Hydrogen and CO_2 Storage in Sandstone: Experimental Insights into Porous Media Behavior

Apoorv Verma[1], Shruti Malik[1], Shankar Lal Dangi[1], Brijesh Kumar Yadav[2], Mayur Pal[1]
[1]Kaunas University of Technology (KTU), Department of Mathematical Modeling, Kaunas, Lithuania.
[2]Indian Institute of Technology (IIT), Department of Hydrology, Roorkee, India

Background

Studies on hydrogen and CO_2 storage in the subsurface are vital for advancing clean energy and climate change mitigation. They help optimize underground hydrogen storage for balancing energy supply and demand and improve carbon capture and storage (CCS) techniques to trap CO2, reducing atmospheric levels securely. These studies can ensure the geotechnical stability of storage sites, minimizing leakage risks, while enhancing our understanding of the storage capacity in porous media like sandstone, leading to safer and more efficient long-term storage solutions. This study explores hydrogen and CO_2 storage on a laboratory scale to determine how these gases behave in porous sandstone media under varying pressure conditions. Further, this study typically investigates to understand how well the porous media can store and retain gases. The study also examines the mechanisms of trapping (capillary and residual trapping) of hydrogen and CO_2, which is essential for long-term underground storage. Besides this, our future research will investigate potential chemical reactions among media-gas-brine, which could be the better way to understand the changes in its properties or gas storage capacity.

Objective

The main aim of this study is to conduct a lab-scale experiment to assess the hydrogen flow behavior in porous media under a controlled system. The specific objectives are as follows:

1. To examine the effectiveness of physical and chemical trapping mechanisms that prevent gas leakage
2. To study the movement and retention of gases in porous and permeable sandstone media

Experimental design

The experimental setup for gas injection in a porous media (sandstone) was constructed using a properly engineered tank to assure safety and accuracy in studying hydrogen and CO_2 storage. The experimental setup typically consists of a tank, with pressure and temperature monitoring sensors for data collection. This systematic approach contributes to a better understanding of hydrogen flow behavior. Also, we employed visualization techniques such as a dye tracer to observe fluid distributions within the sandstone pores.

