addressing environmental concerns associated with greenhouse gas emissions.

In addition to CO_2, nitrogen and hydrocarbon gases are increasingly being incorporated into gas injection strategies. Nitrogen, due to its inert properties and low cost, is used in immiscible gas injection processes to maintain reservoir pressure and displace oil. Hydrocarbon gases, such as methane and natural gas liquids, are also employed for their miscible properties (Almobarak, et. al., 2021, Ozowe, et. al., 2020). These gases can dissolve in oil, lowering its viscosity and improving mobility. The selection of the appropriate gas type is often dictated by the reservoir characteristics and the specific recovery goals. The integration of these gases offers flexibility in designing EOR projects, ensuring optimal recovery under varying reservoir conditions.

Recent advancements have focused on optimizing gas blends to achieve the best possible oil displacement. By combining different gases, such as CO_2, nitrogen, and hydrocarbons, researchers have developed tailored gas mixtures that maximize miscibility and displacement efficiency (Bajpai, et. al., 2022, Hassan, Azad & Mahmoud, 2023, Ozowe, et. al., 2020). These optimized blends consider the specific properties of the reservoir and the crude oil, ensuring a more effective and economical EOR process. The development of such gas blends represents a significant step forward in enhancing the effectiveness of gas injection techniques, leading to higher recovery rates and improved economic viability.

Real-time reservoir simulation has revolutionized the way gas injection EOR projects are designed and managed. Advanced modeling capabilities allow for the accurate prediction of reservoir behavior under various injection scenarios (Bahrami, et. al., 2022, Shawkat, et. al., 2023). These simulations incorporate complex geological data and fluid dynamics, providing detailed insights into the interactions between the injected gases and the reservoir fluids. Enhanced modeling enables operators to optimize injection strategies, predict outcomes, and mitigate potential risks, leading to more efficient and effective EOR operations.

The integration of real-time data and advanced simulation models enhances decision-making processes. Operators can adjust injection parameters in response to real-time reservoir conditions, improving the adaptability and responsiveness of EOR projects. This capability reduces the uncertainty associated with reservoir performance, allowing for more informed and timely decisions that enhance overall recovery efficiency. 4D seismic monitoring, which involves the repeated acquisition of seismic data over time, provides a dynamic view of the reservoir. This technology enables real-time tracking of gas movement within the reservoir, offering valuable insights into the effectiveness of gas injection. By monitoring changes in the seismic response, operators can detect areas where the gas is effectively displacing oil and areas where it is not, allowing for targeted adjustments to the injection strategy.

The ability to track gas movement in real-time significantly improves the management of gas injection operations. Operators can identify and address issues such as gas breakthrough, poor sweep efficiency, and reservoir heterogeneity (Ashry, et. al., 2022, Sharma, et. al., 2020). This proactive approach ensures that the injected gas is utilized more effectively, maximizing oil recovery and minimizing operational costs. Smart well technologies, which include advanced downhole monitoring systems, have significantly enhanced the control and management of gas injection EOR projects. These systems provide real-time data on reservoir pressure, temperature, and fluid composition, enabling operators to closely monitor the performance of the injection process. The availability of detailed downhole data allows for precise control of injection parameters, ensuring optimal gas distribution and improved recovery rates.

Smart well technologies also enable the dynamic adjustment of injection parameters based on real-time data. Operators can modify injection rates, pressures, and gas compositions in response to changing reservoir conditions, ensuring a more efficient and effective EOR process. This capability enhances the adaptability of gas injection techniques, allowing for continuous optimization and improved recovery outcomes.

