Simulation of Fluid Flow and Storage in Fractured Basement: Insights into CO_2 Sequestration Potential

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Abstract

This scientific article investigates fluid flow behavior and the feasibility of carbon dioxide (CO_2) storage in fractured basement rocks (Granite and Basalt) within a tectonically active region. The study specifically focuses on assessing the influence of fracture connectivity on the storage capacity within these fractured network. A simulation-based approach was developed using a python built workflow that generated randomly oriented fractures and classified them based on their connectivity (connected or unconnected) using a mathematical threshold. The study investigates the relationship between the number of fractures and the proportion of connected fractures, as well as the variation of average stored CO_2 volume with respect to the fracture angle. The results demonstrate different trends in storage, influenced by buoyancy and geological stress. To provide a more comprehensive analysis, the dissolution of the injected gas within the preexisting water has also been taken into consideration. Geological understanding is integrated into the analysis to assess the potential of fractured basement formations for carbon storage and to address challenges related to fractured reservoirs. The findings from this study contribute to advancing the knowledge and techniques required for successful implementation of carbon storage in such geological formations.

Introduction

The escalating levels of CO_2 emissions and their significant contribution to the greenhouse effect have prompted growing concerns about their environmental impact. As a result, scientists have been actively searching for reliable and effective methods to mitigate greenhouse gases. Carbon Capture and Utilization (CCU), Negative Emission Technology (NET), and Carbon Capture and Storage (CCS) have emerged as prominent techniques in this regard (IPCC, 2023; Cuellar-Franca and Azapagic, 2015; Ringrose, 2017). Geological storage of CO_2, in particular, has emerged as a promising approach to achieve the temperature increase targets set forth in the Paris climate agreement. Pacala and Socolow (2004) suggested that a combination of different technologies, including CCS, would be necessary to address the climate problem in the coming decades. In line with these efforts, according to a report by The Times of India (2023), Oil and Natural Gas Corporation (ONGC) has pledged to invest ₹1 trillion in green initiatives by 2030, with the aim of achieving net-zero emissions by 2038. ONGC is dedicated to reducing both Scope 1 and Scope 2 emissions, taking full responsibility for its carbon footprint. By employing fracture network simulations and analyzing CO_2 storage within geological formations, ONGC can optimize its carbon capture and storage strategies. Integrating geological knowledge and modeling techniques provides valuable insights into CO_2 distribution, injection techniques, and long-term storage potential, contributing to net-zero emissions and environmental responsibilities.

Fractured basements, which are ubiquitous in sedimentary basins worldwide, have received attention as potential candidates for CO_2 storage (Kelemen et al., 2018; March et al., 2018; Thanh et al., 2019), despite their significant storage potential for both CO_2 and enhanced oil recovery (Agada et al., 2016). Fractured basements offer unique challenges due to complexities associated with fluid flow and transfer mechanisms. Understanding and modeling the behavior of CO_2 in fractured formations are crucial for the successful implementation of CO_2 storage operations. To provide a geological context, we begin by reviewing the main physical mechanisms that occur

Simulation of $C0_2$ Injection and Storage in Fractured Basement: Insights into Sequestration Potential

during CO_2 injection in fractured formations. Injection operations target formations where CO_2 exists in a supercritical state, characterized by increased gas density and improved stored mass per unit pore volume. The density of CO_2 ranges from 600 to 800 kg/m³, depending on pressure and temperature conditions, while brine density ranges from 950 to 1230 kg/m³. The density difference between CO_2 and brine induces its upward flow, necessitating the presence of a capping mechanism to prevent further migration. CO_2 injection in fractured formations creates a multi-phase & multi-component system with buoyancy, injection pressure, and mass transfer between phases (capillarity and dissolution). Modeling fractured formations presents a significant challenge due to the introduction of fractures as high-permeability pathways that enable rapid fluid flow. Injected CO_2 can quickly travel through the fracture system. Understanding the transfer mechanisms is essential, as they directly impact the storage capacity.

This manuscript presents a comprehensive modeling approach that incorporates the complexities of CO_2 storage in fractured formations, considering factors such as displacement, buoyancy redistribution, capillary imbibition, and gas dissolution within preexisting water. The study emphasizes the significance of fracture connectivity, orientation, and geological factors in effective carbon sequestration. Repurposing existing dry or water-bearing wells of ONGC in basement rocks as CO_2 storage sites offers a cost-effective solution. However, careful planning, monitoring, and compliance with regulations are crucial for safe implementation. This research contributes to global CCS projects and the development of storage strategies in fractured basements, advancing sustainable greenhouse gas management. The findings inform decision-making and optimize CO_2 storage operations, promoting a sustainable and environmentally conscious future.

