Numerical Simulation of CO_2 Leakage through Abandoned Wells during CO_2 Underground Storage

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Abstract. The storage of CO_2 in depleted oil and gas reservoirs, coal seams or saline aquifers is an important means of mitigating greenhouse effect in the environment. In CO_2 underground storage projects, well integrity is very important to ensure a safe execution of projects and storage of CO_2. It is a prerequisite for such projects and must be demonstrated for all wells affected by the injected CO_2 including abandoned wells. As part of one comprehensive methodology proposed by the authors, the leakage of CO_2 from the storage reservoir into the atmosphere or overlying aquifers over a certain time frame has been simulated. By building a model consisting of the critical system components, e.g., storage reservoir, casing-cement-rock composite system, injected CO_2 etc, according to a detailed study of features, events and processes (FEPs) which affect well integrity, a simulation is conducted for a time frame of 1000 years without consideration of geochemical influences. For the scenarios simulated, results show that CO_2 leakage rate is very small except for a reservoir under high pressure and poor quality cement-sheaths, which can lead to leakage rates in excess of the maximum allowable value.

Keywords: CO_2 underground storage, well integrity, abandoned well, leakage rate.

1 Introduction

The high energy production in the world results in a correspondingly high emission of CO_2 which is one of the greenhouse gases. To mitigate the negative influences on the environment, one possibility is to store CO_2 in the underground, e.g., depleted oil and gas reservoirs, saline aquifers or coal seams. It is usually referred to as CO_2 Sequestration and specifically as Carbon Capture and Storage (CCS). One important prerequisite for a CCS project is to ensure a long-term and

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safe containment of CO_2 without adversely impacting the environment and the human health during both the injection and post-injection phase. The period for CO_2 sequestration projects is typically 10 to 50 years for the operation phase and 100 to 10,000 years for the post-injection phase (Gérard et al. 2006, Duval 2004) with a most likely value of 1000 years, recommended by IPCC (2005) and Bouc et al. (2007). Usually there are large numbers of wells in the field, some of which are abandoned and plugged. The integrity of wellbores is a risk for the long-term security of geological storage facilities, because CO_2 is known to cause severe corrosion in oil and gas production and transportation facilities, in particular if not designed for CO_2 service. Therefore it is of paramount importance to verify the well conditions and evaluate well integrity prior to the commencement of CO_2 injection.

The background of this work is linked to the CO_2 Large–scale Enhanced Gas Recovery project, conducted on the Altmark Natural Gas Field (CLEAN) in Germany. The Altmark natural gas field is the second largest onshore gas field in Europe and it covers an area of more than 1000 km^2. The natural gas is contained in the geological Rotliegend formation at a depth of approx. 3500 m. There is a geological barrier mainly consisting of a Zechstein salt layer above the sandstone formation. This salt layer can provide a natural barrier against CO_2 and formation fluid migration, and provide a unique abandonment method using the creep effect of salt. During the lifetime of the pilot project, nearly 100,000 tons of CO_2 are to be injected into the hydraulically and structurally isolated Altensalzwedel subfield at a depth of more than 3000 m.

Evaluation of actual well integrity is relatively simple for accessible wells, since they can be surveyed to directly assess the conditions of the wells. The evaluation of the integrity of abandoned wells or the evaluation of well integrity development over longer time frames can only be done indirectly and requires relevant information on geology and wells, and a comprehensive understanding of relevant THMC (thermal–hydraulic–mechanical–chemical) processes affecting well integrity. A comprehensive methodology to evaluate abandoned well integrity starting from a detailed FEP (Features, Events and Processes) analysis has been proposed in Reinicke et al. (2011a and 2011b). As part of this method, the leakage rate of CO_2 from reservoir to the atmosphere and overlying aquifer over long timeframe will be simulated by building a model consisting of the critical system components, e.g., storage reservoir, casing-cement-rock composite system, injected CO_2 etc, according to a detailed study of FEPs which affect well integrity. A simulation is conducted for a timeframe of 1000 years without considering geochemical influences.

