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Thermo-Poro-Mechanical Analysis of the Effects of Low-Temperature CO_2 Injection on Caprock Integrity

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Abstract

For any CO_2 sequestration project, a competent caprock acts as the primary and immediate trapping mechanism that prevents the injected fluid to leak out of the reservoir. This paper reviews the results of a thermo-poro-mechanical model developed to study the effects of low-temperature CO_2 injection on the caprock integrity for a hypothetical CO_2 storage project. A detailed study was conducted to characterize the behaviour of the model and to identify the influence of interactions between fluid flow, heat transfer, and geomechanics in the model. The results show that pressure and temperature distributions in the model are dissimilar and, consequently, their effects on the geomechanical response of the model are significantly different. It was observed that the low temperature of CO_2 has a dominant effect on the geomechanical response of the model. In general, a temperature decrease leads to severe reduction in the values of *in-situ* stresses and, consequently, it increases the potential of fracturing in the aquifer and the caprock. Nevertheless, this potential is smaller in the caprock than in the aquifer as a result of a lower temperature decrease in the caprock. This contrast is accentuated by the pore pressure drop caused by the temperature decrease in the low-permeability caprock with undrained flow behaviour. It is also shown that the behaviour of the model may be approximated by using analytical solutions. The paper also reviews the results of a series of analyses conducted to evaluate the sensitivity of tensile fracturing potential in the caprock to several different modeling parameters. These sensitivity analyses showed that the variation in some parameters such as Poisson's ratio, heat capacity, thermal conductivity, relative permeability, and permeability of the underburden have modest effects on the value of effective stresses in the caprock, while variations in Young's modulus and the thermal expansion coefficient can significantly influence these stresses and the potential for tensile fracturing in the caprock. Sensitivity analyses also show that injection of CO_2 with a temperature closer to the temperature of the aquifer reduces the potential for tensile fracturing in the caprock and aquifer to a great extent. The potential of fracturing in the caprock is also highly reduced by injecting CO_2 at greater depths within the aquifer and farther away from the caprock.

1. Introduction

For any CO_2 sequestration project, a competent caprock acts as the primary and immediate trapping mechanism that prevents the injected fluid to leak out of the aquifer, especially in early times before other trapping mechanisms such as dissolution and mineralization become significantly involved. Injection of CO_2 with temperature and pressure different from the initial values of the target geological formation has the potential to induce fractures in the caprock and compromise its sealing characteristics. Therefore, it is necessary to study the potential for such effects and take proper actions to mitigate their adverse results. During the last decade, thermal issues related to injecting low-temperature CO_2 were major concerns for caprock integrity assessment of CO_2 capture and storage (CCS) projects and researchers have used different modeling approaches and tools, such as one–way modeling (e.g., Goodarzi et al., 2012), iteratively coupled modeling (e.g., Tran et al., 2009), and fully coupled modeling (e.g., Preisig and Prevost, 2011) to address this issue.

The study presented in this paper was conducted to analyze the geomechanical integrity of the caprock for a hypothetical case study using iteratively coupled thermo-poro-mechanical modeling of low-temperature CO_2 injection in an aquifer. The developed thermo-poro-mechanical model consists of different components that are interactively coupled to represent different physics of the problem including fluid flow, heat transfer and geomechanics. The main objective of this study was to characterize the behaviour of the model through identifying the mechanisms of interaction between these physical processes. In addition, several sensitivity analyses were performed to study the effects of variations in different parameters on the potential for tensile fracturing in the aquifer and the caprock.

2. Structure and Characteristics of the Model

An iteratively coupled thermo-poro-mechanical model along with a fracture permeability correction approach was developed to model low-temperature CO_2 injection in an aquifer. The general approach of the modeling is similar to the approach used by Tran et al. (2009). However, the fracture permeability component of that model has not been included in this paper as it is out of the scope of this specific study. A finite-difference model was used for fluid flow-heat transfer simulations and a finite-element model was used for geomechanical modeling. The entire process of modeling was performed using the Computer Modeling Group's (CMG) reservoir compositional simulator, GEM® (CMG, 2012a). The coupling approach is based on the porosity modification as a result of changes in stresses (Tran et al., 2002).

