# Supercritical $CO_2$ Leakage Modelling for Well Integrity in Geological Storage Project

E. HOUDU[1,*], O. POUPARD[1] and V. MEYER[1]
[1]OXAND S.A. France
*Corresponding author: emmanuel.houdu@oxand.com

**Abstract:** $CO_2$ capture and storage (CCS) projects constitute a promising solution to control and reduce these emissions among the portfolio of measures to reduce GHG emissions. It is now commonly accepted that risk assessment and management is a crucial area of research and development. Wellbore integrity is a key challenge to ensure long term safety and for public acceptance.

For this objective, a two-phase flow model in porous media based on Darcy's law has been proposed to simulate the $CO_2$ leakage within the well at rat hole area. This zone corresponds generally to a bad cementation zone and needs a particular attention. The numerical simulations have highlighted the competition between the effects of gas flow and the liquid flow in this specific area. The rat-hole zone constitutes a key element to consider in the long term integrity performance of a well in a CCS project. An improvement of the knowledge of the flow in this specific area within the well will be a support in assessing the performance and the risks from a well integrity perspective (i.e. $CO_2$ leakage) of CCS projects.

**Keywords:** $CO_2$ geological storage, well, rat hole, 2-phase flow, gas leakage

## 1. Introduction

Greenhouse Gas (GHG) emissions are a major issue in the context of global climate changes. In the favourable context of the Kyoto protocol (1997) and deadlines of 2008-2012 for reducing GHG emissions, $CO_2$ capture and geological storage (CCS) projects constitute a promising solution to control and reduce these emissions among the portfolio of measures to reduce GHG emissions [1]. It is now commonly accepted that risk assessment and management is a crucial area of research and development, as far as they are directly linked to the evaluation of the impacts on health, safety and the environment (HSE), on the one hand, and efficiency in terms of GHG emission reduction, on the other hand [2 - 4]. Wellbore integrity is a main challenge to prove the reliability and safety over long term of the $CO_2$ storage within geological formations (saline aquifers, depleted reservoir, coal seams …) [5 - 6]. This is a key issue for public acceptance and environmental impact. Well integrity describes the fact that a well will not be a source of leakage (i.e. the stored gas is confined within the storage reservoir, or at least it does not reach shallow formation (i.e. potable aquifers) (seepage) and surface (leakage)).

A quantitative risk-based methodology has been developed by OXAND to evaluate the Performance and Risks (P&R$^{TM}$) associated with wells integrity [7 - 10]. Mathematical models and numerical simulation tools will play an important role in quantifying the capacity for stored $CO_2$ to leak through well system.

For this objective, a two-phase flow model in porous media based on Darcy's law has been proposed to estimate the $CO_2$ leakage within the well towards targets (surface, potable aquifer …) and identify the pathway within the system. A specific issue from well integrity perspective is focused on the rat hole (see figure 1 and figure 2) area in the $CO_2$ pathway leakage. This zone corresponds generally to a bad cement quality and requires a particular attention. The goal of this paper is to propose a 2-phase flow model to evaluate the influence of the rat hole configuration on the $CO_2$ flow up from the reservoir to the surface.

COMSOL multiphysics Earth science modulus has been used to study the $CO_2$ flow in this particular zone of the well (i.e. the rat-hole). The main goal of the development of this case with COMSOL multiphysics was to demonstrate the effect of the water flow on the $CO_2$ flow up.

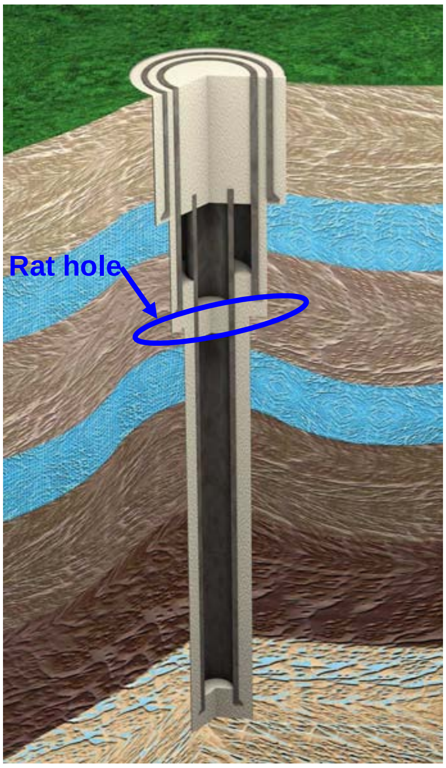

**Figure 1:** Scheme of an abandoned and plugged well and near geological formations

## 2. Description of physical modeling

### 2.1 Local equilibrium equation system

The $CO_2$ transport process through the well and its near environment consists in the following set of equations obtained from the mass and momentum conservation principles [11]. 2 phases flow is modeled. One phase is considered as a wetting one and the other phase as a non-wetting one.