2 Problem Description

A scenario is achieved by a combination of Features, Events and Processes (FEPs) which are all static and dynamic activities influencing well integrity. By using some semi-quantitative tools, e.g., interaction matrix, risk matrix etc, the most critical FEPs and system components are recognized. The developed scenarios will be evaluated by using simulation models. For the simulation, the radial models shown in Figure 1 are employed to simulate the leakage into (a) the atmosphere and (b) an overlying aquifer. In steps of increasing complexity, single-phase and two-phase simulations will be carried out. A Schlumberger Black Oil simulator E100 will be used for the simulations including chemical processes, more advanced simulators are planned for use in the future.

In the simulations, the reservoir is modeled as a closed tank containing 100,000 ton (approx. 5.55×10^7 Sm^3) of CO_2. Representative reservoir properties of interest are assigned to the model, i.e. a depth of 3,400 m, a temperature of 125 ^{0}C, a porosity of 15 %, an initial water saturation of 20 %, and a permeability of 100 mD. Two values were assumed for the reservoir pressure. The first pressure of 50 bar reflects the current pressure while the second pressure of 450 bar resembles initial conditions. For this model, potential leakages were simulated for 1000 years assuming three different cement permeabilities: permeabilities representing good cement, poor cement, and defected cement (e.g., cracked cement, debonded cement, or cement with channels).

A three dimensional radial model was built with 10 grids in the radial direction, 4 grids in the azimuth direction and 39 grids in the vertical direction. The top view and side view of the model are shown in Figure 2. The basic parameters for system geometry and reservoir parameters, used in the simulation work, are listed in Table 1. They are representative of the area of interest for the CLEAN project.

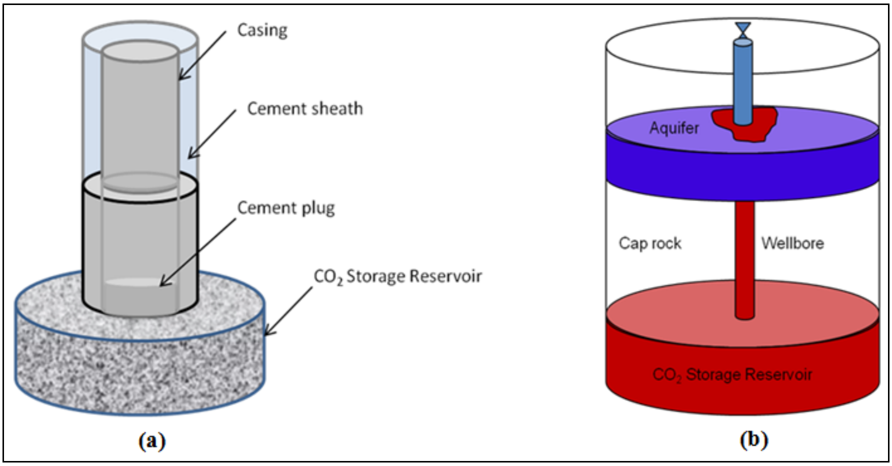

Fig. 1 Radial model used to simulate (a) CO_2 leakage to the atmosphere and (b) an overlying aquifer

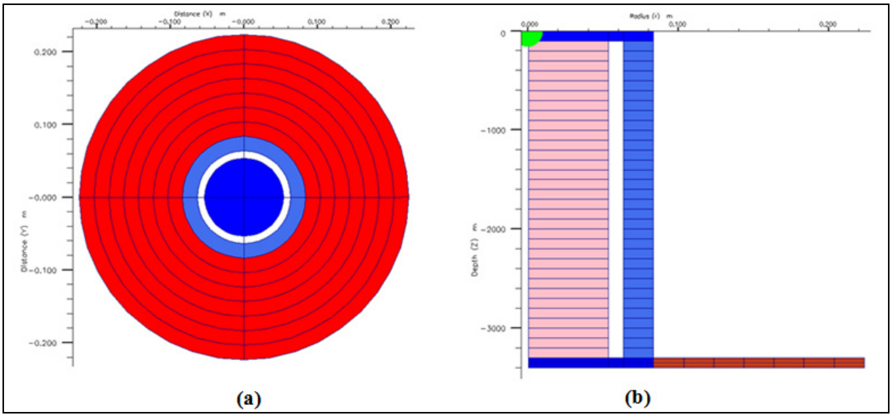

Fig. 2 Well model for CO_2 leakage through cement sheath (a: top view; b: side view. In this figure, the red color represents formation, light blue represents cement sheath, deep blue represents cement plug, pink represents mud between plugs, and white represents casing)