In total, 10 stratigraphic units were considered in the developed two-dimensional model (Figure 1). These units cover the entire depth from the ground surface to the underburden. The mid-depth and the thickness of the aquifer are 1850 m and 38 m, respectively, and the corresponding values for the caprock are 1830 m and 3.5 m, respectively. A plane strain solution was used for geomechanical analyses. A horizontal width of more than 10 km was considered to ensure that the geomechanical response of the model is not influenced by the lateral constraints at the model boundaries. A horizontal CO_2 injection well was considered at the mid-depth of the aquifer. The existing plane of symmetry in the geometry allowed a significant reduction in the amount of computational effort by modeling only a half of the system geometry. To capture the abrupt variation of model behaviour, fine gridding resolution was required close to the injection well and in the vicinity of the boundary between the aquifer and the caprock.

Equations of state and fluid properties for CO_2 were developed using the CMG's equation of state (EOS) multiphase equilibrium and properties determination program, WinProp® (CMG, 2012b). Rowe-Chou and Kestin correlations (Rowe and Chou, 1970; Kestin et al., 1981a,b) were utilized in this software to calculate aqueous density and viscosity of the injection fluid, respectively. Henry's Law constants calculated by WinProp® (CMG, 2012b) were used to model CO_2 solubility in the aqueous phase. Porosity and permeability in the aquifer were assumed to be 6% and 7 md, respectively, characteristic of certain carbonate aquifers in the Alberta basin. A very small permeability of 1×10^{-10} md was assigned to the caprock. Typical values were used for the CO_2–brine relative permeability curves for the aquifer (Bennion and Bachu, 2010). For practical reasons and to consider the effect of hysteresis in the model, maximum residual gas saturation was used to determine the imbibition curves as functions of drainage curves (CMG, 2012a).

Typical values of mechanical properties, pore pressures, *in-situ* stresses, and thermal properties were assumed for the geological units in the developed model. These values are based on hydrogeological and geomechanial studies perfomed for geological formations in the Alberta Basin. As will be discussed later in this paper, sensitivity analyses were conducted to assess the effects of variations in these parameters on the modeling results.

3. Behaviour Characterization of the Model

A coupled thermo-poro-mechanical model consists of different components that are interactively coupled to represent different physics of the problem including fluid flow, heat transfer and geomechanics. The main objective of this paper is to characterize the behaviour of the model through identifying the mechanisms of interaction between these physical processes. The role of a specific physical process in the model can be identified by comparing the results of two modeling scenarios: one that includes this process and another that lacks it. Therefore, to study the roles of fluid flow, heat transfer, and geomechanics, the results of four different modeling scenarios were compared:

- i) Isothermal flow model without geomechanics
- ii) Isothermal flow model with geomechanics
- iii) Thermal flow model without geomechanics
- iv) Thermal flow model with geomechanics

The general characteristics for these four scenarios were mentioned in the previous section. In all these scenarios, CO_2 was injected at a rate of 40 scm^3/day per meter of width for 10 continous years. In the isothermal scenarios, the temperature of the injected CO_2 was considered to be eaual to the aquifer temperature (i.e., 65ºC), while in the thermal scenarios low-temperature CO_2 is injected at a well bottomhole temperature of 15°C. The results of these scenarios during the first 10 years after the start of injection were compared at two different observation points: one point is located along the plane of symmetry within the aquifer (almost 9 meters below the caprock) and the second point is located along the plane of symmetry in the caprock and very close to the aquifer (less than 1 meter above the aquifer). The reason that the immediate