Wetting phase:

$$\delta_S \frac{\partial S_w}{\partial t} + \nabla \cdot \left[ -\frac{k \cdot k_{r,w}}{\eta_w} \nabla (p_w + \rho_w g H) \right] = 0 \qquad (1)$$

Non-wetting phase:

$$\delta_S \frac{\partial S_{nw}}{\partial t} + \nabla \cdot \left[ -\frac{k \cdot k_{r,nw}}{\eta_{nw}} \nabla (p_{nw} + \rho_{nw} g H) \right] = 0 \qquad (2)$$

Where:

- $\delta_S$ is the porosity,
- $k$, absolute permeability of the porous medium (in $m^2$),
- $k_{r,I}$, relative permeability of phase i,
- p, pressure ($kg.m^{-1}.s^{-2}$),
- $\rho$, density ($kg.m^{-3}$),
- $\mu$, dynamic viscosity ($kg.m^{-1}.s^{-1}$),
- $g$, acceleration of gravity.

The kinetics part of the equations (1) and (2) are based on Darcy's law. Numerous models of flow through porous media based on these laws are referenced in literature [12 – 15].

### 2.2 Equation system in pressure form

The numerical resolution of a 2-phase flow model for $CO_2$ and water subject to relative permeability and capillary effects requires some elements. The equations are defined per phase and provide the associated saturation values in time [12]. Nevertheless to be solved the expression of the previous equations ((1) and (2)) has to be rewritten in function of phase pressure ((3) and (4)):

Wetting phase:

$$C_{p,w} \frac{\partial (p_{nw} - p_w)}{\partial t} + \nabla \cdot \left[ -\frac{k \cdot k_{r,w}}{\eta_w} \nabla (p_w + \rho_w g H) \right] = 0 \qquad (3)$$

Non-wetting phase:

$$C_{p,nw} \frac{\partial (p_{nw} - p_w)}{\partial t} + \nabla \cdot \left[ -\frac{k \cdot k_{r,nw}}{\eta_{nw}} \nabla (p_{nw} + \rho_{nw} g H) \right] = 0 \qquad (4)$$

The two phases, the wetting one and the non-wetting one are coupled by capillary pressure. The capillary pressure is given by (5):

$$p_c = p_{nw} - p_w \qquad (5)$$

and the relation between the saturation $S_w$ and capillary pressure is shown as (6):

$$C_{p,w} = -C_{p,nw} = \frac{\delta_s \partial S_w}{\partial p_c} \qquad (6)$$

with $C_{p,i}$ the specific capacity for phase i.

This last relation (6) enables to express the local equilibrium equations ((1) and (2)) in function of pressure relative to the phases.

In order to close the biphasic flow model a behavior law is used. The relationship between the effective saturation of wetting phase $\Theta$ and capillary pressure $p_c$ is obtained from Van Genuchten's model (7) [16].

$$\left(1+\left(\frac{p_c}{p_{ec}}\right)^N\right)^M = \frac{1}{\Theta}, \quad \Theta = \frac{S_w - S_{rw}}{1 - S_{rw}} \qquad (7)$$

with $p_{ec}$ capillary pressure head

In addition, the sum of the phases saturations has to be equal to one:

$$S_w + S_{nw} = 1 \qquad (8)$$

and the relationships between the saturations and relative permeabilities are obtained from Mualem's model (9 and 10) [17].

$$k_{r,w}(\Theta) = \sqrt{\Theta} \cdot \left(1 - \left[1 - \Theta^{1/M}\right]^M\right)^2 \qquad (9)$$

$$k_{r,w}(\Theta) = \sqrt{\Theta} \cdot \left(1 - \left[1 - \Theta^{1/M}\right]^M\right)^2 \qquad (10)$$

$\alpha$, M, N, L are the four unknown Van Genuchten constants. The data are determined from Charbonneau and al [18].

