Implications of Carbon Dioxide-Methane Interaction on Time-Lapse Seismic Interpretation and Modeling

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Abstract

The interaction between CO_2 and hydrocarbon fluids in reservoirs could complicate the modeling of time-lapse seismic responses. By adopting seismic modeling workflows that do not consider the interaction and mixing between CO_2 and reservoir hydrocarbons, we might not properly capture the properties of the fluids in the pore space. Further, the distribution of the compounds in the reservoir depends on the degree of interaction. To support a time-lapse seismic feasibility study for injection into a depleted gas field, we conducted a modeling study to evaluate the seismic modeling needs where CO_2 interacts with the residual hydrocarbons. The gas in the field was primarily CH_4, which thus forms the spine of this study. The results show that for the field considered, the choice of strategy has little impact on the seismic properties, but that this depends on the temperature, pressure, and composition.

Introduction

Carbon Capture and Storage (CCS) can play a vital part of the global effort to reduce CO_2 emissions (Benson et al., 2012). A requirement for the injection of CO_2 is to verify that the injection conforms to established models and that the CO_2 is contained within the subsurface, as outlined in, for example, the EU CCS directive (European Commission, 2009). A commonly applied method to establish conformance and containment is time-lapse, or 4D, seismic, see for example, Urosevic et al. (2010); Eiken et al. (2011); Meadows and Cole (2013); Roach et al. (2017) and Furre et al. (2017).

When modeling time-lapse responses in the oil and gas industry, it is typical to talk about saturations of "gas", "oil", and "water", and model the expected changes in the elastic properties as one is replaced by another, e.g., Landrø (2001). To model the property impact of CO_2 injection into a pore space that consists of hydrocarbons, the most straightforward choice is to include a saturation of "CO_2". This strategy is simple because it requires only knowledge of the physical properties of the individual

components at the given pressure and temperature, and the application is readily available in geophysical modeling tools. However, suppose CO_2 mixes with the reservoir fluids. In this case we get "gas" and "oil" phases that consist of both hydrocarbon molecules as well as CO_2, whose properties can be determined using Equations of State (EoS), as seen in Caspari et al. (2012) and Caspari (2013). Examples of modeling the time-lapse feasibility of CO_2 injection into depleted gas fields can also be found in Toh and MacBeth (2023a); Toh and MacBeth (2023b); and MacBeth et al. (2024).

PVT simulations indicate that CH_4 and CO_2 will combine into a single phase for the temperatures and pressures in the field, echoed in Hughes et al. (2012), where we find "CO_2 and natural gas are miscible in all proportions at reservoir conditions". It is noted for completeness that there are also sources that use the word "immiscible" to describe the interaction between CH_4 and supercritical CO_2 (Worden, 2024).

We will consider two property modeling methods. Firstly, treating the CH_4, CO_2, and brine as separate phases, here called the "component" method. Secondly, employing EoS to account for the interaction between CO_2 and CH_4, here called the "mixture" method. There are some interactions also with the brine, but these are not thought to be significant for the seismic property modeling.

The results were then applied as support to a feasibility study for CO_2 injection in a depleted gas field with a thin oil zone. For the feasibility study, the fluid distribution is also key. Therefore, it was natural to couple the work with reservoir simulation of the behavior of the fluids within the reservoir.

Method

For the modeling of the elastic properties of CO_2/CH_4 mixtures we used the open-source python library CoolProp (Bell et al., 2014) in combination with the commercial software PVTsim Nova. A range of compositions and conditions were modeled.

For the property modeling method treating the CH_4, CO_2, and brine as separate phases, the saturations are inferred from the simulator gas mole fraction and gas saturation under an assumption that the sum of the saturation of the CO_2 and CH_4 should equal the simulator gas saturation. This assumption allows us to compute the properties of the "component" method with only the properties of the components. For the method labelled "mixture", the properties are computed from the properties and saturation of the gas mixture and brine.

The reservoir simulator used in the feasibility study has behavior corresponding to the "mixture" method. The simulation includes the history of production on the field up to the proposed injection start, to capture the development over the lifetime of the field.

Results

Figures 1a-c show the modeled density of a CO_2-CH_4 system as a function of temperature and pressure for different molar compositions for the "mixture" method. Figures 1d-f show the percentage difference introduced using a component-based modeling scheme. The difference reaches up to ±30% but could also be close to 0. The temperature of the field is ~65 °C with a pressure of ~180 bar, indicating that we expect very small differences related to the modeling choice.