CO_2 in Reservoir Conditions

The critical temperature of CO_2 is 31.1°C, and its critical pressure is 7.38 MPa. Below a depth of around 800-850 m, where the underground temperature and pressure prevail, CO_2 exists in its supercritical state. In this state, CO_2 behaves as a gas-like compressible fluid with a density ranging from approximately 600 kg/m3 (at 30°C and 8 MPa) to 800 kg/m3 (at 160°C and 70 MPa). The viscosity of supercritical CO2 varies between approximately 0.04 cP (at 30°C and 8 MPa) and 0.08 cP (at 160°C and 70 MPa). Comparatively, fresh water shows a density decrease from 1,000 kg/m3 at surface conditions to about 900 kg/m3 at a depth of 7,000 m, with viscosity declining from 1.0 to 0.2 cP (Van der Meer, 2005).. In the Norwegian North Sea reservoirs, the brines have a CO_2 solubility of around 5 g per 100 g water (van der Meer et al., 1992; Kennedy and Thodes, 1961; Earlougher, 1977; Holloway and Savage, 1993).

CO_2 storage in fully water-saturated reservoirs involves several key mechanisms:

- *Displacement*: Injected CO_2 displaces the formation water within the reservoir.
- *Dissolution*: CO_2 can dissolve in the formation water, contributing to its storage.
- *Reactivity*: The minerals and pore fluids in the reservoir rocks may react with CO_2, affecting its storage capacity.
- *Mixing/Interaction*: Interaction occurs between the original natural gas and injected CO_2, influencing the overall storage dynamics.

Our model incorporates a CO_2 density of 750 kg/m3 and a solubility of 5 g injected gas per 100 g water within the initially water-saturated fractures. These values provide a basis for simulating and analyzing the behavior of CO_2 within the geological formations under consideration.

Methodology

The methodology employed in the python code combines geological context and a mathematical approach to simulate CO_2 storage in fractured basement. This integrated approach allows for a comprehensive understanding of fluid behavior within the subsurface reservoir and facilitates the estimation of storage capacity. The following steps outline the approach used in the code (Figure 1):

[1] *Geological Context:* The workflow begins by defining the dimensions of the basement

domain, representing the spatial extent of the geological formation. These dimensions, including x, y, and z sizes, establish the geological context for the simulation.

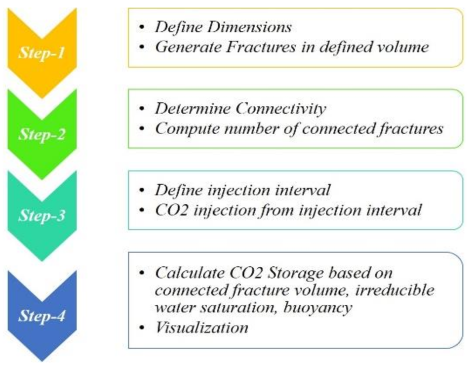


Figure 1: Workflow of the Fluid Flow Simulation and Storage computation in Fractured Basement Reservoir

[2] *Fracture Generation and volume computation:* Next the workflow generates a set of fractures within the defined geological domain. The number of fractures is determined, and their properties, such as lengths and widths, are randomly generated using appropriate distributions. By mimicking the natural variability of fractures, this approach captures the heterogeneity of the geological system. We also calculate the volume of individual fractures based on their dimensions for estimating the storage capacity of CO_2 within the fractured reservoir.

[3] *Fracture Connectivity:* We determine fracture connectivity by defining a distance threshold. This information is essential for understanding the flow pathways and connectivity within the fractured reservoir.

[4] *CO_2 Saturation and Injection:* We assume initial 100% water saturation values to fractures based on their positions within the reservoir. Fractures adjacent to injection interval, representing the targeted zone for injection, are assigned to be first saturated with CO2 and consequently the connected fractures. Whereas, Fractures outside the connected network represents complete water saturation.

