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ARTICLE

# EVALUATING CAPILLARY THRESHOLD PRESSURE IN CAPROCKS FOR CARBON STORAGE

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**Abstract:** Increased $CO_2$ emissions have resulted in extreme climatic variations and as the forecast is that the global temperature will hit its highest-ever level in the next five years. This comes at a time when there is an urgent need for effective and smooth means of reducing greenhouse gas emissions. Geological Sequestration of Carbon (GCS) is a new alternative: the effective and safe storage of $CO_2$ underground. The most critical part of the process is the leakage assessment and geological formation safety as a long-term sink of $CO_2$. Caprock is important in this process as an efficient long-time sequester for $CO_2$, as it is more permeable to $CO_2$ than geological reservoirs. Of all the other processes involved in trapping, the most effective in the immediate phase after the injection of $CO_2$ is capillary trapping. The $CO_2$ remains stored under the caprock until the critical pressure that initiates movement is achieved. Traditional methods, such as mercury intrusion porosimetry and core flooding experiments, do not tend to be replicated correctly in-situ and often complicate the process. Measurements made in such a manner usually overestimate threshold pressures for one of many reasons, be it late flow signal recognition in the low permeability of caprocks or incompletely saturated cores. For these purposes, in-situ-type novel equipment was developed for easy and direct capillary pressure measurement, core saturation, and effortless reproduction of in-situ conditions at higher pressures. This new technique measures the pressure in the outflow directly, so the values of threshold pressure it gives are very exact.

**Keywords:** capillary threshold pressure, caprock, confining pressure, $CO_2$ injection, $CO_2$ sequestration

# 1. Introduction

The rise in $CO_2$ emissions has led to drastic changes in the climate, with global temperatures likely to increase at record levels in the coming five years [1]. The need for $CO_2$ storage has never been stronger to reduce greenhouse gas emissions. In this context, Carbon Geological Sequestration (CGS) is proposed as an effective method to store $CO_2$ underground safely and effectively [2]. One critical aspect of $CO_2$ storage is to assess the leakage and safety potential of the formation for long-term retention. Generally, caprock is mostly responsible for trapping $CO_2$ over a long period due to its low permeability, hence the integrity and sealing potential of caprock is of the utmost importance for long-term $CO_2$ storage. Among all of the trapping mechanisms available, capillary trapping plays a vital role where the buoyant $CO_2$ can migrate upwards and accumulate under the caprock and the capillary leakage is the result in the rise of $CO_2$ phase above its threshold pressure. Threshold pressure can be defined as the minimum pressure required to instigate fluid displacement in the caprock [3]. Capillary trapping is typically assessed by means of a mercury intrusion porosimeter which doesn't represent in-situ conditions, or core flooding experiments by measuring the $CO_2$ saturation at residual conditions using standard approaches. However, the core has to be saturated separately in such approaches, which requires additional apparatus and adds an extra layer of complexity and can also change the in-situ condition of the core, resulting in deviated threshold pressures. Secondly, these measuring procedures usually rely on the flow rate in the core which can be detected late even if the threshold pressure is achieved due to the very low permeability of the cap rock and this can give an overestimation of the threshold pressure. One of the most popular methods to determine capillary pressure is a step by step approach as this represents the most in-situ conditions mostly the confining pressure which has a significant impact on the outcome [4]. Some studies have designed tools for measuring capillary threshold pressure and they usually measure the outer flowrate corresponding to the entry pressure. However, it is difficult to confirm the flow situation at the outlet because of the low permeability of caprock which may result in increased threshold pressure values [5, 6]. In this study, we have designed innovative equipment to make capillary pressure measurements easier by saturating the core sample with the same equipment and simultaneously replicating in-situ conditions at higher pressures and measuring the outlet pressure directly rather than the flow, giving accurate measurements of the threshold pressure.

# 2. Apparatus Design

The apparatus for measuring capillary threshold pressure under confining pressure conditions consists of three main systems (Figs 1 and 2): a high-pressure system, a gas injection system, and a gas emission system.