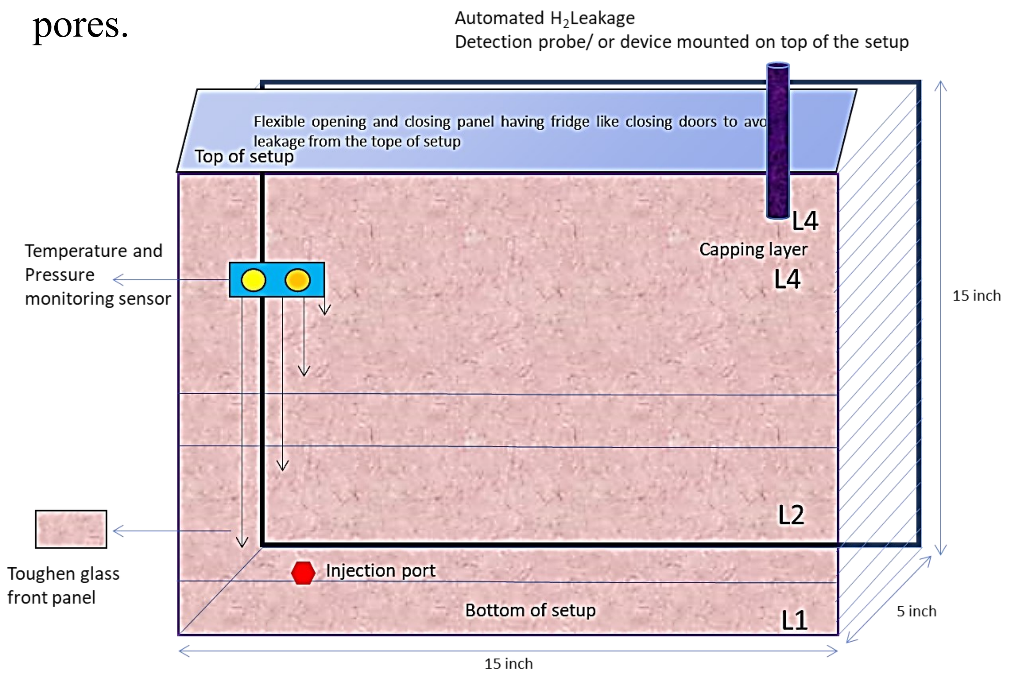


Figure 1. Schematic design of tank setup

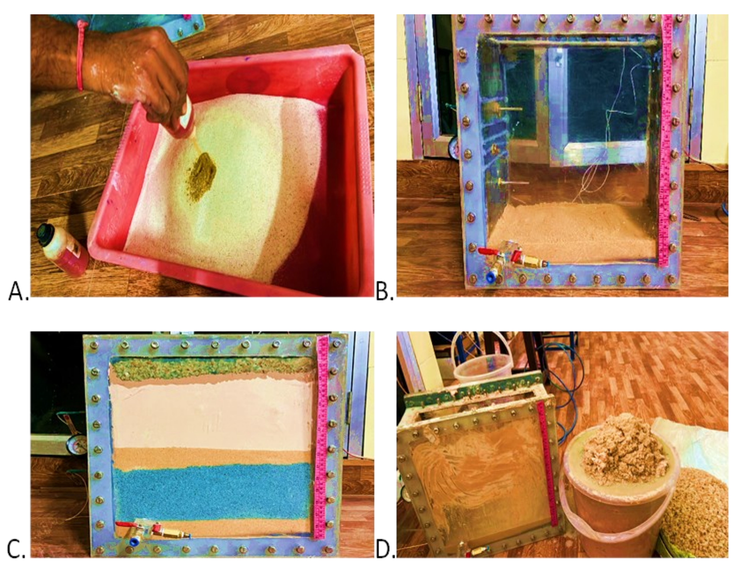


Figure 2. Preparation of tank and material A) manual mixing of BTB dye to coat the sand B) after mixing manual filling for layer preparation C) final layered tank with various materials and saturated with DI water D) after injection/run of experiment taking out the material to clean the tank for next run.

Table 1. Characteristics of material used in the experiment

Material	Porosity	Permeability (darcy)	Grain size (mm)	Avg. grain size (mm)
Sand	39	3087	0.5	0.5
Sandstone	41	8308	0.8	0.8
Clay	48	492	0.18	0.18
Gravel	46	524357	5-7	6