Table 1 Basic data for the simulation

Parameters	depth, m	casing inner radius, m	casing outer radius, m	cement sheath thickness, m	gross res. thickness, m
Values	3400	0.053	0.063	0.02	140
Parameters	porosity, fraction	res. permeability, mD	initial res. S_w, fraction	brine density , kg/m^3	brine viscosity, cp
Values	0.15	100	0.2	1196	0.37

3 Capillary Pressure and Relative Permeability Correlations

In order to simulate the liquid and gas two-phase flow through the cement, the capillary pressure and relative permeability curves play a paramount role. The acquisition of the capillary pressure function is usually based on experimental data or in its absence by empirical correlations. The two models most often used are the Brooks and Corey correlation and the van Genuchten correlation (Brooks and Corey 1964 and 1966, van Genuchten 1980, Burdine 1953, Mualem 1976). The relationship of capillary pressure in terms of water saturation as well as the relative permeability equation for Brooks and Corey correlation is:

$$S_e = \frac{S_l - S_{lr}}{1 - S_{lr} - S_{gr}} = \left(\frac{p_d}{p_c}\right)^{\lambda} \quad \text{for } p_c \geq p_d \tag{1}$$

$$k_{rw} = S_e^{(2+3\lambda)/\lambda} \tag{2}$$

$$k_{rnw} = (1 - S_e)^2 (1 - S_e^{(2+\lambda)/\lambda}) \tag{3}$$

where Se is the effective water saturation, Pd is the displacement pressure or threshold pressure and λ is pore size distribution index which is a material constant. The parameter λ typically ranges from 0.5 for a wide range of pore sizes to 5 for a uniform pore size rock (Flett et al. 2004). In the Brooks & Corey equation, if λ=2, we can use the standard Corey correlation.

The relationship of capillary pressure in terms of water saturation and the relative permeability equation for the van Genuchten correlation is:

$$S_e = \frac{S_l - S_{lr}}{1 - S_{lr} - S_{gr}} = \left[1 + (\alpha p_c)^n\right] \quad \text{for pc} \geq 0 \tag{4}$$

$$k_{rw} = S_e^{\varepsilon}\left[1 - (1 - S_e^{1/m})^m\right]^2 \tag{5}$$

$$k_{rnw} = (1 - S_e)^{\gamma}\left[1 - S_e^{1/m}\right]^{2m} \tag{6}$$

In the equation, α, ε, γ, n and m are Van Genuchten parameters.

After a detailed evaluation of empirical relative permeability correlations, in this work two different models are selected. For a good cement sheath whose permeability is assumed to be lower than 0.01 mD, the van Genuchten correlation is used. In the equation, ε = 0.5, γ = 0.5, m = 0.44 according to Mainguy and Coussy (2001). For poor and highly defected cement, the Brooks and Corey correlation is used. The relevant parameters in the equation are from a DGMK project which has been conducted by the Institute of Petroleum Engineering at Clausthal University of Technology. In the project the capillary pressure was measured in the lab for four types of rocks with different porosities, based on which the relative permeability is obtained.

4 Numerical Model Development

For the modeling process, the following assumptions have been made. Altogether these assumptions should lead to conservative results in the opinion of the author.

- The model consists of the most important system components: part of a reservoir, composite system, cement plug, CO2 and reservoir fluid (brine).
- Caprock above the formation is considered impermeable to the flow for CO2 and water. Leakage from the reservoir via the wellbore is the only way for CO2 to escape.
- The initial conditions in the reservoir are homogeneous.
- The reservoir is penetrated by only one abandoned well.
- No ageing processes (casing corrosion and cement carbonation) are considered.