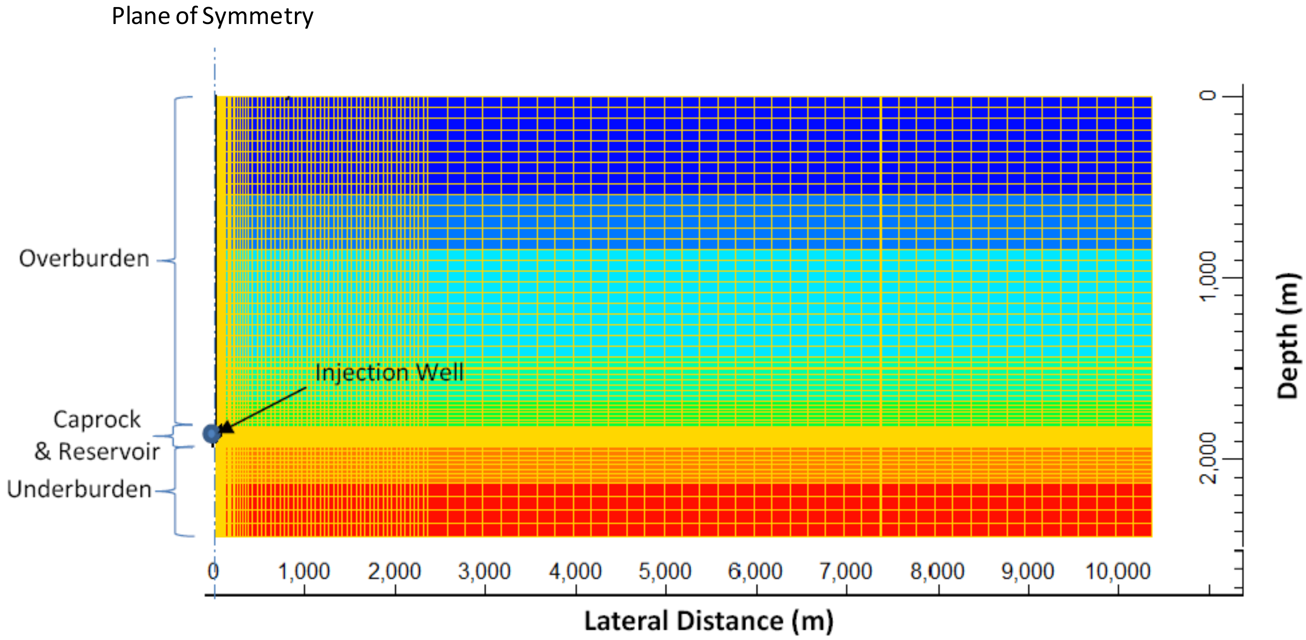

Figure 1. Geometry of the developed model including its gridding and geomechanical units.

block above the aquifer was not considered as an observation point is to minimize the 'cell-to-node projection error' that may lead to misleading conclusions on the behaviour of the caprock (Settari et al., 2005, Goumiri and Prevost, 2011)

3.1. Pore Pressure and Temperature Change in the Aquifer and Caprock

Temperature and pressure changes at the observation point located within the aquifer for the four studied modeling scenarios are shown in Figures 2a and 2b, respectively. Comparing the results of isothermal and thermal scenarios in Figure 2a shows that injecting low-temperature CO_2 reduces the temperature of the observation point within the reservoir by almost 11.3 ℃ after 10 years of injection (Figure 2a) while the pore pressure change within the aquifer is not significantly affected by the low temperature of the injected CO_2 (Figure 2b). A similar behaviour was observed in the modelings performed by Preisig and Prevost (2011) and Goodarzi et al. (2012). Comparing the results of the scenarios with and without geomechanics in Figures 2a shows that, as expected (e.g., Zimmerman, 2000), the effect of geomechanics on the aquifer temperature change is negligible. Nevertheless, the effect of geomechanics on the aquifer pressure change is more significant as a result of compressible behaviour of the aquifer rock (Figure 2b).

