Title

Modeling Transient Leakage Signals from Abandoned Wells with T2Well: Effects of Plug Gap Aperture

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Modeling transient leakage signals from abandoned wells with T2Well: Effects of plug gap aperture

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Abstract

Both known and unknown (unmapped) plugged and abandoned wells are potential leakage pathways for CO_2 from geologic carbon sequestration (GCS) sites. Although many abandoned wells have cement bridge plugs installed to prevent leakage, the seal between the cement and the inner casing wall is subject to failure creating a leakage flow path for formation fluids and CO_2. In this study, we carried out detailed T2Well simulations of non-Darcy flow of CO_2 and brine leakage up the gap between cement and inner casing wall and into the open fluid-filled column of a prototypical abandoned well. The goal of our study was to understand the expected leakage behavior dynamics, leakage rates, and the temporal signals associated with leakage that can be targets of near-surface monitoring. Simulation results show that the leakage of CO_2 and brine upward in this system is transient with interesting phase interference behavior as buoyant CO_2 flowing upward displaces brine as it flows through the cement-casing gap, into the column of brine, and upward to the top of the well. Oscillatory flows with varying pressure, temperature, and flow rates of CO_2 and brine show strong dependence on gap aperture. The temporal patterns of leakage may be detectable with surface and near-surface monitoring approaches. In addition to helping with detecting and locating leaking wells, these transient leakage signals may provide information on the cause of leakage that could inform effective remediation design and execution approaches.

Keywords: Wellbore leakage, cement plug, non-Darcy flow, wellbore simulator, T2Well, TOUGH

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1. Introduction

Both known and unknown (unmapped) plugged and abandoned wells are potential leakage pathways for CO_2 from geologic carbon sequestration (GCS) sites (Gasda et al., 2011). Abandoned wells are often not plugged over their full length but rather they are filled with fluids such as brine, drilling mud, or corrosion inhibitor fluids, and a cement bridge plug is placed above the reservoir to seal off the perforated section from the rest of the well. The seal between the cement used to plug the well and the steel casing is subject to failure creating a leakage flow path for formation fluids and CO_2.

Before a leaking plugged and abandoned well can be fixed, the leakage must be detected and stopped. Challenges arise because CO_2 leakage rates through degraded cement seals may be small and fluid leakage manifestations on the ground surface from plugged and abandoned wells may be difficult to detect. In this study, we have carried out detailed non-Darcy flow simulations of CO_2 and brine leakage up the gap between cement and inner casing wall and into the open fluid-filled column of a prototypical abandoned well. The goal of our study is to understand the expected leakage behavior dynamics, leakage rates, and the temporal signals associated with leakage that can be targets of near-surface monitoring for leakage detection.

2. Conceptual Model

The prototypical abandoned well system under consideration is shown in Fig. 1. In the system as shown in Fig. 1a, a 2000 m column of inhibitor fluid fills the open well above a 10 m-long cement bridge plug. The perforated section of the well at the bottom is in hydraulic connection to the permeable reservoir. As with many plugged and abandoned wells, there is no wellhead and the top of the casing is assumed to be covered by a permeable rusted steel plate and 1 m of soil (Fig. 1a) which we model as porous media coupled to the open well. As shown in Fig. 1b, we include a semi-circular gap between the cement plug and the casing wall, the thickness of which is varied as a parameter in the simulations. Reservoir fluids (CO_2 and brine) have the potential to leak up the gap between cement and inner casing wall into the column of inhibitor fluid and onward to the ground surface through the permeable materials (rusted steel plate and soil) at the top of the well.

