IMPERIAL UNIVERSITY OF CAMBRIDGE OpenGoSim

The use and limitations of reduced physics models for various applications, including screening and probabilistic analysis

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Key Knowledge Deliverable 2.2

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Key Knowledge Deliverable Cover Sheet

This Key Knowledge Deliverable (KKD) has been produced by University of Cambridge as part of the DESNZ CCUS Innovation 2.0 programme. The document is reflective of the status of the project at the time of writing. The material presented could have been subject to change as the project matured. These documents should not be considered a full representation of the final project.

Description of the project: In StrataTrapper we translate cutting edge research carried out at Imperial College London and the University of Cambridge on the geological fluid dynamics and trapping of CO2 into innovative characterisation and modelling software tools that will be used by industry to reduce risks and costs of CO2 storage projects. The tools will be commercialised through incorporation into the CO2 reservoir simulation platform OpenGoSim, in addition to being made open-source. We will work with industry partners bp, Storegga, and Drax power to demonstrate the applicability of these tools to the Endurance field in the Southern North Sea and the East Mey Site in the Central and Northern North Sea. The result of the work will be the commercialisation of the StrataTrapper reservoir simulation tools for the rapid screening, risking, project design, and management of CO2 storage.

This report contains key knowledge deliverable 2.2, a report detailing the use and limitations of reduced physics models for various applications, including screening and probabilistic analysis.

The following is the full list of KKD’s to be published under StrataTrapper:

KKD1.1 Open-source research codes for the characterisation of multiphase flow heterogeneity and conversion to flow functions for reservoir simulation

KKD1.2 A report detailing the workflows for reservoir characterisation, and model creation and use

KKD2.1 Open-source research codes for the rapid estimate of the impacts of heterogeneity on lateral plume migration, residual and dissolution trapping

KKD2.2 A report detailing the use and limitations of reduced physics models for various applications, including screening and probabilistic analysis

KKD3.1 Publicly available models of the Endurance and East Mey sites

KKD3.2 A report analysing the impacts of multiphase flow heterogeneity on CO2 migration and trapping in the case study sites

KKD4.3 StrataTrapper Workshop to CCS project developers

KKD5.1 Annual reports & KKD5.2 Project final report

Any enquiries regarding this publication should be sent to us at:
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Model description

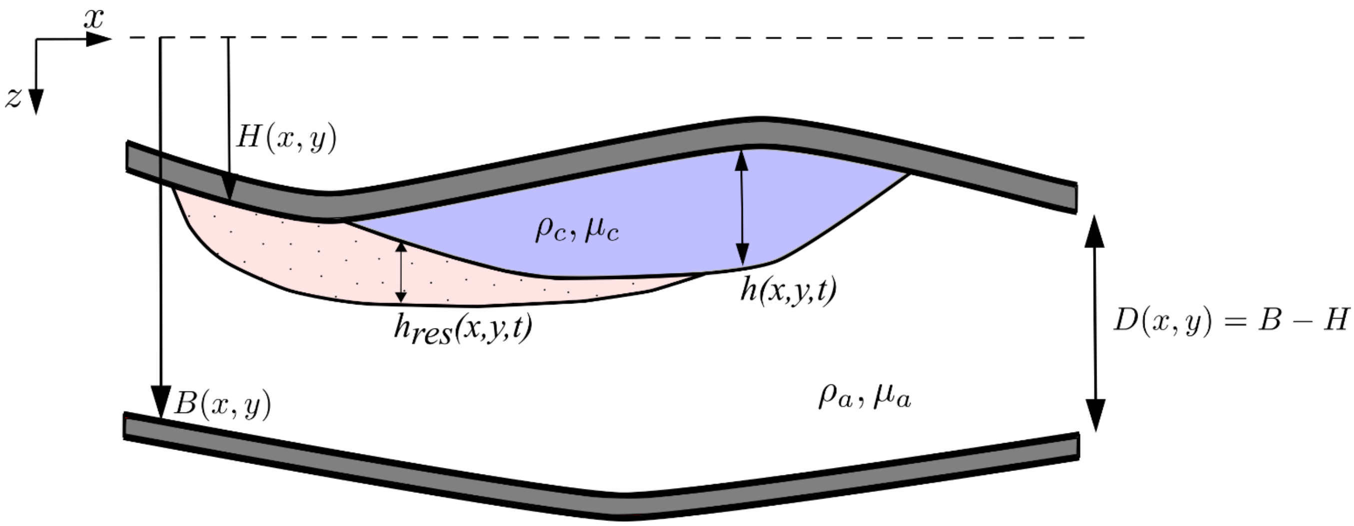

Figure 1: Model schematic for the vertically integrated, gravity-dominated, reduced-physics simulator. The mobile CO2 is situated in a layer of thickness $h(x,y,t)$ below the caprock, and beneath this lies a region of residually trapped CO2 of thickness $h_{res}(x,y,t)$.

