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Non-Intrusive Surface Heat Mapping for Detecting CO2 Leakage in P&A Wells

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Abstract

Improperly plugged and abandoned (P&A) wells can pose significant risk to the safety of the subsurface CO2 storage operations. In the event of CO2 leakage through a P&A well, strong temperature cooling signal may be observed at surface. Such cooling has been previously investigated as a potential tool to detect CO2 leakage in the event of sudden loss of P&A wellbore integrity during post-CO2-injection period. In this study, the surface temperature signal associated with CO2 leakage *during CO2 injection* considering *pre-existing wellbore integrity issues* is modelled. The cooling signal is shown to be more significant given the overpressure caused by CO2 injection in the reservoir. The cooling plateaus with stabilization of leakage rate and strengthens with increased leakage rate. The strong cooling corresponding to CO2 leakage and its sensitivity to leakage rate suggests that surface heat mapping can be used as a proxy to leakage rate to identify leaking P&A wells during CO2 injection and monitor leakage rate variations over time.

Introduction

Identifying problematic P&A wells through intrusive well re-entry procedures is expensive as it may require drilling rigs on site. Non-intrusive methods capable of identifying leaking wells are desirable. CO_2 concentrations, carbon isotopic concentrations, and CO_2 fluxes can be monitored at the surface or near-surface to identify anomalies corresponding to leakage in the vicinity of a leaking well (Oldenburg et al. 2003). Vegetative stress imaging and UAV drone monitoring systems can also be used to detect CO_2 anomalies (Madsen et al. 2009). The surface or near-surface temperature can be also non-intrusively monitored (Pan and Oldenburg 2020). Given the strong cooling signal observed during CO2 leakage, temperature monitoring at the surface can be an effective method to detect P&A wells experiencing wellbore integrity issues.

Pan and Oldenburg (2020) previously investigated the temperature behavior in response to CO_2 leakage through a well. They fix the pressure and saturation in the reservoir at 1 bar above hydrostatic pressure and 50% saturation, respectively. This condition was set to model a well experiencing a sudden failure of cement plug during the post-injection period when stabilized conditions has been established in the reservoir. In departure, the modeling herein focuses on the leakage behavior during CO_2 injection caused by pre-existing integrity failure. Therefore, the leaking well is exposed to varying pressure and saturation conditions expected during CO_2 injection. This is done by explicitly modeling the CO_2 injection in the reservoir and allowing leakage to occur simultaneously. As expected, higher leakage rates are observed compared with Pan and Oldenburg (2020).

Like Pan and Oldenburg (2020), we model leakage by introducing an opening at the interface of a cement plug and inner wall of the well casing. The leakage is permitted by assigning an equal permeability to the cement plug representing the aperture of the opening. However, unlike Pan and Oldenburg (2020), the cement plug is placed at the surface, not at the well bottom. As a result, oscillatory geyser-like rate variations are no longer observed at the beginning of leakage.

Model settings

We model CO_2 migration through a P&A well intersecting the CO_2 storage zone. Flow and heat transport in the reservoir coupled with the wellbore is modeled using T2Well (Pan and Oldenburg 2014). The P&A well is considered open to flow all the way from the reservoir up to the base of a cement plug which ideally should be sealing the well at surface. The cement plug is 33-m (100 ft) in thickness.

The CO_2 injection well is set at the corner of the model, and the P&A well is at 75-m distance from it (see Figure 1). This is a quarter-symmetry model representing a square reservoir with the injection well in the center. CO_2 is injected at 2 kg/s rate and considering that the model is quarter-symmetry model, this rate represents a case where injection rate is 8 kg/s or 250,000 ton/year.

The model is discretized into 27 grids in each of x-, y-, and z- directions making 27^3 cells. The model extent in x- and y- directions is 5 km. Within the 1-month period of simulation, the pressure effect does not reach the reservoir boundaries. Therefore, setting the reservoir lateral boundaries is not of importance for the modeling herein.

The model's topmost cell (1-m thick) represents the surface conditions and assigned fixed ambient temperature (35 °C) and atmospheric pressure conditions. The second cell from the top (9-m thick) is where the temperature observations are reported as surface temperature variations. This cell is right above the cement plug which is 33 m in thickness. Initial geothermal gradient is 0.025 °C/m resulting in 60 °C at the reservoir top at 1000 m depth. The pressure varies hydrostatically with depth throughout the model.

Porosity of the reservoir is 0.12 and that of caprock is 0.05. Permeability of the reservoir is 100 mD and that of caprock is 0.001 mD. Permeability is isotropic in the model, identical in all directions for any given cell.