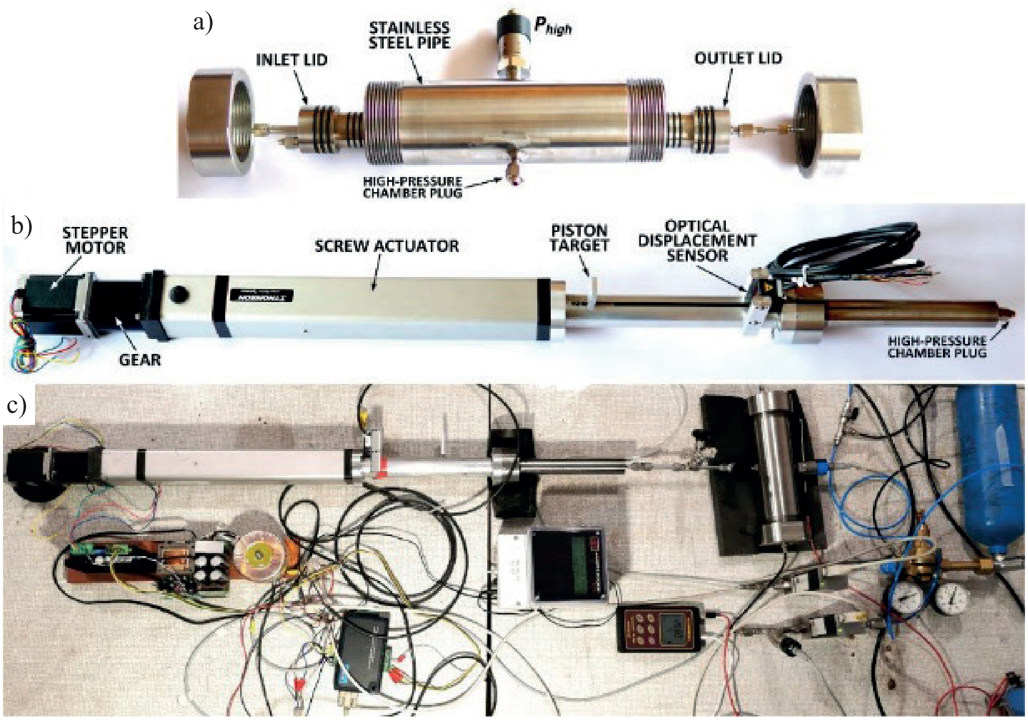


**Fig. 1.** Photos for the apparatus for measuring capillary threshold pressure: a) the high pressure core holder; b) the injection system with a piston; c) the overall design of the equipment and the connections of the vessel's inlet with the injection system

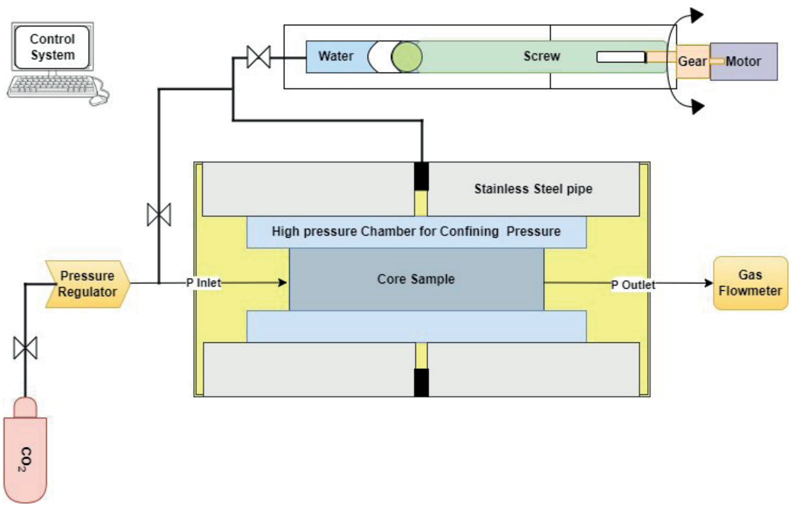


**Fig. 2.** Schematics for the apparatus for measuring capillary threshold pressure

**High-pressure system:** This is the part of the system where the core is loaded, saturated, and is subjected to confining and injection pressures with the help of a mechanical actuator which regulates the fluid in the high-pressure vessel. This high pressure system allows to set high confining pressure which represent the in-situ conditions of the reservoir. The confining pressure of this system can be set according to specific reservoir in situ conditions at different pressure ranges. For these measurements, the confining pressure was set to 15 MPa which is equivalent to 150 bars.