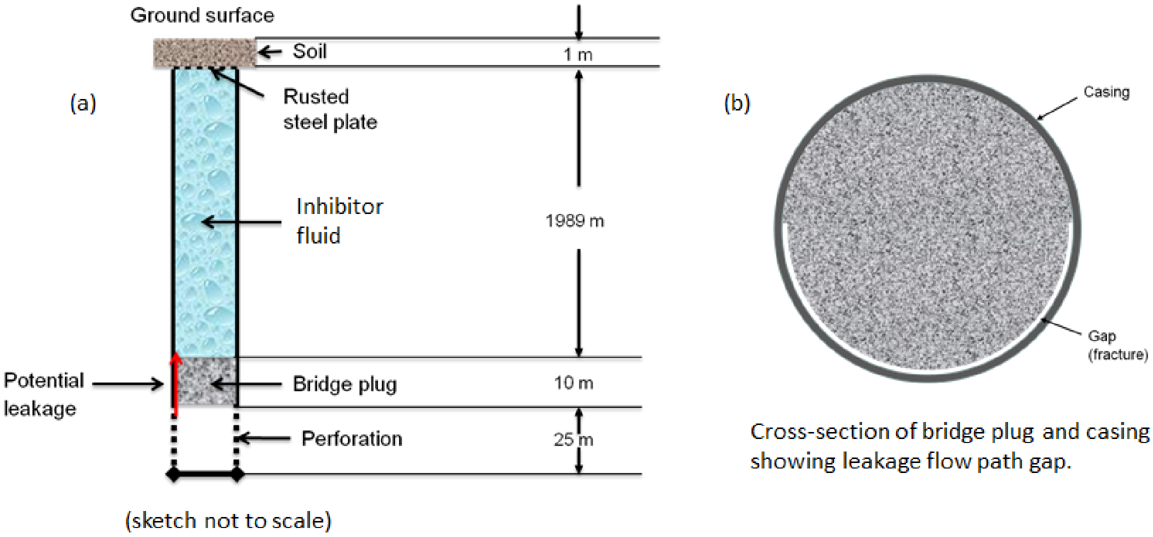

Figure 1. (a) Conceptual model of abandoned open well with bridge plug, and (b) cross section of bridge plug showing the gap (over one-half of the circumference) the aperture of which was varied in the simulations shown here.

Properties of the various features of the modeled system are presented in Table 1. We present in Table 2 the properties of the various layers, and note that all layers were assumed to have pore compressibilities of 3×10^{-9} Pa^{-1}, thermal conductivities of 3.0 W/m ºC, and specific heats of 1000 J/kg ºC).

Table 1. Well and plug properties.

Feature	Value
Well length	2024 m (from -1 m to -2025 m)
Casing ID	0.15962 m (7-inch casing, wall thickness = 9.09 mm)
Bridge plug	10 m thickness (from -1990 to -2000 m)
Perforation	25 m (from -2000 m to -2025 m)
Well wall roughness	45×10^{-6} m
Gap (fracture) wall roughness	100×10^{-6} m
Gap aperture	Various
Effective porosity	Various, a function of aperture
Effective perimeter of gas	Various, a function of aperture
Rusted steel plate at top of the abandoned well	Assumed same permeability as cover soil (100 Darcy)

Table 2. Layer properties.

Layer	Depth (m)	Porosity	Lateral permeability (m2)	Vertical permeability (m2)
Reservoir sand	2000-2025	0.25	10^{-12}	10^{-12}
Cap rock	1980-2000	0.05	10^{-18}	10^{-18}
Overburden	10-1980	0.05	10^{-18}	10^{-18}
Soil2	1-10	0.45	10^{-15}	10^{-15}
Soil1	0-1	0.45	10^{-10}	10^{-10}

All formations above the reservoir are saturated with water under hydrostatic pressure. The reservoir is set initially to a given gas saturation with the pressure at the bottom grid cell equal to the hydrostatic pressure. The wellbore above the reservoir (including the plug) is saturated with water under hydrostatic pressure whereas wellbore below the plug is under the same conditions as the reservoir. The geothermal gradient is 30 °C/km and the ambient temperature at land surface is assumed to be 25 °C. The entire domain is under natural ambient thermal conditions initially. The CO_2 phase saturation in the reservoir is variable in the model, but we set it to 0.5 for the simulations shown here. Conditions at the top of the model are held at atmospheric pressure and ambient temperature.

3. Methods

We have used T2Well to simulate the non-Darcy flow in the column of inhibitor fluid in the well and in the gap between the cement plug and the casing coupled to the reservoir at the bottom and soil layer at the top in which Darcy flow occurs. T2Well is a numerical simulator for modeling non-isothermal, multi-phase, and multicomponent fluid and energy flow in integrated well-reservoir systems where coupled Darcy and non-Darcy flows occur [2]. In T2Well, the flow in the well is described by the two-phase viscous momentum equations whereas the flow in the reservoir is described by two-phase Darcy's law. By applying the drift-flux model (DFM), the two-phase momentum equations can be lumped into a single momentum equation of the mixture from which is calculated the mixture velocity. Non-Darcy flow includes phase slip, potential for counter flow, and effects of friction of the flow on the walls as controlled by local Reynolds number. Despite the fact that the flow in the well and gap are approximated as one-dimensional flows in the DFM, phase slip is modeled giving rise to an interplay of buoyancy forces and phase interference that causes interesting and plausible transient behaviors. The thermophysical properties and phase diagnostics of CO_2 and brine are calculated using the equation of state model implemented in ECO2N Version 2 [3].