Leakage through the P&A well is assumed to be facilitated by a uniform gap at the interface of the casing and the cement plug. The gap aperture is assigned 50, 200, and 400 microns to capture the effect of this opening on the temperature response. The effective permeability of the plug, k_{eff} for any given aperture can be estimated by $k_{eff} = \phi_{gap} k_{gap}$ (assuming that the permeability of the cement matrix is zero). Let a be the aperture of the gap, and R be radius of the wellbore. Given that $a \ll R$, $\phi_{gap} = \frac{2\pi R a}{\pi R^2} = \frac{2a}{R}$. Also, treatment of the gap as an open fracture, we can write, $k_{gap} = \frac{a^2}{12}$ which results in $k_{eff} = \frac{a^3}{6R}$. Accordingly, the permeability corresponding to gap aperture 50, 200, and 400 microns is 2.31481E-13, 1.48148E-11, 1.18519E-10 m^2, respectively. The model properties are summarized in Table 1.

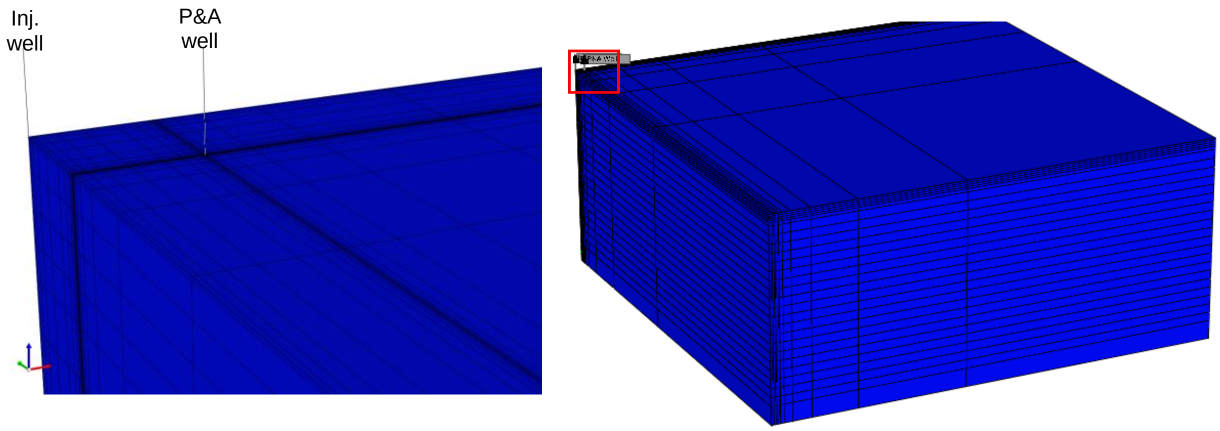

Figure 1. The 3D model and placement of the wells. The left shows the magnified portion shown in the red box.

Table 1. Modeled reservoir and wellbore properties.

Reservoir top depth (m)	1000
Wellbore inside diameter (m)	0.18
Plug thickness (m)	33
Reservoir thickness (m)	20
Reservoir porosity (fraction)	0.12
Caprock porosity (fraction)	0.05
Inter-well distance (m)	75
Reservoir permeability (mD)	100
Caprock permeability (mD)	0.001
Cement plug aperture (micron)	50, 200, 400

Results

It takes time for the injected CO2 to arrive at the base of the P&A well at the reservoir depth. However, brine leakage begins with the start of CO2 injection given that it is driven by the overpressure caused by injection. If the P&A well is filled by a denser fluid than the reservoir brine, brine leakage will be delayed until the overpressure is large enough to overcome the fluid initially filling the wellbore. Nevertheless, leakage creates a local pressure minimum in the reservoir at the location of the P&A well. This makes the largest pressure gradient in the reservoir to be toward the P&A well. Accordingly, the P&A well in the reservoir can be analogous to a draining hole positioned at a lower elevation to effectively streamline the rainwater in a drainage system. In essence, the P&A well acts like a short-circuit creating a least-resistance path toward which the injected CO2 is directed. This condition would obviously exacerbate the unwanted CO2 leakage. In addition, it makes the CO2 leakage to begin earlier for a higher-leakage case given that it presents the least resistance to upward CO2 flow in the wellbore.

Brine leakage increases with time and reaches a maximum at the time of CO2 arrival at the P&A well. For the 400-micron-aperture case, the brine leakage rate reaches 0.3 kg/s just before CO2 arrival. However, brine leakage is completely eliminated soon after arrival of the high-mobility CO2. CO2 reaches the P&A well at the reservoir depth after 17.1 days for the 400-micorn case. The arrival time is slightly longer for the 50-micorn case, which is at 17.3 days. Also, it takes less time for CO2 surface leakage to begin for the higher leakage case. CO2 leakage at surface begins at 0.2 and 0.9 days after CO2 arrival at the bottom of the well for the 400- and 50-micron cases, respectively.

