Effects of batch-wise CO_2 injection on well integrity: a numerical model of cement interface debonding

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Batch-wise CO_2 injection

Offshore geological CO_2 storage requires transporting CO_2 by pipeline or by vessel to offshore storage sites. Pipelines provide a continuous flow rate but require building a new costly infrastructure. Offshore transportation by ships is more flexible than pipelines, but provides an intermittent flow rate and may require a temporary offshore storage. To be economically feasible, CO_2 transportation by ship and offshore unloading will require fast, cyclic injection at high injection rates.

Transport by ships can be performed in semi-pressurized carriers with the capacity of 10 to 50 kt CO_2 (CCUS-T2013-09-D08, 2016). The CO_2 is transported in liquid state, to optimize the transport in terms of volume, either at a low pressure, close to the triple point (at 7-8 bar, temperature of -50 °C and density of about 1150 kg/m^3) or at a medium pressure (at 16 bar, -28 °C and 1050 kg/m^3). Injecting CO_2 directly in liquid state would be energetically efficient because liquid CO_2 flows more easily downwards by gravity due to the density of CO_2 close to water density; however, liquid CO_2 injection has been feared because of its low temperature causing the formation of gas hydrates in the near-well region, thermal contraction and associated stress reduction that may cause fracturing in the storage formation, the caprock and the wellbore (Vilarrasa and Rutqvist, 2017).

This study focusses on the integrity of wells and describes a numerical model developed to investigate thermal effects of injecting CO_2 at a lower temperature than that of the surrounding rock. Example simulations are performed to illustrate use of the model. The approach will be used in the European and national funded ALIGN-CCUS[1)] project which unites 31 research institutes and industrial companies in the shared goal of supporting the quick and cost-effective deployment of carbon capture, utilisation and storage.

Numerical model for assessing the structural integrity of wells

The nonlinear finite element simulator DIANA (DIANA FEA, 2017) is used to generate meshes for 2D numerical models of the well system and run structural and heat transfer simulations. The workflow is automated by a dedicated user interface: the user-defined input and model parameters are used to generate meshes and define the whole non-linear (phased, staggered) analysis, which mimics the different loads acting on the well system throughout the entire lifetime of a well, from the drilling phase, well completion, testing, operations and abandonment (e.g. Bosma et al.,1999, Schreppers, 2015).

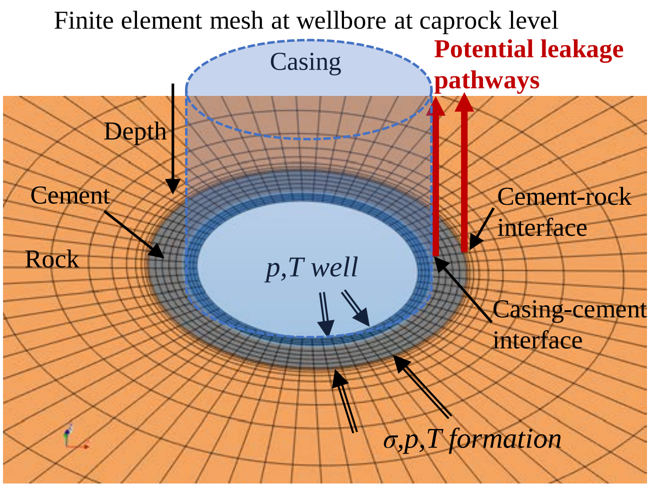

Fig. 1: Mesh for a 2D plane strain finite element model of the near-well region for assessing structural integrity of the wellbore through its lifetime.