4. Results

Results of T2Well simulations using a radially symmetric RZ grid show interesting transient flows and related leakage signals. We present in Fig. 2a the pressure at four different locations for a 1 mm gap aperture and reservoir gas saturation of 0.5. As shown, the “wellhead” pressure (actually pressure at the base of the soil) increases quickly associated with breakthrough of the gas phase to the base of the soil, followed by oscillations around 0.6 MPa. Note that 0.6 MPa is larger than the expected fracture pressure at this shallow depth, meaning that leakage will tend to breach to surface, a phenomenon that is well-known from well-blowout experience [4, 5]. Oscillations in pressure near the ground surface may be manifest as variable leakage flows to the ground surface over minute-to-hour time scales. The pressure immediately below the plug is almost constant whereas the pressure immediately above plug decrease significantly as the well above plug becomes drier as inhibitor fluid is forced out of the well column. Oscillations in temperature are small as shown in Fig. 2b, but overall cooling in the soil layer is larger and could be detectable as an anomaly using repeated infrared temperature monitoring approaches. Fig. 1c shows the gas saturation increasing with time to steady-state values with minor oscillation. The well below the soil becomes very dry while the base of the well column (point above the plug) remains wet ($S_g = 0.2$). The point below plug quickly becomes totally dry within a fraction of a second which leads to no liquid water flow from the reservoir up through the plug gap.

To illustrate further the complex flow dynamics that occur in this simple system, we show in Fig. 1d the fluid mixture velocity throughout the well column over time. As shown flow can be upward or downward in different places in the column. In other words, the flow in the well is highly transient and variable as gas exsolves increasing volume and upward buoyancy forces. Despite its simplicity relative to Navier-Stokes two-phase flow, the DFM is capable of describing complex interactions of two-phase flow. These complex interactions cause transient well flow phenomena that may stand out from variations caused by natural vadose and shallow aquifer processes driven by diurnal and/or seasonal forcings [6].

Simulations were carried out for various values of the gap aperture as shown in Fig. 3. Liquid-phase flow diminishes as the gap aperture decreases as expected (Fig. 3a). But relatively large oscillations in liquid flow rate occur as gas and liquid interfere in the system. For the case of the 0.1 mm gap aperture, there is no gas leakage at all and the liquid leakage rate is very small (~1 g/s). As shown in Fig. 3b, gas-phase flow is highly oscillatory for the 1 mm gap aperture. The simulations could not be completed for the large gap apertures because shortly after the liquid leakage rate reaches its peak, decompression causes temperatures in parts of the system to become too low for the thermophysical models implemented in ECO2N.

5. Conclusions

We have used T2Well to simulate the leakage of CO_2 and water through a gap between a cement plug and casing into a fluid-filled well column. Results show oscillatory flows and strong dependence of behavior on gap aperture. The signals of leakage such as pressure, temperature, and flow rate from such a system are transient and may stand out from variations arising from natural forcings (barometric pressure, day-night, weather) at the ground surface. Therefore, leakage of CO_2 and water from unknown abandoned wells may be detectable and measurable. Furthermore, analysis of the leakage signals may allow diagnosis of the cause and/or source of leakage that can inform remediation efforts.