CO2 leakage rate variation at surface is shown in Figure 2a. The leakage rate continues to increase for all cases except for the 50-micron case which shows slow stabilization. CO2 leakage rate at surface closely corroborate with surface temperature cooling shown in Figure 2b. After 30 days, CO2 leakage rate stabilizes at ~0.005 kg/s for 50-micorn case while temperature cool down also stabilizes at about -2 °C. Also, over this period, CO_2 leakage rate reaches 0.045 and 0.068 kg/s for the 200 and 400-micorn cases, respectively while the corresponding temperature cooling reaches -7.65 and -10.28 °C. This cooling is large enough to be detected at the surface to identify P&A well leakage. More importantly, the cooling signal stabilizes with leakage rate stabilization while strengthen with the leakage rate increase.

It should be noted that CO_2 entering the P&A wellbore at its bottom is at reservoir temperature which is much warmer than surface ambient temperature. However, CO_2 leakage at the surface shows strong cooling not warm-up. This is mostly attributed to the JT expansion cooling which suppresses the warm-up caused by CO_2 advective heat transfer as it flows up the wellbore.

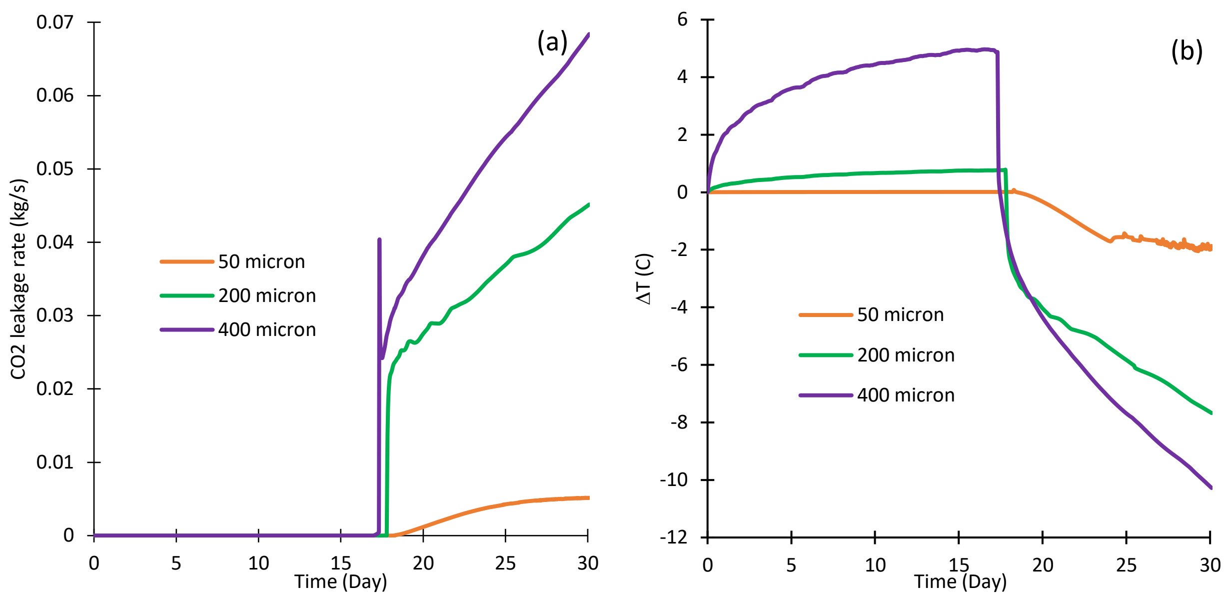

Figure 2. Temperature change from initial value. For the sealing case, the temperature change is shown at the base of the cement plug, while for the leaking cases it is presented at the surface.

Conclusions

In contrast with previous studies investigating surface temperature response to CO_2 leakage from P&A wells, we modeled CO_2 leakage during CO_2 injection through a well with pre-existing integrity issues. CO_2 leakage was permitted by an opening at the interface between the cement plug at surface with the inner wall of the well casing. Given the rising overpressure and CO_2 saturation in the reservoir at the base of the P&A well, CO_2 leakage rate increases over an extended period of time accompanied by an increased temperature cooling signal which can exceed 10 °C for the cases modeled herein. The similarity of the leakage rate behavior and that of the temperature signal at surface suggest that temperature cooling can be reliably used as a proxy to detect and track the evolution of CO_2 leakage over time.

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