The integration of machine learning and artificial intelligence (AI) into gas injection EOR has opened new avenues for predictive analytics. Machine learning algorithms can analyze vast amounts of reservoir data to identify patterns and predict future behavior. These predictive models provide valuable insights into the likely outcomes of different injection strategies, enabling operators to make data-driven decisions that enhance recovery efficiency (Shawkat, et. al., 2023, Wang & Chen, 2023). AI-driven analytics also contribute to increased operational efficiency. By automating data analysis and decision-making processes, AI reduces the time and effort required for reservoir management. This automation allows operators to focus on higher-level strategic tasks, improving overall productivity. The use of AI in optimizing injection parameters and predicting reservoir behavior leads to higher recovery rates and more cost-effective EOR operations.

The recent advances in gas injection techniques for EOR, including the development of advanced gas compositions, technological innovations, and the integration of digital technologies, have significantly enhanced the efficiency and effectiveness of oil recovery processes (Kamyab, et. al., 2023, Onwuka, et. al., 2023). These advancements, coupled with real-time data monitoring and AI-driven analytics, provide a comprehensive framework for optimizing gas injection operations, leading to higher recovery rates and improved economic viability. As the industry continues to evolve, these innovations will play a critical role in meeting global energy demands while addressing environmental and economic challenges.

3. Challenges in Gas Injection Techniques

One of the primary challenges in gas injection techniques for Enhanced Oil Recovery (EOR) is the high cost associated with the procurement and injection of gases. Acquiring gases such as CO_2, nitrogen, and hydrocarbon gases involves significant expenses. The cost of CO_2, for instance, can be substantial, especially if it has to be captured, transported, and stored before injection (Kudapa & Krishna, 2023, Osimobi, et. al., 2023). Additionally, the infrastructure required for gas injection, including compressors, pipelines, and injection wells, adds to the overall cost. These capital-intensive requirements can make gas injection projects economically challenging, particularly for smaller oil companies or in fields with lower oil prices.

The economic viability of gas injection EOR is heavily influenced by the volatility of oil markets. Fluctuating oil prices can impact the financial feasibility of EOR projects. When oil prices are low, the high operational costs of gas injection may not be justified by the revenue generated from the additional oil recovered (Kleinberg, et. al., 2018, Ponomarenko, Marin & Galevskiy, 2022). This economic uncertainty makes it difficult for companies to commit to long-term EOR projects that require significant upfront investment. As a result, the decision to implement gas injection techniques often hinges on favorable market conditions, which are not always guaranteed.

Maintaining the long-term stability of injected gases within the reservoir is a significant technical challenge. Over time, gases like CO_2 can dissolve into the reservoir fluids or react with the reservoir rock, potentially reducing their effectiveness in displacing oil (Eyinla, et. al., 2023, Tan, et. al., 2022). Ensuring the sustained presence and activity of these gases is crucial for maximizing oil recovery. Additionally, the behavior of injected gases can be influenced by reservoir temperature, pressure, and chemistry, requiring precise control and monitoring to maintain optimal conditions.

Reservoir heterogeneity poses another major technical challenge for gas injection EOR. Natural variations in reservoir properties, such as porosity, permeability, and fluid saturation, can lead to uneven gas distribution and inefficient oil displacement (Ganat, 2020, Milad, et. al., 2021). In heterogeneous reservoirs, gas may preferentially flow through high-permeability zones, bypassing significant portions of the oil-bearing formation. Addressing this issue requires advanced modeling and simulation techniques to understand the reservoir's complexity and develop tailored injection strategies that account for these variations.

Effective gas distribution and displacement within the reservoir are critical for the success of gas injection EOR. Achieving uniform gas injection and ensuring that the gas effectively displaces the oil towards the production wells can be challenging (Yu, et. al., 2022, Zheng, et. al., 2022). Factors such as gravity segregation, viscous fingering, and gas channeling can impact the efficiency of gas injection. These phenomena can lead to early gas breakthrough and reduced sweep efficiency, ultimately diminishing the overall recovery factor. Overcoming these challenges requires continuous monitoring and adjustment of injection parameters, as well as the use of advanced technologies like smart wells and 4D seismic monitoring.