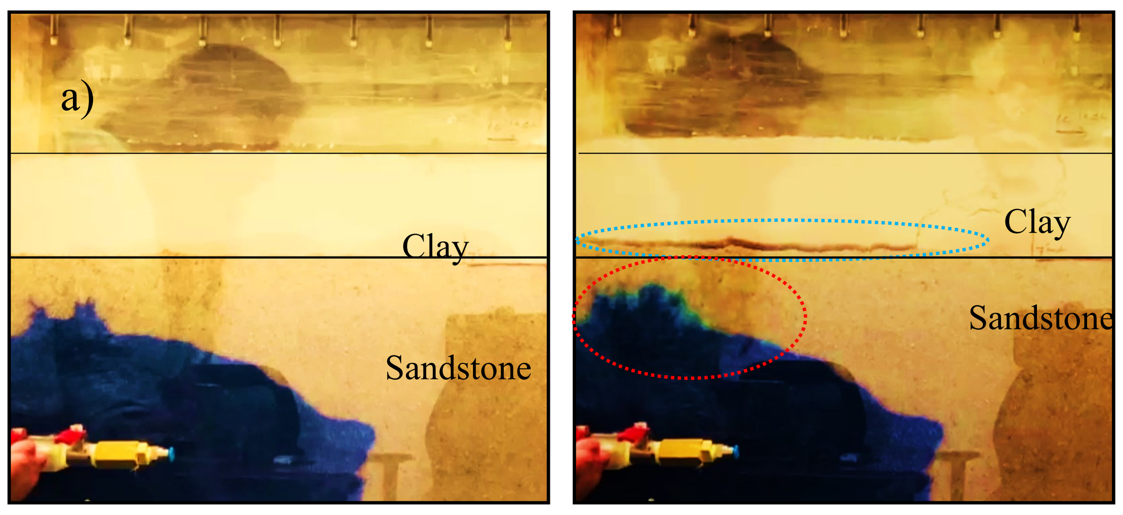
Specifications

- The tank was made of a **20 mm** thick acrylic sheet, which was chosen for its longevity and robustness.
- The tank's dimensions, **15 X 15 X 5 inches**, was designed particularly to create a controlled environment that is manageable in size while being large enough to imitate real subsurface conditions.
- The **top and bottom of the tank** were made from steel material because of its high tensile strength and durability under pressure.
- The process began with the selection and preparation of **layering materials** including **sandstone, gravel, fine sand, and clay**.

Results

Case 1-Compressed air injection

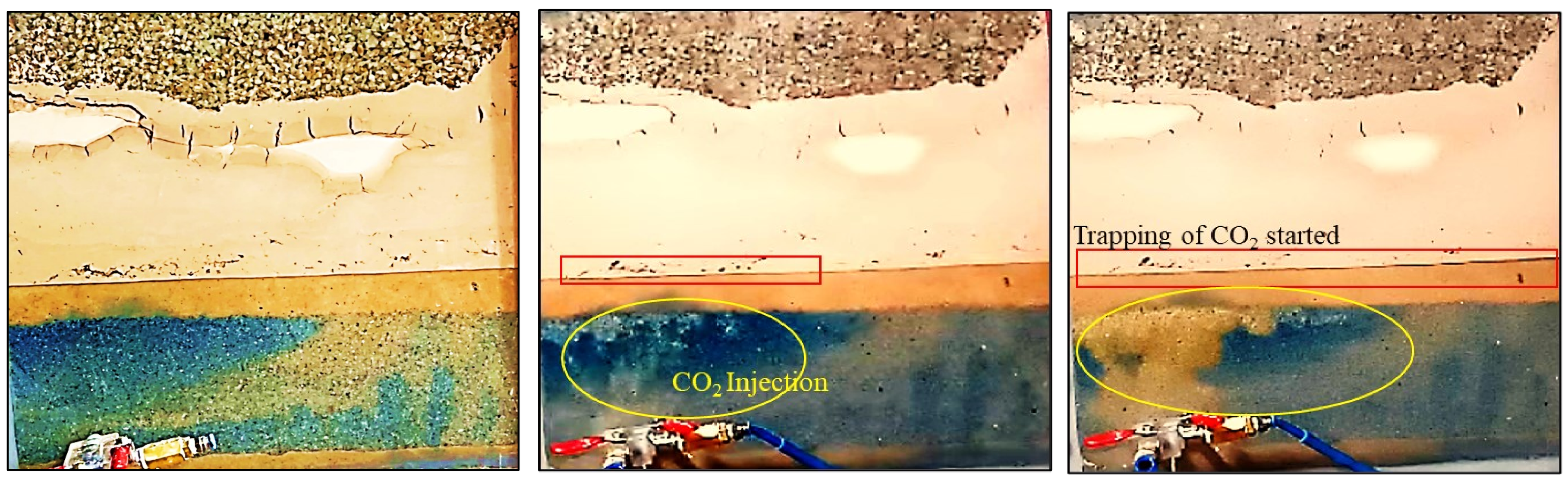
a) Before injection   b) After injection



Displacement of clay layer after injection of air at 0.5 bar pressure
Migration of methylene blue dye after injection of air in sandstone layer at 0.5 bar pressure

Initial trial examinations revealed that injecting methylene blue dye mixed with brine at a constant rate primarily tested the mechanical performance of the apparatus. After introducing compressed air at around 0.5 bar of pressure, an abrupt crack emerged, causing the clay layer to be displaced from its original position. The sandstone layer, which was 5-6 inches deep, was unaffected by this injection, however, the 3-inch clay layer was displaced, indicating that the pressure can cause disturbance within the layers. The lessons learnt from this case were applied to the subsequent experimental cases.