### 2.3 Cylindrical coordinate

The resolution of a 2-phase flow model in a well requires a cylindrical coordinate system. The axial coordinates correspond to the vertical axis of the well. Such a system leads to the following equations (11 and 12):

Wetting phase (water):

$$C_{p,nw} \frac{\partial (p_{nw} - p_w)}{\partial t} + \frac{1}{r} \nabla_r \cdot \left[ -r \frac{k \cdot k_{r,nw}}{\eta_{nw}} \nabla (p_{nw} + \rho_{nw} g D) \right] = 0 \qquad (11)$$

Non-wetting phase ($CO_2$):

$$C_{p,nw} \frac{\partial (p_{nw} - p_w)}{\partial t} + \frac{1}{r} \nabla_r \cdot \left[ -r \frac{k \cdot k_{r,nw}}{\eta_{nw}} \nabla (p_{nw} + \rho_{nw} g D) \right] = 0 \qquad (12)$$

## 3. Problem description and methods

Detailed problem specifications are given below; they include system geometry, elements properties (wellbore environment), initial and boundary conditions. This problem explores the $CO_2$ flow within well from $CO_2$ geological storage. A 2D axisymmetric flow geometry has been used. Figure 2 represents a schematic view of the system considered for this study. It includes:

- In black, stainless steel tubulars called(i.e. casings);
- In grey, cement sheaths that ensure the confinement of the holes between geology and the casings;
- Geological formations in contact with the well;
    - A limestone layer with average permeability;
    - A clay formation with very low permeability (caprock);
    - A connected aquifer with high permeability;
    - The reservoir in which CO2 is stored (very permeable layer).

The cement sheaths are initially considered water-saturated. Moreover the presence of a connected aquifer ensures a water supply within the cement sheaths.

Thanks to considering the pressure differential gradient between the $CO_2$ reservoir and the upper well elements, and the cement sheaths permeability, $CO_2$ gas can flow through the well.

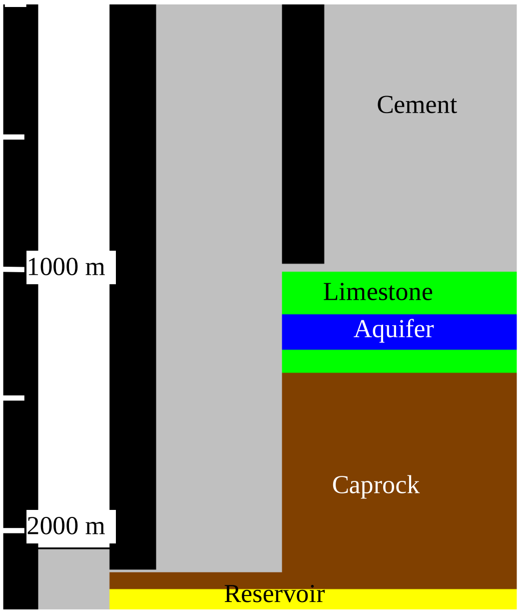

**Figure 2: System scheme bringing forward the rat hole zone**

For each well element: cement sheath, casing and for each near environment element: geological layers such as the $CO_2$ reservoir, the caprock, or the connected aquifer, porosity values, permeability values, and parameters of

Van Genuchten law and Mualem's model are defined. **Figure 3** presents the permeability value of each system zone at logarithmic scale.

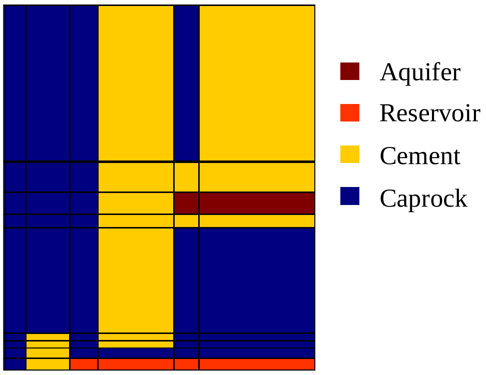

**Figure 3:** Intrinsic permeability values from the highest to the lowest value: aquifer (dark red), reservoir containing $CO_2$ (red), cement sheath (yellow), and caprock (blue)

**Table 1**: Permeability data, intrinsic permeability values

| Well Elements | Intrinsic Permeability [mD] |
|---|---|
| Aquifer | 1000 |
| $CO_2$ reservoir | 40 |
| Cement sheath | 0.1 |
| Caprock | 0.001 |

The initial and limit conditions assessed for the simulations were the following:

- Reservoir water saturation is at the residual water saturation;
- All other elements are considered water-saturated;
- The aquifer is at hydrostatic pressure ($P_{atm}$ = 1 bar);
- The reservoir pressures (wetting fluid and non wetting fluid) are time dependent as follows in Figure 4.