While CO_2 injection for EOR offers the dual benefit of enhancing oil recovery and providing a means for carbon sequestration, it also raises environmental concerns. The capture, transportation, and injection of CO_2 generate emissions and energy consumption, which can offset the environmental benefits of sequestration (Babarinde & Adio, 2020, Cao, et. al., 2020). Additionally, the potential for CO_2 leakage from storage sites poses a risk to the environment and public health. Ensuring the safe and permanent storage of CO_2 is critical to minimizing its environmental impact. This requires robust monitoring and regulatory frameworks to prevent and detect leaks.

The development of eco-friendly and sustainable gas injection methods is an ongoing challenge. There is a growing need for alternative gases and techniques that minimize environmental impact while maintaining or enhancing oil recovery efficiency (Qureshi, et. al., 2023, Tabatabaei, et. al., 2022). Research into the use of renewable and low-impact gases, such as hydrogen or biogas, is ongoing. These alternatives aim to reduce the carbon footprint of EOR operations and improve their overall sustainability. Additionally, advancements in technology that increase the efficiency of gas injection and reduce the amount of gas required can contribute to more environmentally friendly EOR practices.

Gas injection techniques for Enhanced Oil Recovery face significant challenges, including economic feasibility, technical hurdles, and environmental concerns. High operational costs and the volatility of oil markets can impact the financial viability of these projects (Karimov & Toktarbay, 2023, Zhou, et. al., 2023). Technical challenges such as maintaining the stability of injected gases, managing heterogeneous reservoir conditions, and ensuring effective gas distribution require advanced solutions and continuous monitoring. Environmental concerns, particularly related to CO_2 emissions and the need for sustainable practices, necessitate ongoing research and development. Addressing these challenges is crucial for the successful implementation and optimization of gas injection EOR techniques, ensuring that they remain viable and environmentally responsible methods for enhancing oil recovery in the future.

4. Case Studies and Real-World Applications

The Weyburn-Midale CO_2 Project is one of the most well-documented CO_2 EOR projects in the world. Located in Saskatchewan, Canada, this project has significantly increased oil recovery rates by injecting CO_2 into the Weyburn oil field. Initiated in 2000, the project utilizes CO_2 captured from a coal gasification plant in North Dakota, which is transported via a 320-kilometer pipeline (Al-Qasim, Kokal & Al-Ghamdi, 2021, Albertz, Stewart & Goteti, 2023). The injection of CO_2 has led to an estimated increase in oil recovery by 14-16% of the original oil in place. This project not only demonstrates the effectiveness of CO_2 EOR in enhancing oil recovery but also serves as a large-scale example of carbon sequestration, storing over 30 million tonnes of CO_2 to date.

The Scurry Area Canyon Reef Operators Committee (SACROC) Unit in West Texas is another prominent example of successful CO_2 EOR implementation (Hovorka, 2022, Panja, Jia & McPherson, 2022). Initiated in the early 1970s, SACROC has undergone several phases of CO_2 injection, leading to substantial improvements in oil recovery. By 2008, the field had produced an additional 200 million barrels of oil, thanks to CO_2 injection. The use of CO_2 has extended the life of this mature oil field and significantly increased its production rates, highlighting the potential of CO_2 EOR in revitalizing aging reservoirs.

At Prudhoe Bay, the largest oil field in North America, gas injection techniques have been employed to optimize reservoir management and enhance oil recovery (Davis, et. al., 2023, Jensen, et. al., 2023). The Prudhoe Bay Unit has implemented a gas cycling process that involves the injection of produced gas back into the reservoir to maintain pressure and improve oil displacement. This technique, combined with water alternating gas (WAG) injection, has led to better reservoir management and higher recovery rates. The project's success in optimizing gas injection strategies demonstrates the importance of tailored approaches in different reservoir conditions.