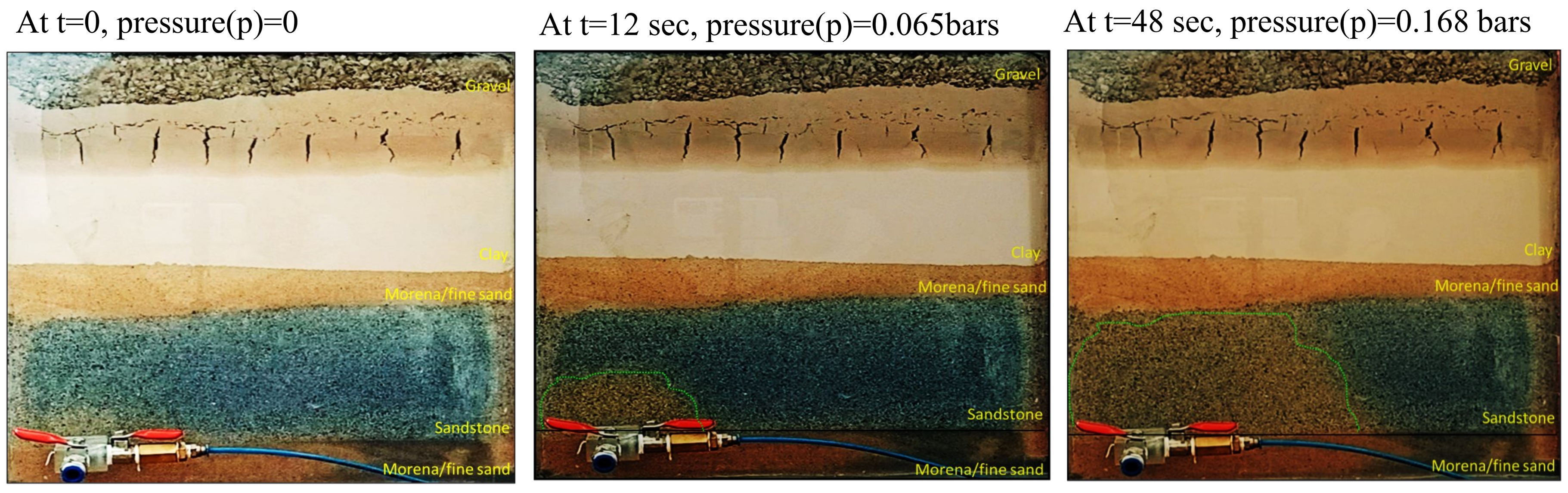
Case 2-CO_2 injection



Case 3- Hydrogen and CO_2 mixture injection

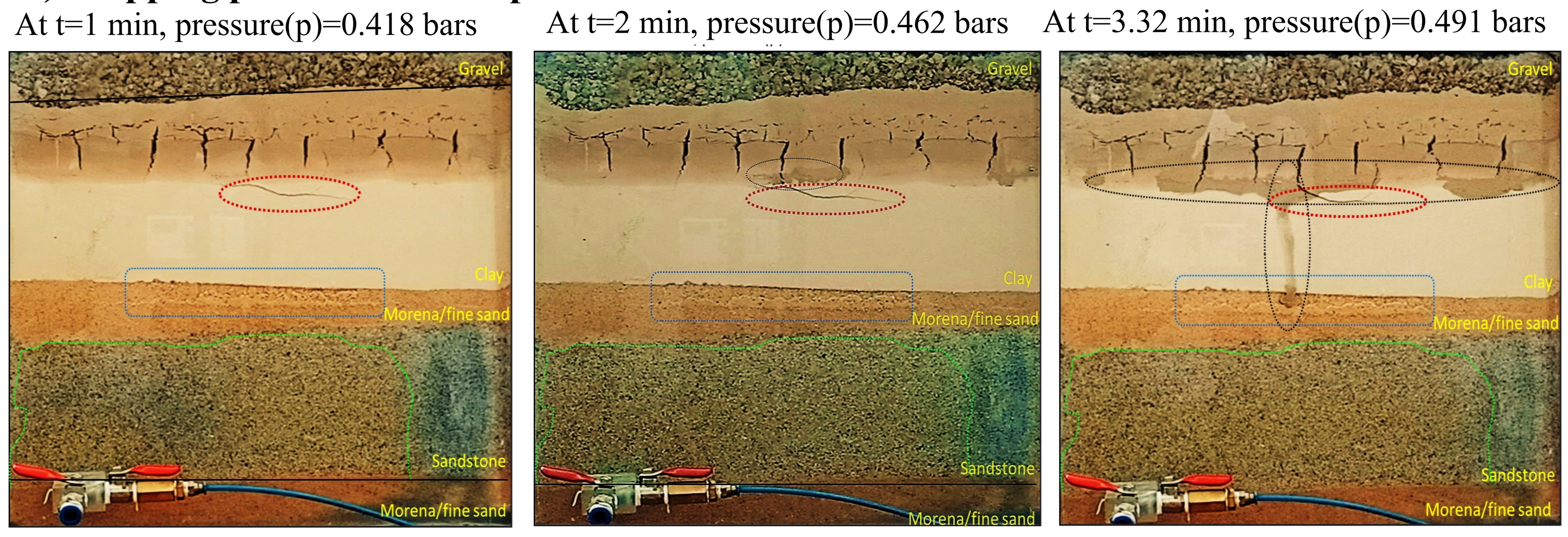
a) Injection phase

At t=0, pressure(p)=0   At t=12 sec, pressure(p)=0.065bars   At t=48 sec, pressure(p)=0.168 bars



b) Trapping phase and development of fracture/fault

At t=1 min, pressure(p)=0.418 bars   At t=2 min, pressure(p)=0.462 bars   At t=3.32 min, pressure(p)=0.491 bars



Gas movement from left to right of the tank   Leakage due to expansion of the tank from the top
Trapping of Hydrogen and CO_2
Development of crack in cap layer (clay) at pressure >0.280 Hydrogen and CO_2

Conclusions

Gas Migration in Sandstone: The movement of hydrogen and CO_2 through the sandstone media was observed from left to right, showing that the porous structure of the sandstone facilitated gas migration. This confirms that sandstone acts as a permeable medium, allowing gases to flow through its interconnected pores.

Gas Trapping Below Clay Layer: The gases are trapped in the center of the tank, just below the clay layer. This behavior indicates that while sandstone allows gas flow, it relies on an overlying impermeable layer (such as clay) to trap the gases and prevent further vertical movement. This demonstrates the effectiveness of porous sandstone media for storing gases when combined with a sealing layer.

Pressure Build-up and System Response: As gas injection continued, pressure gradually built up within the tank, reaching a maximum of 0.49 bar. At this point, the porous sandstone media still retained the gas without showing signs of leakage through the geological formation itself.