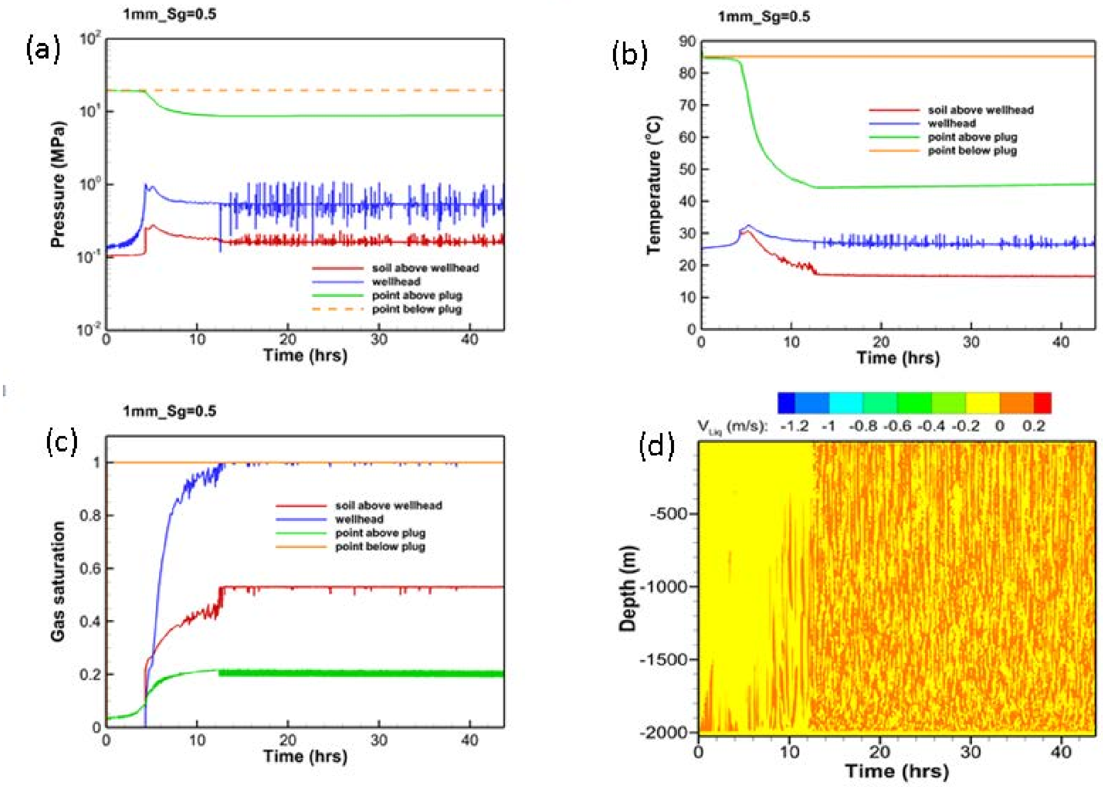

Figure 2. Simulation results as a function of time for 1 mm gap aperture. (a) Pressure at four different locations. (b) Temperature at four different locations. (c) Gas saturation at four different locations. (d) Velocity of fluid flowing in the well at various depths showing upward (negative velocity) and downward (positive velocity) motions occur at different times and at different depths in the well.

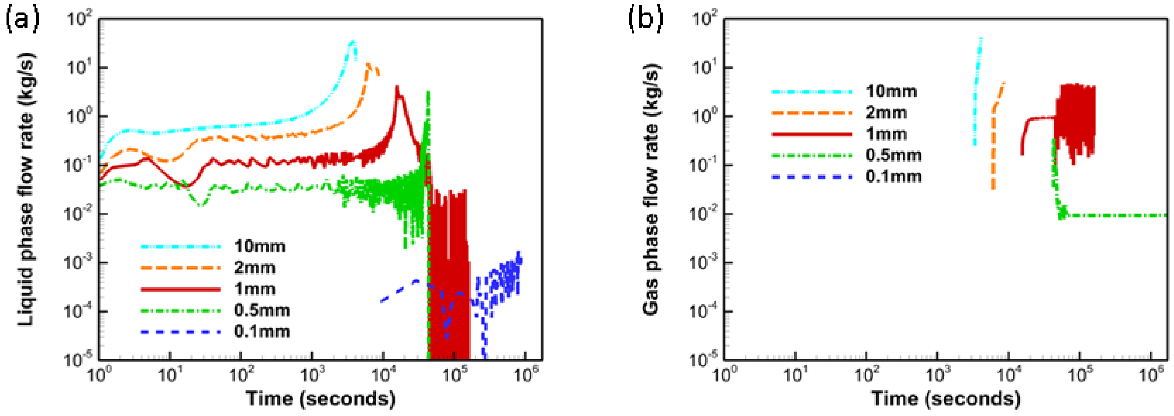

Figure 3. Simulation results as a function of time for five different gap apertures. (a) Liquid phase flow rate diminishes as gap aperture shrinks, while oscillations in liquid phase flow become more pronounced for smaller apertures at late time. (b) Gas-phase flow rate is zero at the start and starts first for large gap apertures and highly oscillatory for the 1 mm gap aperture.

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