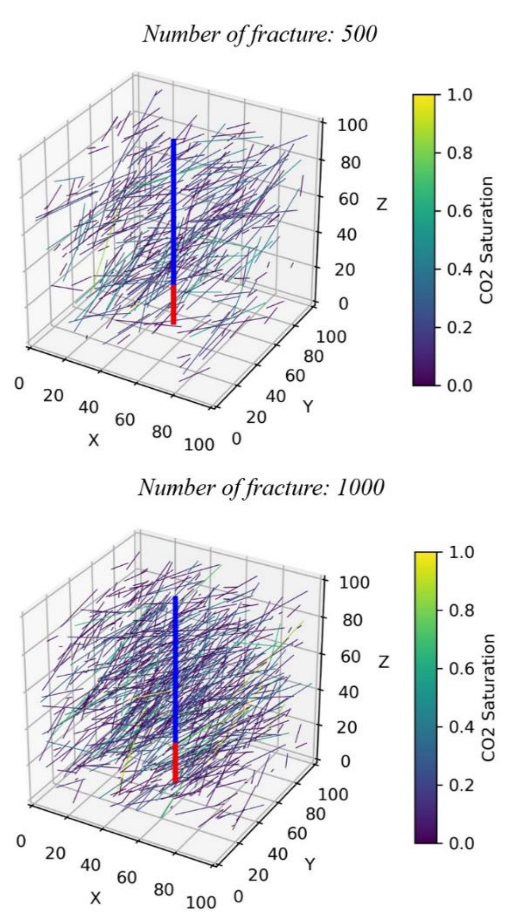


Figure 2: Randomly oriented fractures within the defined 3D geological domain.

[5] *Simulation of CO_2 Saturation:* We simulate the behavior of CO_2 within the fractured reservoir. It considers factors such as fracture connectivity, capillarity, stress and buoyancy effects. For fractures within the injection interval, CO_2 saturation is computed based on fracture volume, irreducible water saturation and dissolution. For fractures connected to the injection interval, the algorithm calculates the average CO_2 saturation of connected fractures. This approach captures the spreading and distribution of CO_2 within

the connected fractures. Unconnected fractures, which are not influenced by the gas migration from the injection interval, are assigned a gas saturation of 0.

[6] *CO_2 Storage Calculation:* Next the code calculates the CO_2 storage in fractures by multiplying the CO_2 saturation of each fracture by its corresponding volume. This calculation represents the potential capacity of individual fractures to store CO_2. By summing the storage values of all fractures, the algorithm provides an estimate of the overall storage potential within the fractured reservoir.

Results and Discussion:

We have run the simulation with four sets of fracture (number of fractures: 500 and 1000: Figure 2). The results obtained from all the simulations, incorporating geological context and a mathematical approach, provide valuable insights into the behavior of CO_2 storage within fractured formations (Table 1).

Table 1: Parameters for the mathematical simulation based storage capacity estimation in fracture basement reservoir

Parameter	Unit	Case 1	Case 2
Total Fractures		500	1000
Connected fractures		83	201
Irreducible water saturation	%	0.15	0.15
Formation volume factor	Bbl/STB	1.45	1.45
Average CO_2 density	Kg/m^3	750	750
CO_2 storage	Kg	18553860.2	49340730.4

These findings contribute to a deeper understanding of fracture characterization, CO_2 flow and the potential for carbon sequestration. The 3D visualization of fractures and their associated CO_2 storage offers a comprehensive assessment of the reservoir's spatial distribution. The outputs allows for the identification of preferential flow pathways for CO_2 migration in addition to the regions with limited CO_2 migration potential.

A significant outcome of the simulation is the identification of CO_2 saturated fractures adjacent to the injection interval and connected to it. These fractures serve as key pathways for CO_2 migration and storage within the reservoir. The count of connected fractures provides a quantitative measure of the extent of storage. Analyzing CO_2 volumes in relation to distances from the center of the injection interval reveals no discernible trend (Figure 3). Which suggests that the distance of the fractures does not significantly impact the storage capacity of CO_2. Other factors, such as fracture permeability, connectivity, capillarity and buoyancy may have a more dominant influence on CO_2 storage capacity.

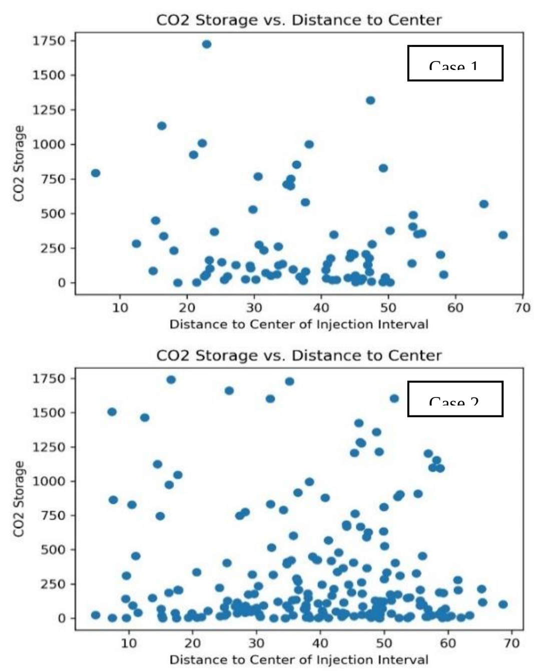
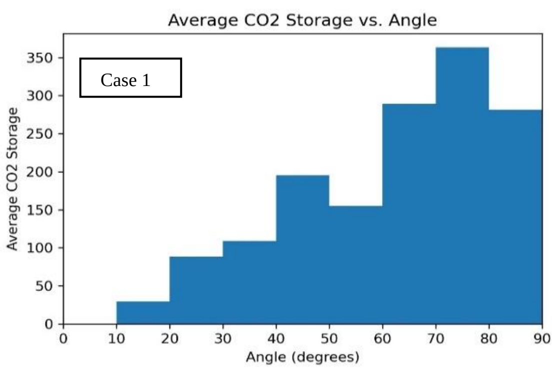