The model of the well system, representing a cross-section normal to the well axis, comprises the casing, the cement and the surrounding rock formation (Fig. 1). The chosen 2D modelling approach is computationally efficient and simulations can easily be repeated for various depths along the wellbore. Complete plane strain elements are used for bulk materials. Zero-thickness interface elements are used for the casing-cement and the cement-formation interfaces. The well materials are modelled with: a von Mises elasto-plastic material model for the steel casing; a combination of the Mohr-Coulomb elasto-plastic model and the multi-directional fixed crack model for the cement; a Mohr-Coulomb elasto-plastic model for the rock formation; and the Coulomb friction model with a tension cutoff for the interfaces between materials.

A probabilistic analysis based on numerical simulations with random sampling of the model's input parameters can be employed in the workflow. The key parameter to consider is the cement quality, i.e. the variations in cement properties. Well cement is essential for casing support and zonal isolation while the quality of cement downhole is often poorly known due to the lack of historical well data, deterioration of cement properties over time due to exposure to different loads during well operations or simply because of the limitations of currently available cement evaluation tools.

Use of the numerical simulation tool is illustrated on an example of a vertical CO_2 injection well. The analysis is focused on debonding of the interfaces between different well materials that could occur during primary cementing, testing and well operations. The model is set at the level of the caprock at a depth of 3,500 m. The temperature difference between the cold CO_2 and the ambient rock formation is 80°C. The CO_2 is injected continuously for 2 years. The random variables in the probabilistic model are the Youngs modulus and the Poisson's ratio of cement, and the tensile strength of the interfaces. The input variables follow a truncated-normal statistical distribution. Distribution parameters are based on the ranges of the input variables reported in the literature. For the well cement, different distributions are used for the elasticity modulus of a stiff class G cement and a flexible cement.

Fig. 2a plots the output results of example simulations of cold CO_2 injection for a stiff cement: for the assumed set of model input parameters, there is only 3% certainty that debonding will not occur during injection, 7% certainty that the width of micro-annulus will be less than 100 µm, 84% certainty less than 200 µm and 99% certainty less than 240 µm. On the other hand, use of a flexible cement significantly reduces the risk of debonding, which does not occur in 44% of realizations in this numerical experiment (Fig. 2b).

In future work, the model should be used to investigate the effects of intermittent CO_2 injection on the integrity of well system. Further, probability density function of model output parameters could be fed into a well integrity risk assessment tool.

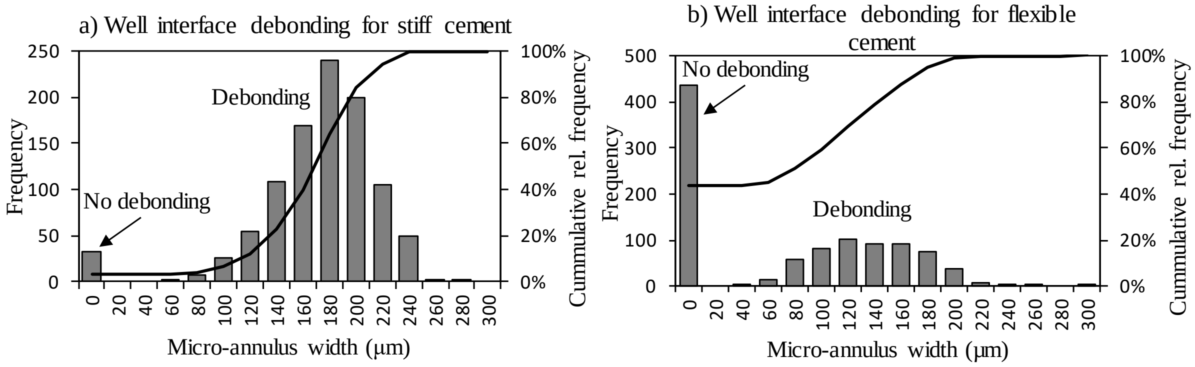

Fig. 2: Histogram of width of micro-annulus formed in an injection well at the level of the caprock during injection of cold CO_2. Numerical probabilistic simulations with the DIANA FE simulator for (a) a stiff well cement and (b) a flexible well cement.

Acknowledgements

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