**Gas injection system:** This system consists of inlets that provide the gas flow to the core and are regulated by a pressure controller. This same system is used to saturate the core by a diverging valve that injects the fluid for confining and saturation pressure.

**Gas outlet system:** Here a precise pressure monitor is attached which reacts to any changes in the outlet pressure corresponding to the inlet pressure.

## 3. Methodology

Three caprock samples (Fig. 3) were selected from different well sites in Poland representing different types of rock. Their porosity and permeability were determined and presented in Table 1. Capillary pressure tests were carried out using the original apparatus on samples that were subjected to a high confining pressure of 15 MPa equivalent to 150 bars. At first, a sample was placed in a rubber sleeve which then was placed inside the high-pressure steel vessel that was filled with water to generate the confining pressure for in-situ conditions. After the placement of the core, followed by maintaining the confining pressure the core is subjected to saturation by water. Once the core has been completely saturated, the inlet is diverted for $CO_2$ injection. The injection pressure is initially set to 2 MPa and is increased incrementally. The pressure is monitored continuously at each step until stability is reached, unless there is an observed change in the outlet pressure, indicating the threshold pressure for the specific sample.

**Fig. 3.** Core sample 1, core sample 2, core sample 3

**Table 1.** Porosity and permeability of rock samples

| Caprock sample | Porosity [%] | Permeability [mD] |
|---|---|---|
| Sample 1 | 7.30 | 0.036404 |
| Sample 2 | 2.09 | 0.007668 |
| Sample 3 | 1.70 | 0.001750 |

## 4. Results

The graphs in Figure 4 show the inlet (green) and outlet (red) pressure conditions and variations for rock sample 1, 2 an 3 over a period of time. For rock sample 1, the inlet pressure started with 2 bars and it was left over time until no pressure change was observed at the outlet. Later the pressure was increased to 3 bars and was continued till 4 bars at which point the change in outlet pressure can be seen. This pressure range between 3–4 bars was regarded as the capillary threshold pressure due to the continuous rise at the outlet for sample 1 rock. For rock sample 2 the inlet pressure also started with 2 bars and was also left over a period of time to see any changes at the outlet. For this rock sample, the outlet pressure kept increasing even at 2 bars representing that it reached its threshold pressure. In the case of rock sample 3, the initial inlet pressure was set at 2 bars, and the system was allowed to equilibrate until no pressure changes were detected at the outlet. Despite gradually increasing the inlet pressure to 60 bars, no corresponding pressure change was observed at the outlet. This suggests that the threshold for this particular rock sample has not been reached, even at the elevated pressure of 60 bars. These measurements were repeated to verify the accuracy and results of the equipment.