The simulation processes cover two steps: single-phase flow (only CO_2) and two-phase flow (CO_2 and formation water) from the reservoir up to the surface or overlying aquifer which has a depth of 500 m.

During the life time of the wellbore, many processes could result in a mechanical failure of the casing-cement-rock composite system, leading to defects, e.g., gas channel, micro-annulus and micro-cracks, etc. The estimation of cement permeability is based on a detailed mechanical integrity evaluation. The resulting defects can be used to estimate the permeability based on empirical equations shown in Equation 7 and 8 (Huerta and Checkai 2009, Etiope and Martinelli 2001, Carey et al. 2009, Tran Viet 2012). The permeabilities are average permeabilities across the whole annulus area (A). Since the mechanical model is not included in this paper, three different types of cement are simulated. Each cement is assigned a different permeability value, for demonstration purposes. Table 2 lists the different cement permeabilities selected for the simulation.

For:

- Micro-annulus between cement and casing or cracks of cement sheath

$$kA = \frac{WB^3}{12} \tag{7}$$

- Gas channels

$$kA = \frac{\pi R^4}{8} \tag{8}$$

where A is annulus area, W is inner casing/cement sheath circumference for micro-annulus or cement sheath thickness for micro-cracks, B is the separation between casing and cement sheath for micro-annulus or aperture of the crack for micro-cracks, R is radius of the channel.

Table 2 Different cement qualities and effective permeabilities

Cement Quality	Permeability (mD)	Micro-annulus (mm)	Cracks (mm)	Gas channel (mm)
Good cement	0.01	-	-	-
Poor cement	10	0.014	0.038	0.124
Defected cement	1000	0.065	0.177	0.392

5 Results and Discussion

For single-phase flow, the cement and the formation are assumed to be saturated with CO_2. The results are shown in Table 3 for an initial reservoir pressure P_R=50 bar and in Table 4 for P_R=450 bar. For the two-phase simulations it has been assumed that CO_2 is not soluble in water due to high salinity in water. The results for flow to the atmosphere are shown in Table 5 (P_R=450 bar). For two-phase flow into an overlying aquifer, the wellhead is shut off and CO_2 cannot escape to the atmosphere. However it will flow into the near ground aquifer. The brine content in the closed aquifer is assumed to be 1×10^6 Sm^3. The depth is 500 m. The results are shown in Table 6.

Table 3 Simulation results for different cement qualities in the case of P_R=50 bar (Single phase)

Cement quality	Permeability (mD)	Leakage volume (%)	Reservoir pressure drop (%)	Peak leakage rate (Sm^3/day)
Good cement	0.01	0	0	0.000004
Poor cement	10	0.005	0.004	0.0074
Defected cement	1000	0.5	0.4	0.742

Table 4 Simulation results for different cement qualities in the case of P_R=450 bar (Single phase)

Cement quality	Permeability (mD)	Leakage volume (%)	Reservoir pressure drop (%)	Peak leakage rate (Sm^3/day)
Good cement	0.01	0.001	0.04	0.0006
Poor cement	10	0.226	1	0.343
Defected cement	1000	16.8	30	34.45

Table 5 Simulation results for two phase flow to atmosphere in the case of P_R=450 bar

Cement quality	Permeability (mD)	Leakage volume (%)	Reservoir pressure drop (%)	Peak leakage rate (Sm^3/day)
Good cement	0.01	0	0.016	0
Poor cement	10	0.003	0.03	0.00883
Defected cement	1000	4.39	11.79	7.597

Table 6 Simulation results for two phase flow into an overlying aquifer in the case of P_R=450 bar

Cement quality	Permeability (mD)	Leakage volume (%)	Reservoir pressure drop (%)	Peak leakage rate (Sm^3/day)
Good cement	0.01	0	0.016	0
Poor cement	10	0.004	0.03	0.006
Defected cement	1000	2.212	6.15	3.363