The phase transition of CO_2 is highlighted in all sections to illustrate how it controls the implied error. For the high-CO_2 mixture, with a mole fraction CO_2 of 0.9, there is a region of pressure and temperature where the fluid exhibits 2-phase behavior separating into gas and liquid phases of different compositions. This region is not visible on the other compositions, as it is out of the plotting range.

Figure 2a shows the gas saturation and composition as a function of injection time for a single cell in the simulation model, used here as an illustration. Using the assumptions outlined above, we can show the hypothetical saturations in Figure 2b. It is important to recall that these are hypothetical values controlled

by the assumptions. Figure 2c shows both modeling strategies' modeled density of the gas and fluid, and Figure 2d shows the velocities.
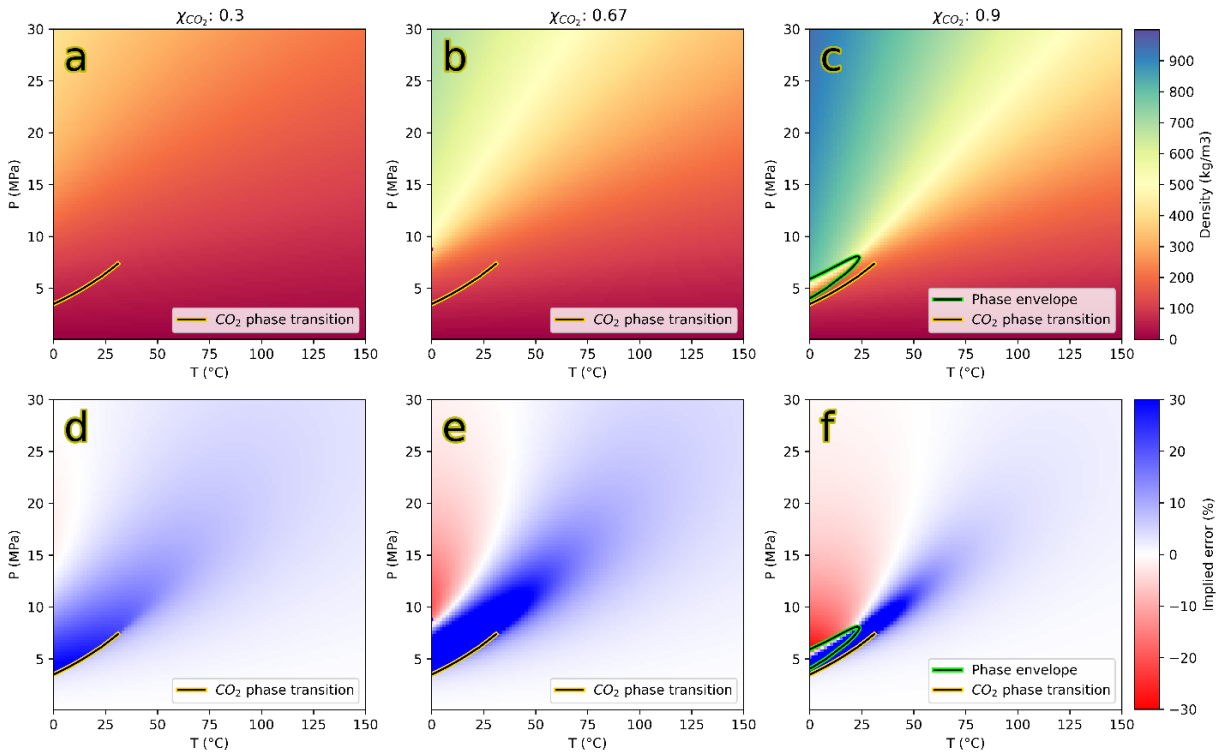

Figure 1: (a-c) Density of CO_2-CH_4 mixtures as function of temperature and pressure for different molar fractions of CO_2. (d-f) The difference, in %, between the density modeled as a mixture compared to as separate components.

Discussion

In Figure 1, the pure CO_2 phase transition is displayed in all the plots, even though it does not represent a phase transition for any mixtures. This curve illustrates how the difference imposed by treating the mixture as separate components in the modeling relates to this transition. In a component-based modeling scheme, the density responds discretely when a single component undergoes a hypothetical phase transition. For Figure 1c, the phase envelope of the mixture demonstrates the smooth transition that the "mixture" density experiences. The errors are generally low at pressures below the CO_2 phase transition, and at higher temperatures and pressures.

