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Using hydrocarbon fields of the UK North Sea as analogues for effective pore throat radii prediction in mudstone caprocks

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Abstract

For geological CO₂ storage, seals prevent the supercritical CO₂ from migrating to other geological strata. The major sealing mechanism is capillary sealing. The effective pore throat radius of caprocks plays a decisive role in determining capillary entry pressure. A model for effective pore throat radius using data from shale caprocks from UK North Sea oil fields has been established in this study. The model could be used in the assessment of CO₂ storage sites in saline aquifers for which measured data are lacking.

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Keywords: carbon storage; caprocks; capillary sealing; pore throat radius; UK North Sea; saline aquifer

1. Introduction and background

The retention capacity of seals is of great importance for geological carbon storage, but usually it is a difficult property to estimate, especially for carbon storage in a saline aquifer where there is typically little or no data regarding the potential seal. In contrast, for storage in a depleted oil or gas field, the seal is known to retain buoyant fluids (oil or gas) over geological periods of time, hence it may be presumed to hold CO₂. This study presents a distribution of calculated pore throat radii of seals from the UK North Sea, for use in the assessment of saline aquifers for geological carbon storage.

Capillary sealing is believed to be the major mechanism in sealing hydrocarbon and CO₂ reservoirs. Capillary forces act to stop a buoyant fluid migrating upward. Capillary sealing is a result of the balance between the buoyancy of a
defined CO$_2$ column exerted on a caprock and the capillary entry pressure of that caprock [1]. The calculation equations for buoyancy force and capillary pressure are Eq. (1) and Eq. (2). For a seal to be effective, the buoyancy force must not exceed the capillary entry pressure at the crest of the reservoir (Eq. (3)):

\begin{align*}
P_b &= \Delta \rho gh = P_n - P_w \\
\therefore P_c = \frac{2\sigma \cos \theta}{r} \\
\therefore P_b &\leq P_c
\end{align*}

When $P_b = P_c$, the column height can be expressed as:

\[ h = \frac{2\sigma \cos \theta \Delta \rho g y}{\rho_h} \] (4)

According to Eq. (4), the pore throat radius is an important parameter for the capillary entry pressure of a seal. Pore throat radius is defined as the narrowest passages that the non-wetting phase fluid (petroleum or CO$_2$) must passes through in order to travel through a volume of rock (the red arrow in Fig. 1).

![Figure 1: Schematic of capillary sealing of a seal rock. The pore throat size is marked with red arrow.](image-url)
The conventional method for measuring the pore throat size ranges of shales and tight sandstones are mercury injection porosimetry experiments (MIP) [2 - 5]. Yang and Aplin [6] established a pore throat size distribution model for mudstones based on measured pore throat radius (using high pressure mercury injection method). The result shows a very good fit between the modelled and the measured pore throat radii (Fig. 2).

![Figure 2: Measured and modelled pore throat radius](image)

However, the MIP method has shortcomings:

- The calculation is based on the assumption that the interfacial tension and contact angle of mercury is constant, but both vary under pressure.
- The size of samples and the preparation method of the sample can effect the results.
- Often it is difficult to obtain caprock samples.
- Even if sufficient caprock samples are available, the measured pore throat radius for the samples would not necessary to be the effective pore throat radius on a reservoir scale.

MIP measurement can frequently not be applied to the caprocks of a saline aquifer, because very few caprock samples are available where there have been no hydrocarbon production activities. Even for oil and gas fields, caprock samples are scarce. The pore throat radii of a limited number of core samples may not represent the effective pore throat radii at the reservoir scale, especially if the caprocks are heterogeneous. One published example [6] is based on eleven mudstones from Norwegian Margin of the North Sea at burial depths from 855m to 3605m, which may not be representative of the mudstones of the entire North Sea.

A new model for pore throat radii has been created in this study using available data from publications [7]. The aim of this method is to reduce the dependence on individual experimental measurements for the assessment of seal retention capacity for potential CO₂ storage sites. The Monte Carlo method is used for calculating the effective pore throat radius, allowing for uncertainty in the input parameters.

2. Methodology

Effective pore throat radii are calculated from known hydrocarbon column heights using published data from UK hydrocarbon fields, using the method described in Wilkinson et al. [7]. Whereas Wilkinson et al. [7] calculated a
single value of effective pore throat radius for each North Sea field, here we use the Monte Carlo method to allow for uncertainty in multiple input parameters (Table 1). This results in a statistical distribution of results for each oil and gas field, which can then be combined to derive an overall distribution for the region.