The Lula Field in the pre-salt Santos Basin offshore Brazil has seen significant success with gas injection techniques, particularly with the use of associated gas (Godoi & dos Santos Matai, 2021, Vieira, et. al., 2020). The field, operated by Petrobras, employs a combination of gas reinjection and gas lift techniques to enhance oil recovery and manage produced gas. By reinjecting gas that would otherwise be flared, the project has not only improved oil recovery rates but also reduced greenhouse gas emissions. The Lula Field serves as a model for integrating gas injection with environmental sustainability.

One of the critical lessons from successful gas injection projects is the importance of addressing reservoir heterogeneity. Tailored injection strategies, such as selective injection in high-permeability zones and continuous monitoring, have proven effective in overcoming the challenges posed by heterogeneous reservoirs (Li, et. al., 2023). Advanced modeling and simulation tools have been essential in understanding reservoir complexities and optimizing gas injection techniques.

Economic feasibility remains a significant challenge for gas injection projects. Successful implementations, such as the Weyburn-Midale and SACROC projects, have demonstrated the importance of securing long-term funding and leveraging partnerships to share costs and risks. Additionally, optimizing operational efficiency through technological innovations, such as smart well systems and real-time monitoring, has helped reduce costs and improve economic viability.

The integration of advanced technologies, including 4D seismic monitoring, smart well systems, and machine learning, has been a key factor in the success of recent gas injection projects (Al-Rbeawi, 2023, Yao, et. al., 2023). These technologies enable real-time tracking of gas movement, dynamic adjustment of injection parameters, and predictive analytics for reservoir behavior, resulting in more efficient and effective gas injection operations.

Environmental sustainability has become increasingly important in gas injection projects. Successful projects have demonstrated the benefits of using gas injection not only to enhance oil recovery but also to achieve carbon sequestration goals. The development of eco-friendly gas injection methods and the use of associated gas reinjection, as seen in the Lula Field, are best practices that future projects can adopt to minimize environmental impact.

The case studies and real-world applications of gas injection techniques for Enhanced Oil Recovery highlight both the significant advancements and the persistent challenges in this field. Successful implementations demonstrate the potential for increased recovery rates and improved reservoir management through the use of advanced technologies and tailored injection strategies. Lessons learned from overcoming technical and economic challenges provide valuable insights for future projects. By integrating best practices and prioritizing environmental sustainability, the oil and gas industry can continue to optimize gas injection techniques and achieve both enhanced oil recovery and environmental goals.

The Pembina Cardium Field, operated by Pembina Pipeline Corporation, is a notable example of successful gas injection techniques. This project implemented CO_2 flooding to enhance oil recovery in a mature field (Kumar, et. al., 2023, Shabib-Asl, Chen & Zheng, 2022). The use of CO_2 has led to a substantial increase in recovery rates, with an estimated additional 8-10% of the original oil in place being recovered. This project demonstrates the effectiveness of CO_2 injection in improving oil production in aging reservoirs and highlights the role of strategic partnerships in securing CO_2 supplies for EOR projects.

The Al-Shaheen Field, operated by North Oil Company, has successfully implemented nitrogen gas injection as part of its EOR strategy (Mahdaviara, Sharifi & Ahmadi, 2022, Kheloufi & Khatir, 2023). This technique has been particularly effective in maintaining reservoir pressure and enhancing oil recovery in this offshore field. The project showcases the benefits of using nitrogen, a readily available and cost-effective gas, in EOR operations. The Al-Shaheen Field's success underscores the importance of selecting appropriate gas types based on reservoir characteristics and economic considerations.

The Tengiz Field, operated by Tengizchevroil, is one of the world's deepest producing supergiant oil fields. The field has utilized gas injection techniques, including sour gas reinjection, to enhance oil recovery and manage reservoir pressure (Koshim, Sergeyeva & Yegizbayeva, 2022, Rakhmetov, et. al., 2023). The reinjection of produced sour gas (a mixture of natural gas and hydrogen sulfide) has not only increased oil production but also minimized flaring and reduced greenhouse gas emissions. The Tengiz Field exemplifies how integrating gas injection with environmental considerations can lead to sustainable and economically viable EOR operations.