Figure 2a uses a single simulation cell, and each cell has a distinct gas saturation and composition development. The fact that the composition varies from cell to cell also implies that the gas phase's properties in the simulator changes from cell to cell, depending on the local composition. Figures 2c and 2d show that the effect of how we model is negligible for the temperatures and pressures concerned.

Interestingly, the density and velocity of the bulk fluid decreases between time t_a and t_b, before increasing again to time t_c. The way to interpret this is that the front of the plume is slightly enriched with CH_4 so that the initial response to the plume entering a cell is a slight increase in the hypothetical CH_4 saturation (as seen on Figure 2b). The amount of CH_4 in the gas phase goes down, but the gas saturation increases. As the gas phase transitions to being near pure CO_2, the density of the gas phase increases dramatically (Figure 2c, from t_b to t_c), causing the bulk fluid density to increase.
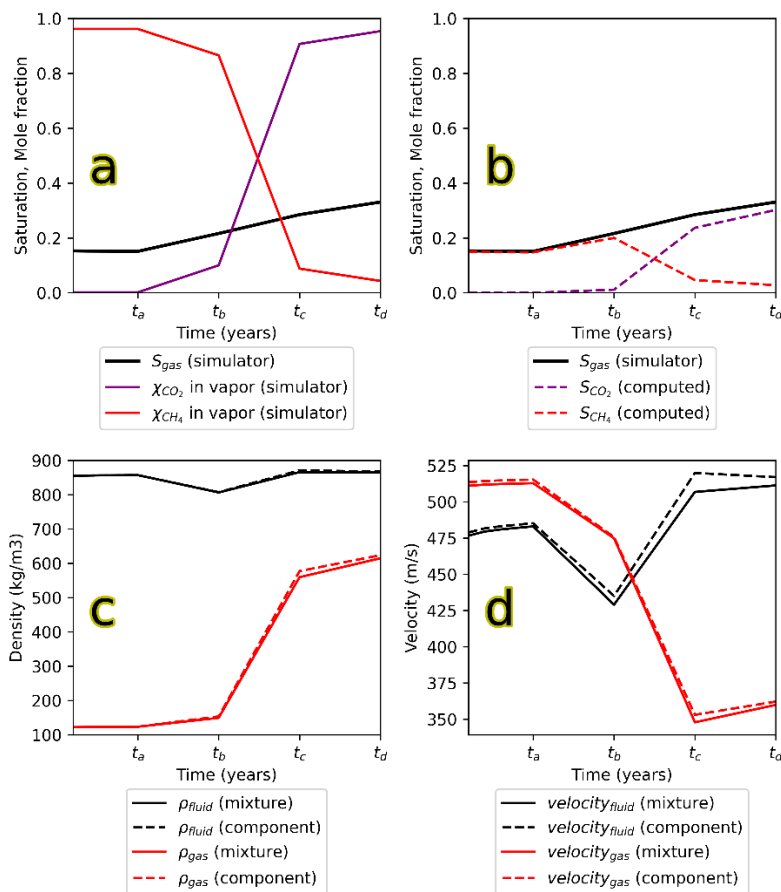
Figure 2: a) Gas saturation and composition development through time. b) Hypothetical saturations computed from the simulator. c) Gas phase and bulk fluid density, modeled as a mixture, and as separate components. d) As (c) but for velocity

Conclusions

The feasibility study revealed that how we modeled the properties of the non-brine components for the depleted gas field had little impact on the properties of a given saturation state. This result enables the use of existing geophysical modeling tools, without compositional fluid modeling. This observation is, however, not a general truth. At specific temperatures, pressures, and compositions, the choice of whether to model the CO_2 and CH_4 as separate phases or a mixture has profound implications on the properties.

Furthermore, whether CH_4 and CO_2 exist as a single phase has an impact on the distribution of fluids in the reservoir. This mixing facilitates the observed reduction and subsequent increase in density and velocity in Figures 2c and 2d. The changes are small in this scenario, and whether they would manifest as detectable signals on the time-lapse seismic (or other methods) is uncertain. In the absence of noise, the results in Figure 2 imply an initial softening from time t_a to t_b, followed by a hardening from t_b to t_c. The mixing effect of CH_4 and CO_2 reproduced in the simulation model shows mobilization of CH_4 in the pore space. This means that both CO_2 and CH_4 have the potential to migrate out of the storage complex. The treatment of the CO_2/CH_4 interaction is a complex task. This paper has focused on the geophysical properties but optimizing CO_2 injection strategies will lean on sufficient understanding and modeling of other properties, such as diffusivity, not discussed here.