The model and corresponding code developed as part of WP2 produce a vertically integrated, gravity-dominated simulator of a buoyant fluid (CO2) injected into a porous reservoir filled with a denser ambient fluid (brine), bounded above and below by caprock and basement sealing layers. The model incorporates buoyancy; topography; heterogeneity of permeability and porosity; residual and irreducible saturations; and dissolution.

Two key assumptions allow us to simplify the Darcy equations that govern the behaviour of the CO2:

1. Flow is assumed to be predominantly horizontal. As a result, vertical flow is neglected and the variation of the pore pressure in the vertical direction is principally due to gravity, i.e. varies hydrostatically.
2. The CO2 accumulates under the sealing caprock at the top of the storage interval soon after injection. This allows us to model the CO2 as a layer building down from the caprock.

Together, these assumptions allow us to vertically integrate the governing equations. This produces a pair of equations that describe conservation of CO2 and conservation of both fluids, respectively. These equations govern the thickness of the layer of mobile CO2, h, and the pore pressure in the ambient fluid, P_a. As a result of this vertical integration, these equations now only depend on the two horizontal spatial variables, x and y, and involve vertical averages of the permeabilities felt by the two fluids.

For more details on the derivation of the model and the corresponding numerical codes, see *StrataTrapper: WP2 D2.1 - Reduced Physics Models of Fluid Flow and Trapping*.

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Because of this dimensional reduction, the code implementing this model is now much quicker to run than a corresponding `Industry-level' full-physics 3D simulator such as Eclipse or TUFT2, and is accurate to machine precision in terms of the calculated current thickness profiles.

Previous Work

Similar reduced-physics models have been previously applied with great success to real-world test sites, including Sleipner (Cowton, 2018), Otway (Gilmore, 2022), and Salt Creek (Benham, 2021).

(Cowton, 2018) studied the behaviour of the CO2 plume in the upper layer of the Sleipner storage site, modelling the behaviour using an unconfined version of the model described here. With this, they were able to accurately recreate the observed plume thickness profiles from seismic measurements and infer the influence of a permeable riverbed detected in seismic surveys along with estimates of its permeability.

(Gilmore, 2022) applied an extension of this unconfined model, now incorporating a simple model of residual trapping, to the Stage 2C injection at the Otway CO2 storage site, and was similarly able to directly investigate the effects of permeability, topography, and residual trapping on the development of the CO2 plume.

(Benham, 2021) developed a reduced physics model of the flow of CO2 along heterogeneous layers in which capillary forces play an important role. This was applied to the Salt Creek injection experiments in order to study the effect of various reservoir properties on the breakthrough time of CO2 at a given observation well.

Each of these reduced physics models benefited from the simplification of the governing equations, allowing for more rapid numerical simulations while still retaining the key physical effects involved. This allowed the relevant parameter space to be surveyed in appropriate detail in a fraction of the time it would take using a full-physics 3D simulator.

Use

The model and code developed as part of this work package can be used to quickly simulate the flow of CO2 in a porous reservoir, in a way that remains faithful to the governing physics controlling the behaviour.

This model incorporates:

- the buoyant advection and spreading of the CO2 plume;

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- the topographic control of the caprock and the confining effect of the basement sealing layer;
- heterogeneities in porosity and permeability;
- the effects of residual and irreducible saturations;
- dissolution of the CO2 in the ambient brine.

With a typical simulation taking on the order of $1-2$ minutes to run on a standard laptop, it's possible to complete a large family of computations in the time that a single comparable run would take in a full 3D simulator such as ECLIPSE or TUFT2. This makes this model ideal for two particular use cases: *Screening* and *Probabilistic Analysis*.

Screening

When designing a storage site, a key consideration is the placement of injection wells and their corresponding injection profiles (how the injection rate varies over time) in order to maximise the amount of CO2 that is trapped within a given period and within the allocated storage region.