Table 1: Uncertainties assumptions of the input parameters for the Monte Carlo simulation

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<td>5%</td>
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</table>

3. **Results and discussion**

3.1 **Pore throat Radius and Burial depth**

A relatively strong linear correlation between pore throat radius and burial depth is found for fields with burial depth less than 3000m (Fig. 3). The effective pore throat radii decrease with the depth increases. The best-fit equation is:

\[ r = 2400 - 0.89D \quad (D < 3000 \text{ m}; \quad R^2 = 0.49) \quad (5) \]

The controlling factor for the decrease of the pore throat radius with depth could be clay diagenesis. Previous studies suggest the transformation from smectite to illite leads to smaller pore throat radii and enhances the capability of capturing and storing fluids [8]. This diagenetic reaction starts from between 1500m to 2000m burial depth at a temperature around 60°C. However, for depths greater than 3000m the effective pore throat radii does not change significantly with depth, and most effective pore throats at this depth are smaller than 250nm radius (Fig. 4).

Equation (5) could be applied to seals of unknown sealing capacity that are formed of the Kimmeridge Clay Formation (KCF) at depths of less than 3000 m, as this is the formation from which the majority of the calibration data were derived. The application of the equation to caprocks of other formation could be misleading. For example, caprocks of the Maureen and Montrose fields are of Paleocene age, which are younger and less affected by diagenesis, and are less overpressured compared to the Kimmeridge Clay Formation. As an exception, field Curlew B shows a much larger pore throat radius than the other fields deeper than 3000m. It is probably because it is highly overpressured and dissected by faulting [9]. Hence, the geological age and the overpressure condition are candidate controlling factors for effective pore throat radius.
3.2 Caprock thickness

Fig. 5 shows no significant correlation between the thickness of the caprock and the calculated effective pore throat radii, indicating the current thickness of the caprock is not a controlling factor for the effective pore throat radius. Most of the caprocks of the UK North Sea are Upper Jurassic mudstones of the Heather and Kimmeridge Clay formations, which experienced differential block tilting, uplift and erosion [10] in the late Jurassic, leading to varying caprock thickness.
3.3 Results after Monte Carlo

The cumulative distribution of effective pore throat radii for 33 fields with shale caprocks is displayed in Fig. 6.

The equation for the cumulative distribution of effective pore throat radii is:

\[ F(r) = \frac{100}{1 + \exp(0.3152 - 0.006998r + 0.2288)} \quad R^2 = 0.9862 \quad (6) \]

The above model is compared with Yang and Aplin’s [6] model in Fig. 7.
Figure 7: Comparisons of cumulative percentage of pore throat radii of this study and that of Yang & Aplin [6]. The black line is the calculated effective pore throat radii using the Monte Carlo method; the blue line is the fitted model (Eq. 6); the diamonds are the mercury injection porosimetry experiments from the Norwegian Margin [6]; the red line is the model fitted to these data.

The two cumulative models show similar exponential trends, but there are several obvious differences between these two distributions:

- Yang and Aplin’s [6] model covers a larger range of pore throat radius, from 1nm to 10,000 nm. In this study, the distribution of the pore throat radii is narrower, from 37nm to 1700nm.
- The probability distribution of Yang and Aplin’s [6] model is approximately a normal distribution. The modal radii is approximately 100nm.
- The two distributions have different degrees of skewness. The distribution of this study is more positively skewed (the tail on the right side is fatter than the left side), with predominantly small pores around 30nm to 100nm than larger pores. However, Yang and Aplin’s [6] distribution is closer to a normal distribution, with most abundant pore throats between 40-400nm.

The difference in pore throat distributions may be due to a number of factors:

- Yang and Aplin [6] used mercury injection porosimetry experiments to measure the pore throat radius, while in this study, the pore throat radii are derived from hydrocarbon column heights.
- Yang and Aplin’s [6] samples are from Norwegian Margin, but the data used in this study are from the UK North Sea.
- The measured pore throat radii from Yang and Aplin’s [6] study are measured on core samples, but the effective pore throat radii from this study are calculated at the reservoir-scale.
- In this study, there are no calculated pore throat radii smaller than 37nm, which could be due to: a) the effective pore throat radii derived from this study will include fractures, if fractures are of greater dimensions than the matrix pore throats; b) the calculated pore throat radii from this study are based on the assumption that the buoyancy force equals to the capillary entry pressure. But the capillary entry pressure may be greater than the buoyancy pressure, so that the real, or measured pore throat radii will be smaller than the calculated value.
4. Conclusions

- A new model for the effective pore throat radius in caprocks of the UK North Sea has been established as a cumulative probability distribution that could be used for assessment of a CO₂ storage site if no sample of a caprock is available.
- Thirty-three oil fields with mudstone caprocks are included in pore throat radii calculation. Calculated effective pore throat radii range from 40nm to 478nm using conventional calculation, but 37nm to 1700nm using the Monte Carlo method which allows for uncertainty in input parameters. The distribution peaks at about 40nm to 60nm.
- For burial depths less than 3000m there is a linear correlation between the depth and the effective pore throat radius, while the burial depths greater than 3000m there is no correlation. It is interpreted that during shallow burial pore throat radius is controlled by mechanical compaction and / or diagenesis.
- Compared to a previous model for pore throat distribution [6], the range of the effective pore throat radius is reduced. Hence there is less uncertainty if the distribution is used to represent a seal for which no samples are available.

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References