Figure 3: CO_2 storage volume with respect to the distnce (middle point of injection interval to middle point of the fractures) of individual connected fractures

The investigation of fracture angles and their influence on CO_2 storage adds a geological perspective to the analysis. By examining the orientations of CO_2 saturated fractures adjacent and connected, the code reveals preferential directions for CO_2 migration within the reservoir. The increasing trend of average storage with fracture dip angle highlights the importance of fracture orientation in determining CO_2 accumulation (Figure 4). This can be attributed to a combination of factors including larger fracture apertures, improved fracture connectivity, and buoyancy effects. As fractures with steeper dip angles experience higher geological stress, they open wider, allowing for greater CO2 storage due to increased fracture aperture. Moreover, the enhanced fracture connectivity facilitates more efficient CO2 migration and accumulation. Additionally, buoyancy plays a role as CO2, being lighter than the surrounding fluids, tends to rise within the fractures, further enhancing its storage capacity. The interplay of these geological and buoyancy effects contributes to the observed increase in average CO2 storage with fracture dip angle.



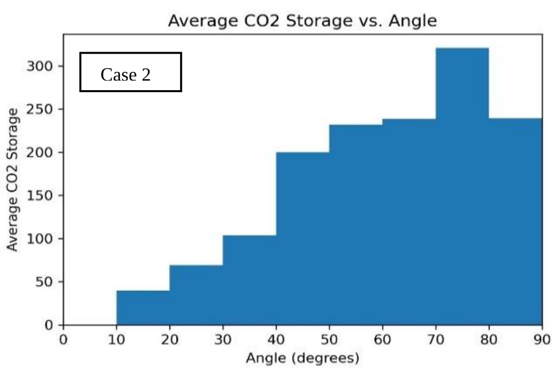


Figure 4: Variation of average CO_2 volume with respect to the angle of the fractures.

Forward Strategy

The study on fluid flow and CO2 storage behavior in fractured basement domains using a simulation-based approach presents a forward strategy for utilizing ONGC's existing wells in basement formations as CO_2 storage sites. The findings emphasize the influence of fracture connectivity and orientation on carbon storage capacity, providing valuable insights for the development of storage strategies in fractured basements. By integrating geological understanding, this research directly contributes to the global implementation of carbon capture and storage (CCS) projects. It underscores the importance of considering the geological characteristics of fractured basements to maximize the effectiveness of carbon sequestration efforts. The relevance of this study is aligned with the potential to repurpose existing wells, utilizing their highly fractured reservoirs for CO_2 storage after the depletion of reservoir pressure. In the western offshore area alone, there are approximately 80-90 wells that can be considered for this purpose. Moreover, even if the wells are initially water-bearing, they can still be repurposed for CO_2 storage without the need for additional casing or further exploratory operations. This forward strategy not only offers a cost-effective solution but also contributes to the repurposing of existing infrastructure.

Conclusion

It is crucial to note that successful implementation of CO_2 storage in basement reservoirs requires meticulous planning, monitoring, and compliance with relevant regulations and best practices. These measures ensure the safety and integrity of the storage operation, further emphasizing the need for careful consideration and adherence to established protocols. Current study insights into the fluid flow and CO_2 storage behavior in fractured basement, coupled with the potential utilization of ONGC's existing wells, offer a holistic approach to address carbon mitigation challenges. By integrating geological understanding and repurposing infrastructure, we can enhance the effectiveness of carbon sequestration while contributing to the global implementation of CCS projects. However, it is essential to proceed with caution and adhere to best practices to ensure the safety and integrity of CO2 storage operations in depleted hydrocarbon reservoirs.

Simulation of C0$_2$ Injection and Storage in Fractured Basement: Insights into Sequestration Potential

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