Simulation Study of Sleipner Plume on Entire Utsira Using A Multi-Physics Modelling Approach

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Abstract

Sleipner CO\textsubscript{2} storage project offshore Norway is a pioneering industrial-scale CCS project in operation since 1996. CO\textsubscript{2} injection is done in the Utsira Formation (part of the Sleipner hydrocarbon reservoir overburden) in a depth-range from 800 to 1000 m using a single, long-reach deviated well \cite{1}. The project operator Equinor has released substantial field data related to the project including several seismic surveys, well data, and benchmark models. Using the available data, several studies have been reported to match simulated plume movement to 4D observations \cite{2}. Most of the published studies have focused on plume development in the so-called Sand Wedge, containing CO\textsubscript{2} in Layer 9, for the simple reason that a full-field Utsira model including all sequences from the injection point close to the bottom of the reservoir to the top-most layer has not been available. One of the main shortcomings of such an approach is the uncertainty in the amount of CO\textsubscript{2} that has arrived in Layer 9. Moreover, as both the arrived volume and the CO\textsubscript{2} plume print in Layer 9 depend on the same seismic data, there exists interdependency between the match parameter and the match reference (4D seismic boundary) if the history-matching is done in this way.

At the bottom-hole condition, the injected CO\textsubscript{2} is in dense phase but due to the relatively shallow depth of the formation, it is safe to assume that some degree of phase change would occur in the CO\textsubscript{2} mobile phase, especially near the top of the Utsira formation as the reservoir condition is very close to the CO\textsubscript{2} critical point. This might considerably affect the plume movement due to both the phase expansion and CO\textsubscript{2} phase density changes close to the critical point. A valid history-matching approach would then involve predicting the phase properties as a function of reservoir condition. Shortcomings of isothermal approaches are consequently evident because modifications of static properties have been used to achieve a reasonable match, however inadequate modelling of dynamic phase properties has been the main reason for the mismatch to observed behavior.

Studies of CO\textsubscript{2}-rich gas reservoirs have indicated that a considerable amount of CO\textsubscript{2} could be dissolved in the underlying aquifer in geological timescale \cite{3}. Estimates of convective flux have indicated that reservoir permeability and heterogeneity play an important role in the onset and extent of dissolution with high permeability resulting in several order of magnitude increase in convective dissolution. The extent of convective dissolution in the high-permeable Utsira Formation is considered significant with a relatively short onset time for formation of dense-phase convective fingers. Convective dissolution and its effect on the amount of mobile gas-phase CO\textsubscript{2} should therefore be included as an important parameter in the history matching process, especially if there are enough evidence indicating that the onset of the convective movement is within the timescale of the data acquisition.

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In this study, we report the results of simulation studies using a recently developed reservoir simulation model that includes all vertical sequences of the Utsira Formation. The base geo-model used in creating the simulation model includes communication pathways such as chimney and feeder that have resulted in the characteristic movement of CO₂ in the storage reservoir as observed from the 4D data. Using thermal reservoir simulation, the effects of temperature gradient and injection induced temperature variations on phase properties of CO₂ have been modelled. By applying ultra-high-resolution mesh, onset of the convective movement of CO₂ dense aqueous phase is estimated. The extent of convective dissolution is calibrated against the observed data from natural CO₂ reservoirs and enhanced dissolution is consequently considered in the history matching process.

The results explain the distinctive pattern of movement of CO₂ plume in Utsira and provide a plausible description of further plume movement. An analysis of the importance of various storage mechanisms and their contribution to total capacity of the Sleipner CCS project will also be also provided.

CO₂ aqueous saturation in Utsira Formation around 500 years after injection showing the downward movement of the dense phase.


Keywords: CCS; Sleipner; history matching; thermal modelling; CO₂ dissolution