Care should be taken when generalizing these results. The amount of residual hydrocarbons, the composition of the residual hydrocarbons, and the specific conditions of the reservoir will all influence the difference in properties, and thus the modeled time-lapse response.

References

Bell, I. H., J. Wronski, S. Quoilin, and V. Lemort, 2014, Pure and pseudo-pure fluid thermophysical property evaluation and the open-source thermophysical property library CoolProp: Industrial & engineering chemistry research, **53**, no. 6, 2498-2508.

Benson, S. M., K. Bennaceur, P. Cook, J. Davison, H. d. Coninck, K. Farhat, C. Ramirez, D. Simbeck, T. Surles, and P. Verma, 2012, Carbon capture and storage, *in* Global Energy Assessment: Toward a Sustainable Future: Cambride University Press, 993-1068.

Caspari, E., 2013, Effect of scale and saturation on effective properties of porous rocks for seismic monitoring of CO2 sequestration: Ph.D. Thesis, Curtin University.

Caspari, E., J. Ennis-King, R. Pevzner, and B. Gurevich, 2012, Prediction of the seismic time-lapse signal of CO2/CH4 injection into a depleted gas reservoir-Otway Project: ASEG Extended Abstracts, **2012**, no. 1, 1-4.

Eiken, O., P. Ringrose, C. Hermanrud, B. Nazarian, T. A. Torp, and L. Høier, 2011, Lessons learned from 14 years of CCS operations: Sleipner, In Salah and Snøhvit: Energy Procedia, **4**, 5541-5548.

European Commission, 2009, Directive 2009/31/EC of the European Parliament and of the Council of 23 April 2009 on the geological storage of carbon dioxide and amending Council Directive 85/337/EEC, European Parliament and Council Directives 2000/60/EC, 2001/80/EC, 2004/35/EC, 2006/12/EC, 2008/1/EC and Regulation (EC) No 1013/2006.

Furre, A.-K., O. Eiken, H. Alnes, J. N. Vevatne, and A. F. Kiær, 2017, 20 Years of Monitoring CO2-injection at Sleipner: Energy Procedia, **114**, 3916-3926.

Hughes, T. J., A. Honari, B. F. Graham, A. S. Chauhan, M. L. Johns, and E. F. May, 2012, CO2 sequestration for enhanced gas recovery: New measurements of supercritical CO2–CH4 dispersion in porous media and a review of recent research: International Journal of Greenhouse Gas Control, **9**, 457-468.

Landrø, M., 2001, Discrimination between pressure and fluid saturation changes from time-lapse seismic data: Geophysics, **66**, 836–844.

MacBeth, C., S. Toh, B. Kopydlowska, and F. Jafarizadeh, 2024, Evaluation of Signals from Monitoring CO2 Injection in the North Sea Using 4D Seismic: 85th EAGE Annual Conference & Exhibition, 2024, 1-5.

Meadows, M. A., and S. P. Cole, 2013, 4D seismic modeling and CO2 pressure-saturation inversion at the Weyburn Field, Saskatchewan: International Journal of Greenhouse Gas Control, **16**, S103-S117.

Roach, L. A., D. J. White, B. Roberts, and D. Angus, 2017, Initial 4D seismic results after CO2 injection start-up at the Aquistore storage site: Geophysics, **82**, no. 3, B95-B107.

Toh, S., and C. MacBeth, 2023a, Is 4D seismic monitoring of CCS in abandoned North Sea reservoirs effective?: 84th EAGE Annual Conference & Exhibition, 2023, 1-5.

Toh, S., and C. MacBeth, 2023b, Repurposing an Abandoned North Sea Reservoir for CO2 Injection-a Sim2Seis Case Study: The Fourth EAGE Global Energy Transition Conference and Exhibition, 2023, 1-5.

Urosevic, M., R. Pevzner, A. Kepic, P. Wisman, V. Shulakova, and S. Sharma, 2010, Time-lapse seismic monitoring of CO2 injection into a depleted gas reservoir—Naylor Field, Australia: The Leading Edge, **29**, no. 2, 164-169.

Worden, R. H., 2024, Carbon Dioxide Capture and Storage (CCS) in Saline Aquifers versus Depleted Gas Fields: Geosciences, **14**, no. 6, 146.