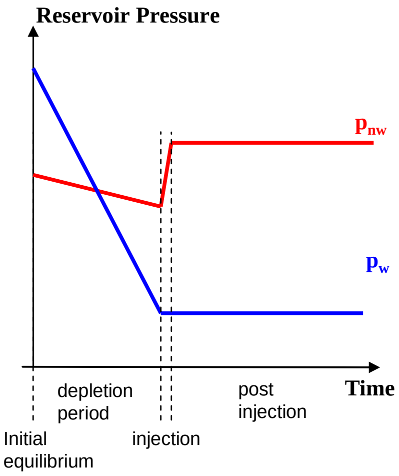

**Figure 4:** Pressures evolutions in time considered for the simulation

The well studied here corresponds to an old production well (for oil production) reconverted into a $CO_2$ injector well. The pressures encountered in the well components are function on the well pressure history during oil production. The initial conditions taken into account for this simulation are deduced from the well production history.

- Constant pressure boundary conditions within reservoir following **Figure 4**;
- No ageing processes (casing corrosion, cement leaching, and cement carbonation) were considered.

Preliminary simulations were performed from a quadrangle mesh for the space discretization. They showed some mathematical distortions. To solve this problem, a triangle mesh in the critical part of the system (see **Figure 5**) has been used. A stabilization of computation has been noted from this grid refinement.

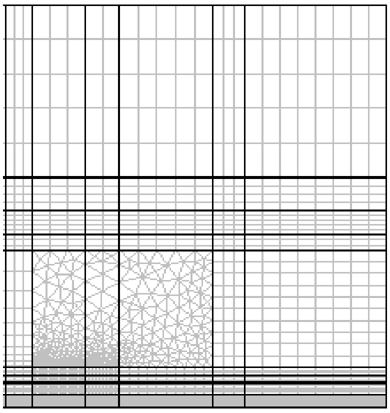

**Figure 5:** System (well and geological formations) space discretization

The model was then applied to predict the 2 phases flow through the rat hole. The results are presented in the following section.

## 4. Results

The main results of this study are shown on Figure 6. They highlighted that, under the pressure conditions considered for this case study the water flow in the rat-hole zone could behave as a key barrier to the CO2 flow up till water saturation is enough. The fact that a connected aquifer is associated with the well ensures a sufficient water supply to prevent CO2 flow up in this part of the well. The CO2 leakage pathway within a well will be obtained by considering the balance between the flows of the two fluids (water and CO2 gas) as shown on **Figure 6**.

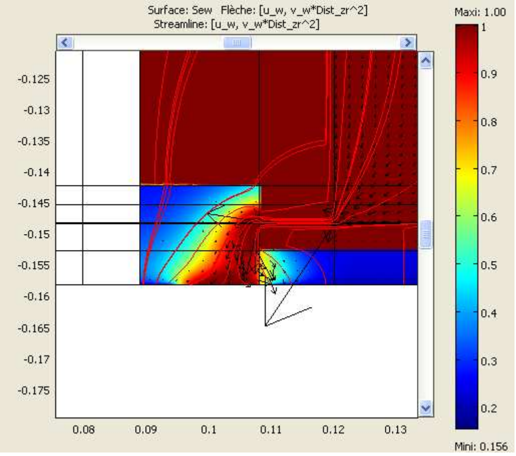

**Figure 6:** Water saturation (in color) and water flow direction (with black arrow) through the rat hole

To ensure the wells safety such studies should be performed on all the wells parts. The risk assessment associated to the wells goes through a better knowledge of the transport phenomenon that can occur in function of the system configuration.

## 5. Conclusions

As a conclusion, the numerical simulations have highlighted the competition between the gas flow and the liquid flow in a specific area of a well. The rat-hole zone constitutes a key element to consider in the long term integrity performance of a well. An improvement of the knowledge of the flows in this specific area within the well will be a support in assessing the Performance and the Risks from a well integrity perspective (i.e. $CO_2$ leakage).

To complete this study, robustness analysis will have to be performed, in particular, to quantify the $CO_2$ leakage in the case of no aquifer protection. Some assumptions have been formulated on the permeability values to solve the numerical simulations. Improvements in the modeling will have to be performed to take into account the significant differences between some parameters values for two linked elements;

Finally, this study will have to be coupled to a macroscopic CO2 leakage modelling within well system. This kind of modeling is essential into a quantitative well integrity risk analysis for $CO_2$ storage projects.

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