Expansion and Leakage: When the system pressure exceeded 0.49 bar, the tank expanded, and leakage occurred. However, the leakage was not through the sandstone or clay, but rather from the top of the system, indicating that while the sandstone media could handle pressure up to a certain point, the structural containment of the system was compromised.

Clay Layer Integrity as Cap Rock: Importantly, the clay layer, which was acting as a cap rock, did not fracture even under increased pressure. This behavior suggests that the sandstone below can store gases effectively if paired with an impermeable layer like clay, which prevents vertical gas escape and ensures containment within the storage formation.

Overall, the study shows that while sandstone media is effective in allowing gas movement and storage, the success of such storage depends heavily on the overlying sealing layer and overall system pressure management.

Acknowledgements

The authors would like to express their sincere gratitude to the **Lithuanian Research Council** for their generous financial support, which made this research possible, under grant no. **P-PD-23-090** and **P-PD-22-022**. Their funding was instrumental in facilitating the project and enabling the advancement of experimental research in this field in Lithuania.

The authors are also deeply appreciative of the **Groundwater Laboratory at IIT Roorkee, India**, for providing access to their state-of-the-art facilities, which were essential for conducting the experiments. The technical support, laboratory resources, and collaborative environment provided by the staff and management of the laboratory played a critical role in the successful execution of this study.