The Ekofisk Field, operated by ConocoPhillips, has employed water alternating gas (WAG) injection as a key EOR technique (Ghasemi, et. al., 2020, Rylance, et. al., 2023). This method involves alternating the injection of water and gas to improve oil displacement and sweep efficiency in the reservoir. The WAG process has significantly enhanced oil recovery rates and extended the field's production life. The success of the Ekofisk Field illustrates the effectiveness of combining different injection fluids to optimize EOR outcomes in complex reservoir environments.

One of the critical challenges in gas injection projects is securing a reliable supply of injection gas and developing the necessary infrastructure. Successful projects, such as the Weyburn-Midale CO_2 Project, have demonstrated the importance of establishing long-term agreements with gas suppliers and investing in infrastructure, such as pipelines and compression facilities, to ensure continuous and efficient gas injection operations (Dziejarski, Krzyżyńska & Andersson, 2023, Zhao, et. al., 2023). Adapting gas injection techniques to the specific characteristics of each reservoir is crucial for success. The Prudhoe Bay Unit's gas cycling process and the Ekofisk Field's WAG injection are examples of tailored approaches that address the unique challenges of their respective reservoirs. These cases highlight the importance of conducting thorough reservoir studies and leveraging advanced modeling and simulation tools to design effective gas injection strategies.

Integrating real-time monitoring technologies, such as 4D seismic and smart well systems, has proven to be a best practice in gas injection projects. These technologies enable operators to track the movement of injected gases, adjust injection parameters dynamically, and make informed decisions based on real-time data (McDonald, et. al., 2021, Sun, et. al., 2021). For instance, the use of 4D seismic monitoring in the Lula Field has provided valuable insights into gas distribution and reservoir dynamics, leading to more efficient EOR operations. Environmental sustainability is increasingly becoming a priority in gas injection projects. Successful projects, such as the Tengiz Field and the Lula Field, have demonstrated the benefits of using gas injection techniques that minimize environmental impact, such as sour gas reinjection and associated gas reinjection. These practices not only enhance oil recovery but also reduce greenhouse gas emissions and contribute to carbon sequestration goals.

The case studies and real-world applications of gas injection techniques for Enhanced Oil Recovery highlight both the significant advancements and the persistent challenges in this field (Karimov & Toktarbay, 2023, Nassabeh, et. al., 2023). Successful implementations demonstrate the potential for increased recovery rates and improved reservoir management through the use of advanced technologies and tailored injection strategies. Lessons learned from overcoming technical and economic challenges provide valuable insights for future projects. By integrating best practices and prioritizing environmental sustainability, the oil and gas industry can continue to optimize gas injection techniques and achieve both enhanced oil recovery and environmental goals.

5. Future Directions and Research Needs

Future research in gas injection techniques is expected to focus on developing innovative gas compositions and injection methods to enhance oil recovery (Al-Shargabi, et. al., 2022, Massarweh & Abushaikha, 2022, Ozowe, et. al., 2020). This includes exploring the use of alternative gases, such as hydrogen and helium, which have shown potential for improving sweep efficiency and reducing residual oil saturation. Additionally, advancements in gas injection methods, such as the use of foam or nanoparticles, may offer new opportunities for increasing the effectiveness of gas flooding processes.

Continued advancements in monitoring and simulation technologies are essential for optimizing gas injection techniques (Kuang, et. al., 2021, Zhao, et. al., 2022). Real-time monitoring tools, such as advanced sensors and imaging technologies, can provide valuable insights into reservoir behavior and gas distribution, enabling operators to adjust injection strategies in response to changing reservoir conditions. Similarly, advanced reservoir simulation models, coupled with machine learning and AI algorithms, can help predict reservoir performance and optimize injection parameters for maximum recovery.