Temperature and pore pressure changes at the observation points located in the caprock for the four modeling scenarios are shown in Figures 2c and 2d, respectively. Comparing the results of the isothermal and thermal scenarios in these figures demonstrates the significant effect of the low temperature of CO_2 on the caprock's pore pressure and temperature change. Figure 2d shows that pore pressure in the caprock significantly decreases when its temperature drops. This is in agreement with the results of Tran et al. (2009). The reason for such a significant pressure decrease in the caprock is the substantial thermal contraction of the brine volume with no chance for fluid flow in this region due to its very low permeability (i.e., undrained behaviour). This behaviour is very important in caprock integrity assessment as pore pressure reduction delays the onset of tensile fracturing in the caprock. Figure 3 shows the variation of pore pressure change versus temperature change in the caprock for both of the thermal scenarios, i.e., without and with geomechanics. For the thermal scenario without geomechanics, according to this figure, 10 years of injecting low-temperature CO_2 reduces the caprock temperature and pressure by almost 3.8°C and 4600 kPa, respectively. This means that pressure in the caprock drops by an average rate of about 1210 kPa/°C as a result of temperature decrease. A simple calculation may be used to explain this rate. In an undrained condition and in the absence of any deformation induced by geomechanics, the expected rate of pressure change induced by temperature change can be calculated as:

$$\frac{dP}{dT} = \frac{\beta}{C_w} \qquad (1)$$

where C_w and β are the compressibility and volumetric thermal expansion coefficient of formation brine, respectively. The values of C_w and β at the initial temperature of the caprock (65°C) can be estimated as 4.3×10^{-7} 1/kPa and 5.5×10^{-4} /°C, respectively (CMG, 2012a). Using these values in Equation (1) results in a rate of 1280 kPa/°C that is reasonably close to the rate calculated by the model. It is important to note that this rate decreases as the formation temperature drops. The reason is the strong non-linear dependency of brine thermal expansion coefficient (β) on temperature. In the thermal scenario with geomechanics, the average rate of the pressure drop caused by the temperature decrease is about 1000 $kPa/℃$ (Figure 3). This rate is less than the rate predicted in the thermal scenario without geomechanics because pore volume changes in this scenario compensate for some of the volumetric changes of the brine.