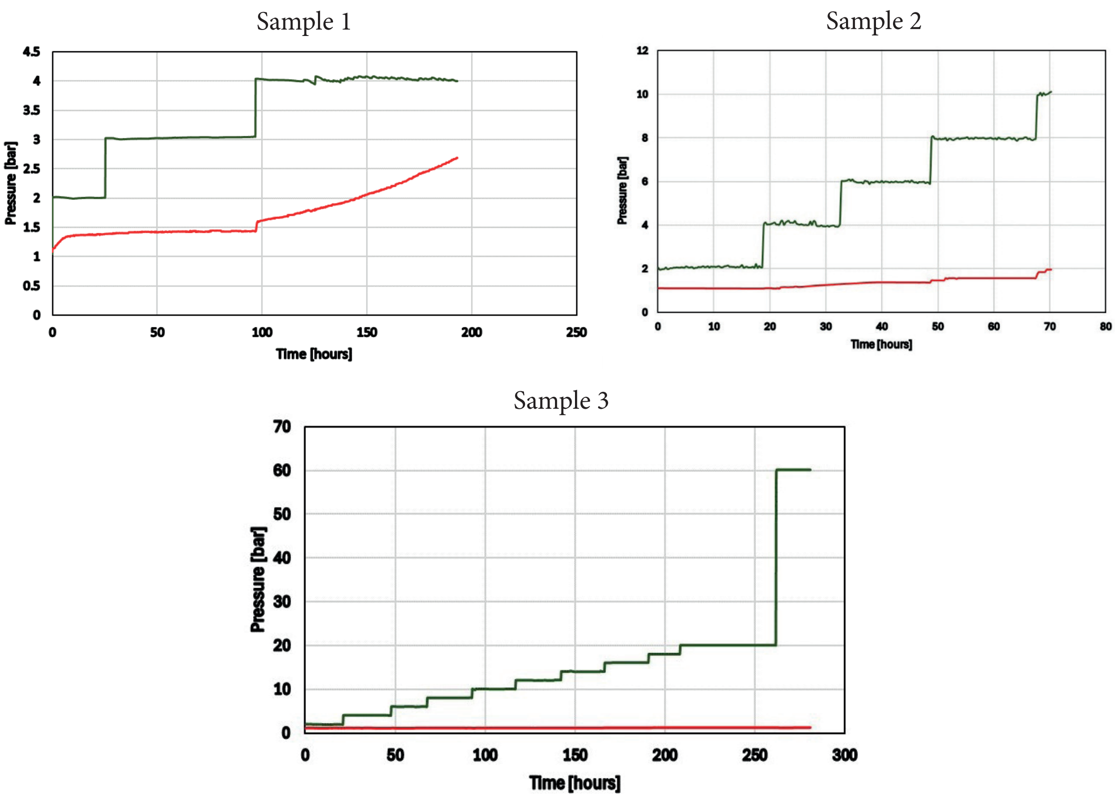


**Fig. 4.** Capillary threshold pressures for sample 1, 2 and 3

# 5. Conclusions

In conclusion, our investigation into the capillary threshold pressures of rock samples has provided valuable insights. For rock sample 1, a clear indication of capillary threshold pressure was observed between 3–4 bars, evidenced by a noticeable change in outlet pressure. Similarly, rock sample 2 displayed a distinct rise in outlet pressure between 8–10 bars, indicative of its corresponding capillary threshold pressure. However, rock sample 3 despite incremental increases in inlet pressure up to 60 bars, no corresponding change in outlet pressure was observed, suggesting that the threshold for this particular sample has not been reached representing in-situ conditions. These findings hold significant value for future $CO_2$ storage projects, enabling the rapid estimation of the total safe depth for storing carbon dioxide.

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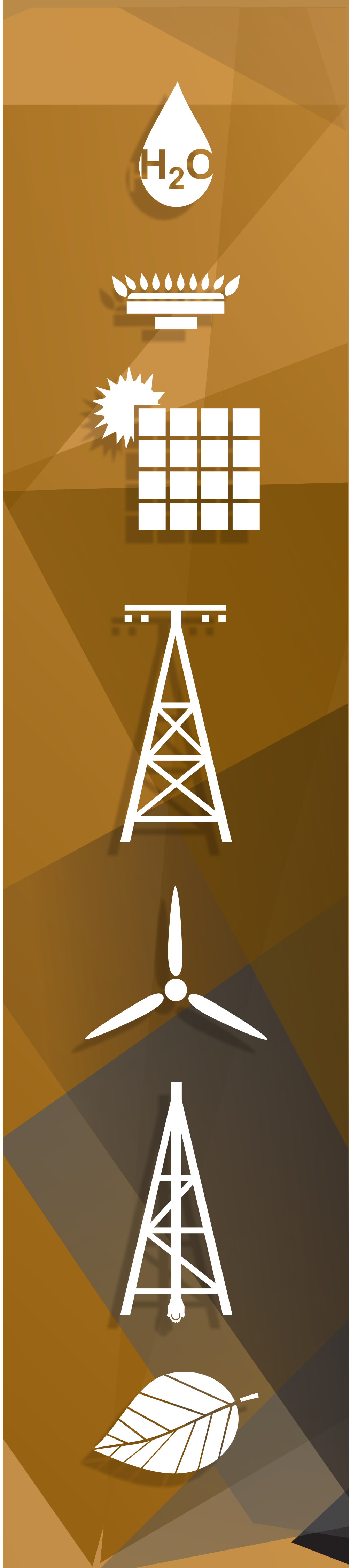
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