Collaboration between the oil and gas industry, academia, and government agencies is crucial for driving innovation in gas injection techniques. Cross-industry partnerships can facilitate the sharing of knowledge, resources, and best practices, leading to the development of more effective and sustainable EOR solutions (Behne, Heinrich Beinke & Teuteberg, 2021, Carmona-Lavado, et. al., 2023). Additionally, collaboration with technology providers and service companies can accelerate the adoption of new technologies and methodologies in gas injection projects.

Addressing the economic and environmental challenges associated with gas injection techniques requires a concerted effort from all stakeholders. Industry partnerships can help identify cost-effective solutions, such as shared infrastructure for gas supply and injection, and collaborative research initiatives aimed at developing greener gas injection technologies. By working together, the industry can overcome barriers to EOR implementation and achieve sustainable oil recovery practices.

The future of gas injection techniques lies in the development of greener and more sustainable practices. This includes exploring alternative sources of injection gases, such as biogas or renewable hydrogen, which can reduce greenhouse gas emissions and minimize environmental impact (Kurien & Mittal, 2022, López-Lorente, et. al., 2022). Additionally, research into carbon capture and storage (CCS) technologies can help mitigate the environmental footprint of gas injection projects by safely storing CO_2 underground.

As environmental regulations become more stringent, it is crucial for gas injection projects to comply with these regulations to avoid costly penalties and reputational damage (Babalola, & Olawuyi, 2022, Wood, 2022). This requires ongoing monitoring and reporting of environmental impacts, as well as implementing best practices for minimizing emissions and protecting ecosystems. By prioritizing environmental protection, the oil and gas industry can demonstrate its commitment to sustainable development and responsible resource management.

The future of gas injection techniques for Enhanced Oil Recovery is promising, with ongoing research and development efforts focused on enhancing recovery rates, reducing environmental impact, and ensuring economic viability (Karimov & Toktarbay, 2023, Wang, et. al., 2023). Collaboration between industry stakeholders, along with a commitment to sustainable practices, will be key to overcoming the challenges and realizing the full potential of gas injection techniques in the years to come.

6. Conclusion

Gas injection techniques have evolved significantly in recent years, offering promising opportunities for enhancing oil recovery from mature reservoirs. This paper has explored the recent advances and challenges in gas injection techniques for Enhanced Oil Recovery (EOR), highlighting key points that underscore the importance of continued innovation and collaboration in the industry.

The development of advanced gas compositions, technological innovations such as real-time reservoir simulation and smart well technologies, and the integration of machine learning and AI have all contributed to improving the efficiency and effectiveness of gas injection for EOR. Despite these advancements, challenges such as economic feasibility, technical hurdles in managing heterogeneous reservoir conditions, and environmental concerns remain. However, ongoing research and development efforts are addressing these challenges and offering potential solutions.

The complexity of reservoir conditions and the dynamic nature of the oil and gas industry require a continuous focus on innovation. Future research should explore new gas compositions, advanced monitoring and simulation technologies, and sustainable practices to further enhance gas injection techniques. Collaboration between industry stakeholders, academia, and government agencies is crucial for driving innovation and addressing challenges. By working together, the industry can overcome barriers and develop more sustainable and efficient gas injection practices.

Gas injection techniques have the potential to revolutionize EOR by significantly increasing oil recovery rates and extending the lifespan of mature reservoirs. Continued innovation and collaboration are essential to unlocking this potential and maximizing the benefits of gas injection for EOR. As the oil and gas industry continues to evolve, there is a growing need for sustainable and efficient oil recovery methods. Gas injection techniques offer a promising solution, but it is essential to prioritize environmental protection and responsible resource management in their implementation. In conclusion, recent advances in gas injection techniques present exciting opportunities for the oil and gas industry to enhance oil recovery and optimize reservoir management. By addressing challenges and embracing innovation, the industry can continue to drive sustainable growth and meet the world's energy needs in a responsible manner.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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