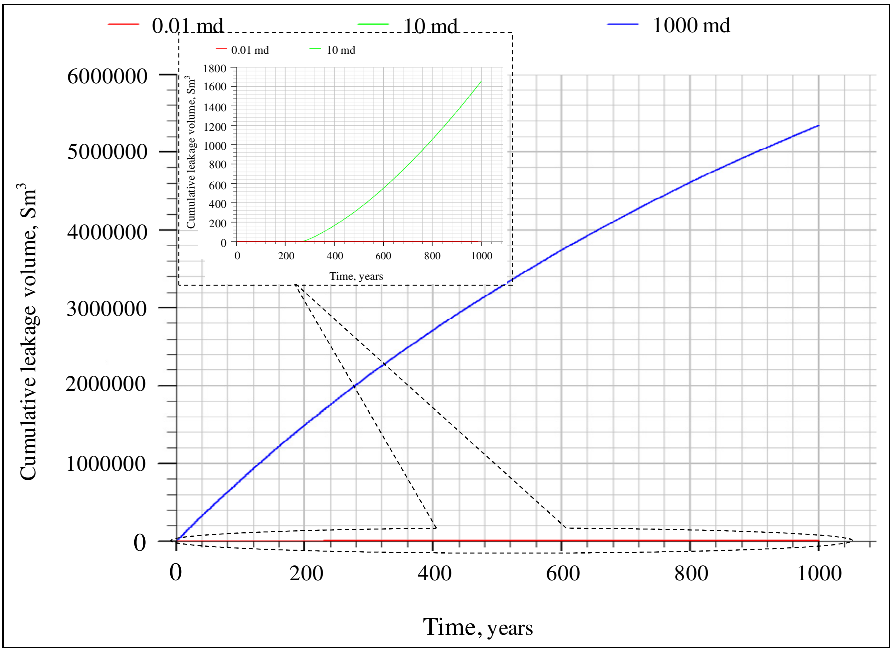

Fig. 3 Cumulative leakage to the atmosphere for two-phase flow (P_R =450 bar)

Figure 3 and Figure 5 show the cumulative leakage for two-phase flow under an initial reservoir pressure of 450 bar into the atmosphere and the overlying aquifer, respectively. Figure 4 and Figure 6 show the initial gas saturation as well as the development in 1000 yrs for three different types of cement in the case of two-phase flow into the atmosphere and the aquifer, respectively. In this figure, the blue represents the original gas saturation of 0% in the cement sheath, and the red represents gas saturation of 100%.

Based on all the results, several observations can be made:

- For severely depleted reservoirs the leakage rate from the reservoir to the biosphere is small, even for relatively high permeability of the cement sheath, e.g., a significantly damaged cement sheath.
- In a more realistic modeling of the two-phase flow of CO2 and water, there is a significant reduction in the leakage rate in comparison to a single-phase modeling because of the two-phase flow characteristics and the capillary pressure. The capillary pressure prevents the CO2 from displacing water.