As an individual run of this model takes much less time than a traditional 3D simulation, this presents the opportunity to explore the parameter space to a much larger degree. A variety of different injection scenarios can then be investigated, with uncertainties in reservoir properties such as permeability factored in, in order to focus on optimal configurations. These results can then be validated and investigated in further detail with complementary simulations in full-physics 3D simulators once particular parameter values of interest have been chosen. Similarly, worst-case scenarios can be identified and investigated, informing decisions about future field measurements in order to narrow down the space of possible outcomes.

If the injection strategy is the aspect of interest, the reduced computation time of this model can be exploited further. The reservoir properties such as topography and vertically averaged permeability need only be computed once, after which they can be reused for a batch computation in which only the injection locations and scenarios are varied.

This can be done by, for example, minimising the L2 residual $\mathcal{R}$ between the simulations and a series of N_t observations on a $(n_x \times n_y)$ spatial grid:

$$\mathcal{R} = \left[\frac{1}{N_t n_x n_y}\sum_{s=1}^{N_t}\sum_{i=1}^{n_x}\sum_{j=1}^{n_y}\left\{\left(\frac{h_{sim}(x_i, y_j, t_s; \boldsymbol{p}) - h_{obs}(x_i, y_j, t_s; \boldsymbol{p})}{\sigma_s}\right)^2\right\}\right]^{1/2}.$$

Here $\boldsymbol{p}$ contains the specific parameter values chosen for the simulations, and the σ_s incorporate the uncertainties in both the reservoir parameters and the observational measurements.

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Probabilistic Analysis

Uncertainties in reservoir properties such as permeability, topography, residual saturations, etc., mean that the ultimate behaviour of the injected CO2 is uncertain. These uncertainties can arise from inherent error ranges in measurements from core samples or seismic observations, or limitations in knowledge of the full spatial structure of the reservoir.

Complementary to the screening method described above, a suite of simulations can be combined with known or estimated uncertainties to produce likelihood estimation maps of CO2 propagation. This can be performed prior to first injection in order to inform decisions on injection strategies, but can also be updated between injection stages, as seismic measurements of plume thickness are made, in order to constrain the space of possible outcomes and reduce uncertainties on the parameters involved.

For example, if, as in the Sleipner case described above, the presence of an old river bed within the reservoir is known but the permeability k_r of it is not, then the expected behaviour can be constructed from a suite of simulations and an accompanying probability distribution $f(k_r)$:

$$\mathbb{E}[h(x,y,t)] = \int f(k_r) h(x,y,t;k_r)\ dk_r\,.$$

This can be expanded straightforwardly to incorporate variations in other parameters. In a similar manner, likelihood maps of plume extent can be constructed from a suite of simulations by calculating contours showing the regions outside of which e.g. 90% of the simulations had $h = 0$ (or $h < h_{threshold}$). These then provide confidence estimates of where the CO2 will ultimately go within the reservoir.

Limitations

The key assumptions made in deriving this model -- that the flow is predominantly horizontal, and that the CO2 builds up beneath the caprock soon after injection due to buoyancy -- are widely applicable, but not universally so. Reservoirs in which there is a high degree of vertical heterogeneity, e.g. with impermeable baffles inhibiting the vertical flow of the CO2, may result in behaviour that is significantly different from what is predicted by this model. Similarly, there are physical mechanisms -- such as thermal effects and compressibility -- that are not included in this model, and which may play an important role in e.g. shallow or under-pressured reservoirs.

As such, there are settings in which the model developed here may not be able to accurately predict the behaviour of the injected CO2. However, it can still provide useful information in these settings, by considering best- or worst-case scenarios if bounds on these neglected physical effects are known. In these settings, the results of this model should be compared against individual runs of a full-physics simulator in order to assess their credibility and the relative importance of the neglected physics.

As with all such models, the veracity of its predictions depends upon the accuracy of the inputs provided. As discussed in the Probabilistic Analysis section above, uncertainties in the inputs can be propagated through to likelihoods of predicted outcomes in order to produce useful outputs for future decision making.

References

Benham, G. P. (2021). Upscaling multiphase viscous-to-capillary transitions in heterogeneous porous media. *Journal of Fluid Mechanics*.

Cowton, L. R. (2018). Benchmarking of vertically-integrated CO2 flow simulations at the Sleipner Field, North Sea. *Earth and Planetary Science Letters*.

Gilmore, K. (2022). *Reduced-order modelling and observations of geological carbon dioxide storage.* University of Cambridge.