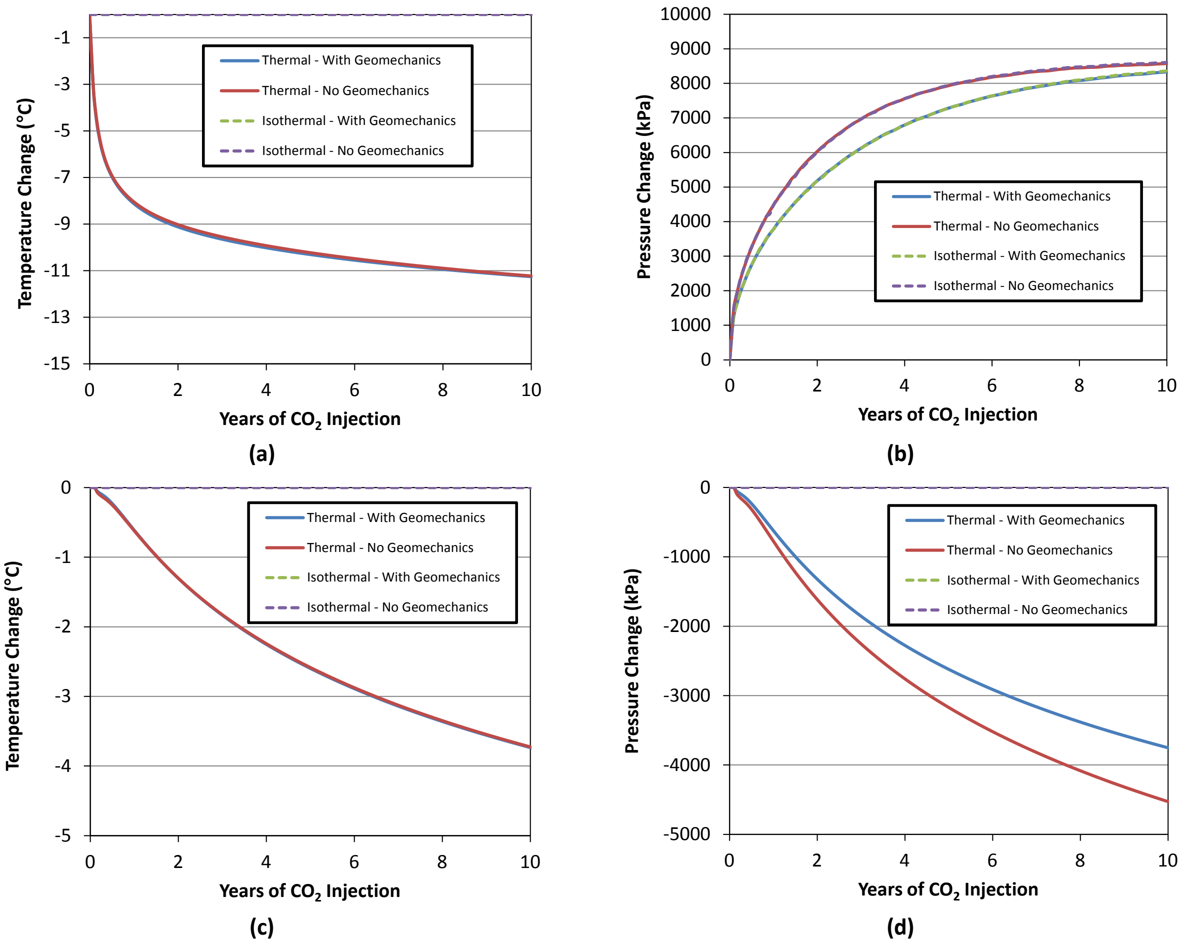

Figure 2. Changes in (a) temperature at the observation point within the aquifer (b) pressure at the observation point within the aquifer (c) temperature at the observation point in the caprock (d) pressure at the observation point in the caprock for different modeling scenarios for 10 years of CO_2 injection.

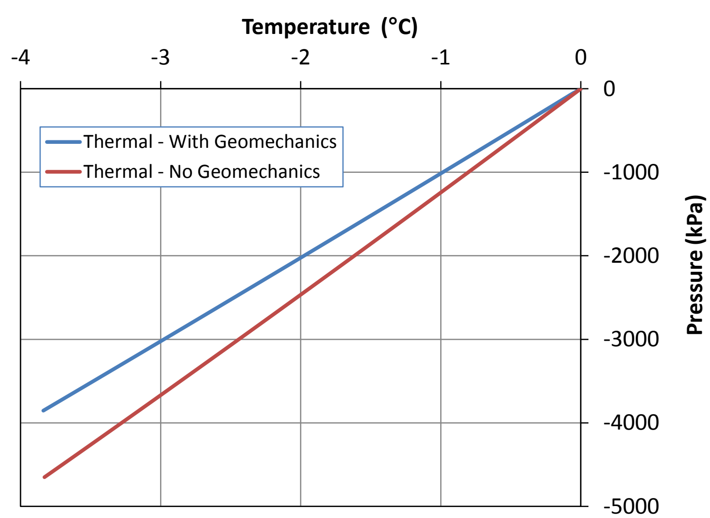

Figure 3. Pressure change versus temperature change in the caprock for 10 years of CO_2 injection.

3.2. Induced Strains in the Aquifer and Caprock

Figures 4a and 4b show the induced strains for both of the isothermal and thermal scenarios with geomechanics at the observation points located within the aquifer and in the caprock, respectively. According to the sign convention used to develop these figures, negative sign means rock expansion and positive sign means rock contraction. Figure 4a shows that, as expected, in the isothermal scenario, injection of CO_2 results in expansion of the aquifer. The induced volumetric strain in this scenario is mainly influenced by the vertical strain since the horizontal strain is negligible. The small value of the horizontal strain can be explained by considering that the pressure change distribution within the aquifer has a much larger lateral extent compared with its vertical extent (i.e., the reservoir thickness); in other words, the pressure change distribution has a very small aspect ratio (i.e., e = vertical dimension/horizontal dimension). Such a pressure change distribution is expected to induce sub-vertical deformations within the aquifer. In addition, it is not expected to induce considerable deformations in the caprock (Soltanzadeh et al., 2007) as can be seen in Figure 4b.