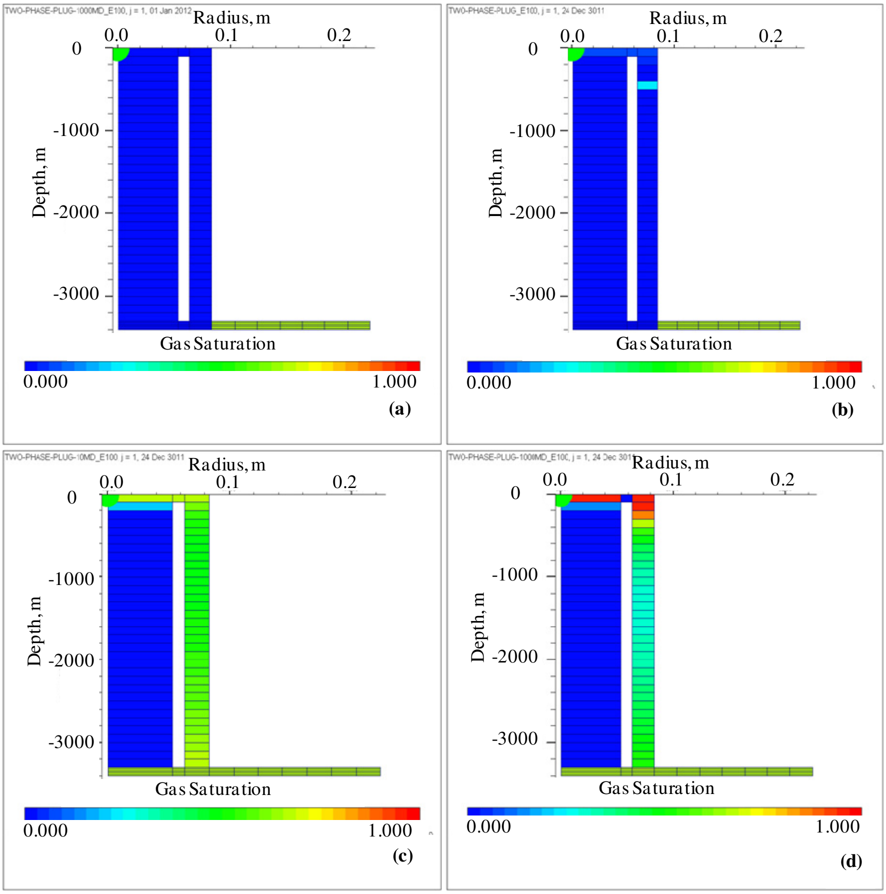

Fig. 4 Gas saturation when t=0(a) and t=1000 yrs for k=0.01 mD(b), 10 mD(c) and 1000 mD(d) in the case of two-phase flow to the atmosphere

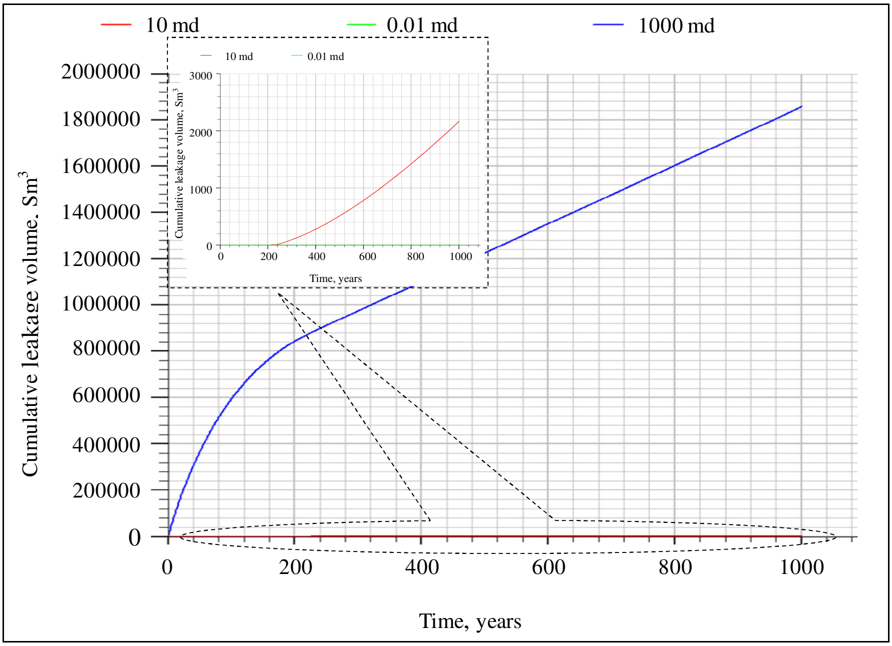

Fig. 5 Cumulative leakage into the aquifer for two-phase flow (PR =450 bar)

- For the higher initial reservoir pressure of 450 bar, i.e. hydrostatic pressure conditions, the leakage rate is much higher.
- Among the scenarios, only when assuming a very pessimistic, worst-case scenario of a single-phase flow under the influence of a hydrostatic reservoir pressure towards the atmosphere (the permeability of the cement is 1000 mD) can the leakage rate reach a value which is above the minimum detectable limit of 50 kg/day (ca. 26.3 Sm3/day) according to SMRI (1996). This leakage rate will lead to a cumulative leakage per year which is above the maximum allowable value that is 0.01%, of the total cumulative stored volume according to Hepple and Benson (2002).
- Because of the aquifer backpressure, the leakage rate and volume into the aquifer are smaller than into the atmosphere under the same conditions.

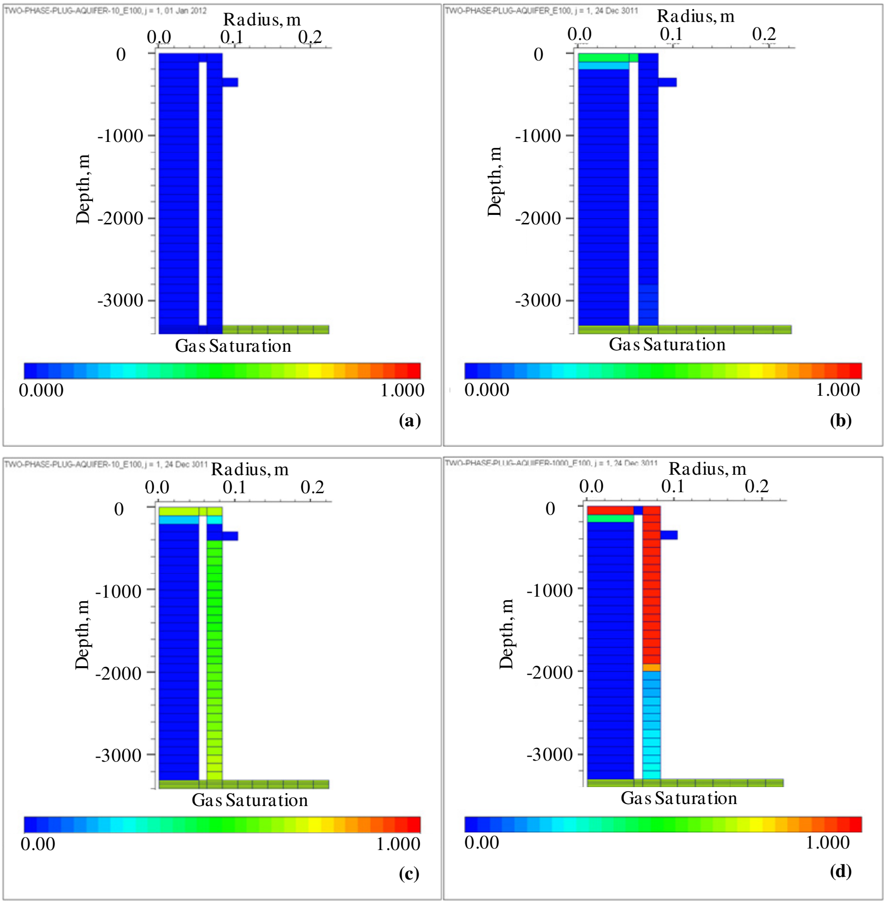

Fig. 6 Gas saturation when t=0(a) and t=1000 yrs for k=0.01 mD(b), 10 mD(c) and 1000 mD(d) in the case of two-phase flow into the overlying aquifer

6 Conclusions and Recommendations

The leakage of CO_2 through an abandoned well has been simulated in this work. The model focuses on a one-phase flow of CO_2 and a two-phase flow of CO_2 and formation water, neglecting well cement degradation. For this, the commonly used relative permeability correlations have been reviewed. The simulation results show that for severely depleted reservoirs the leakage rate from the reservoir to the biosphere is small, even for relatively high permeability of the cement sheath, e.g., significantly damaged cement sheath. Among the scenarios, only when assuming a very pessimistic, worst-case scenario of a single-phase flow under the influence of a hydrostatic reservoir pressure towards the atmosphere (the permeability of cement is 1000 mD), can the leakage rate reach a value above the minimum detectable limit proposed by researchers. Cement based materials are reactive porous media. When exposed to an acidic environment, some dissolution/precipitation processes can occur and lead to modification of mechanical and transport properties. The coupled geo-chemical and geo-mechanical effects on cement properties should also be included into a future model with the help of other types of software.

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