According to Figures 4a and 4b, the low temperature of injected CO_2 has a significant influence on the induced strains in the aquifer and caprock. Figure 4a shows that the effect of temperature is significant enough to shift the induced volumetric strain withing the reservoir from an expanding state in the isothermal scenario to a contracting state in the thermal scenario. This figure also demonstrates that, in contrast to the isothermal scenario, the horizontal strains within the aquifer are signifcant in the thermal scenario. This may be explained by considering the shape of the distribution of temperature change (Figure 5a) which has a vertical extension almost similar to its horizontal extension. Such a region with an aspect ratio near 1.0 is expected to induce thermal strains in the horizontal direction as much as in the vertical direction (Soltanzadeh et al., 2007). To explain the difference between the extents of the distributions of pressure and temperature change, it must be remembered that the former is generally dependent on permeability while the latter is mainly a function of rock thermal properties such as heat capacity and thermal conductivity. The vertical extent of the region of pressure change is limited to the thickness of the aquifer due to the significant permeability contrast between the aquifer and the caprock. However, this is not the case for the region of temperature change where similar thermal properties were assumed for the aquifer and the caprock in the developed model (in reality they are not equal, but the differences are relatively small, within a factor of one, compared with the permeability difference of several orders of magnitude).

As discussed before, the induced strains in the caprock are negligible in the isothermal scenario. Therefore, it is reasonable to assume that almost all the strains in the thermal scenario are induced by the low temperature of injected CO_2 (Figure 4b). Injecting low-temperature CO_2 results in decreasing the temperature and, consequently, the pore pressure in the caprock as discussed in the previous section (Figure 5b). Although both of these changes result in contraction of the caprock, the patterns of strains induced by them are significantly different. The reason is the significant difference between the distributions of temperature and pressure change in the caprock as shown in Figures 5a and 5b.

3.3. Induced Total Stress Changes in the Aquifer and Caprock

Figures 4c and 4d show the induced total stress changes at the observation points located within the aquifer and in the caprock, respectively. These figures contain the results for both of the isothermal and thermal scenarios with geomechanics. In this section, some analytical solutions are implemented to quantitatively evaluate the roles of fluid flow and heat transfer on development of stresses at these observation points.

Soltanzadeh et al. (2007) presented closed-form plane strain solutions to calculate stress changes induced by pore pressure and temperature changes within a reservoir. These solutions were derived for a homogenous and isotropic poroelastic field (with Young modulus of E and Poisson's ratio of ν). According to these solutions, if the geometry of the regions of pressure or temperature changes can be approximated by an elliptical cylinder with an aspect ratio of e, the magnitudes of stress changes within the reservoir may be estimated using the following equations:

$$\Delta\sigma_V = \frac{1-2\nu}{1-\nu}\frac{e}{1+e}\Delta C \quad (2)$$

$$\Delta\sigma_{H(in-plane)} = \frac{1-2\nu}{1-\nu}\frac{1}{1+e}\Delta C \quad (3)$$

$$\Delta\sigma_{H(out-of-plane)} = \frac{1-2\nu}{1-\nu}\Delta C \quad (4)$$

where $\Delta\sigma_V$, $\Delta\sigma_{H(in-Plane)}$, and $\Delta\sigma_{H(out-of-Plane)}$ are the vertical stress change, horizontal stress change in the cross-section plane, and horizontal stress change normal to the cross-section plane, respectively; and ΔC is given by:

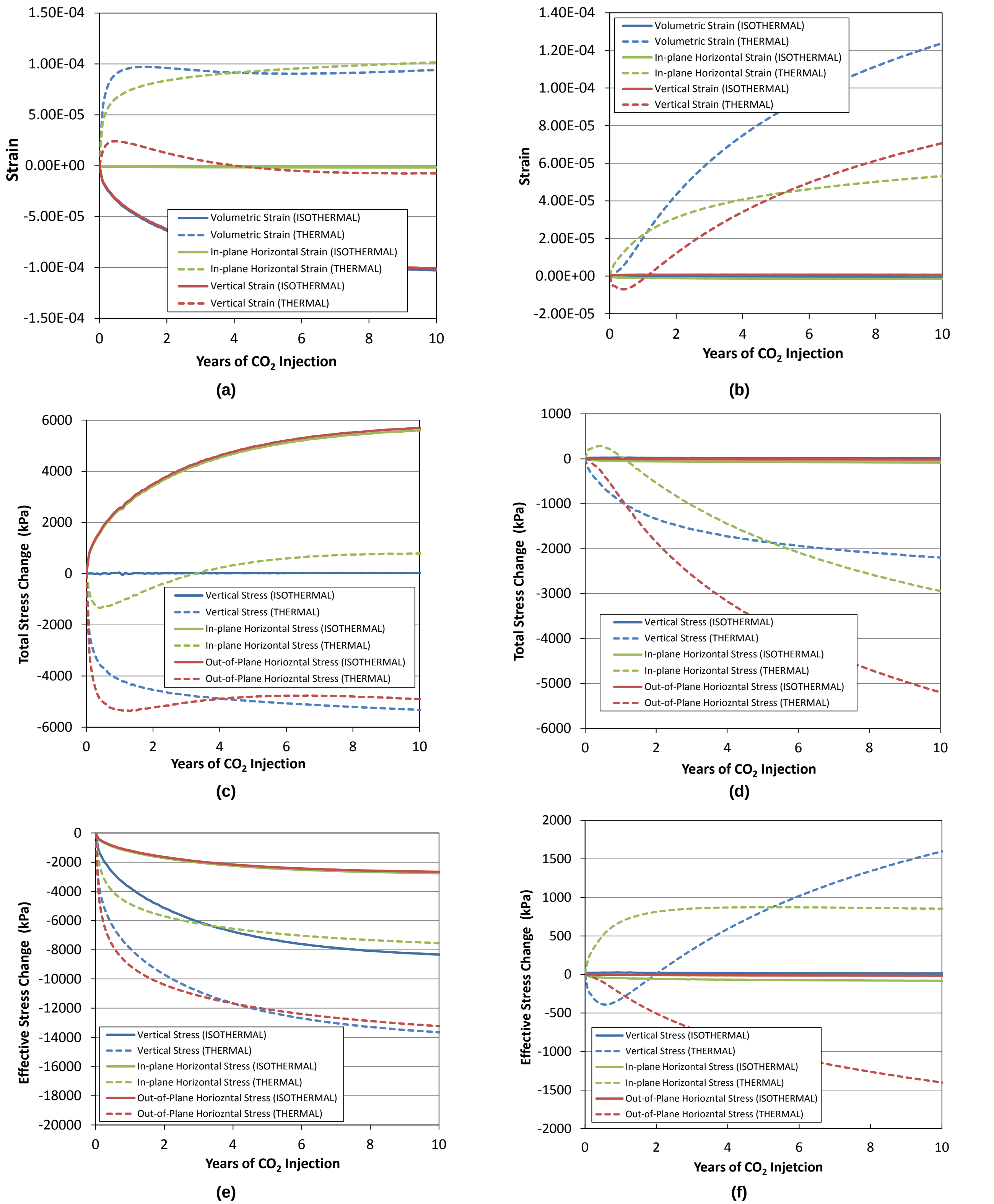

Figure 4. Results of Geomechanical Analyses: (a) variation of strains at the observation point located within the aquifer; (b) variation of strains at the observation point located in the caprock; (c) variation of total stresses at the observation point located within the aquifer; (d) variation of total stresses at the observation point located in the caprock; (c) variation of effective stresses at the observation point located within the aquifer; (d) variation of effective stresses at the observation point located in the caprock.

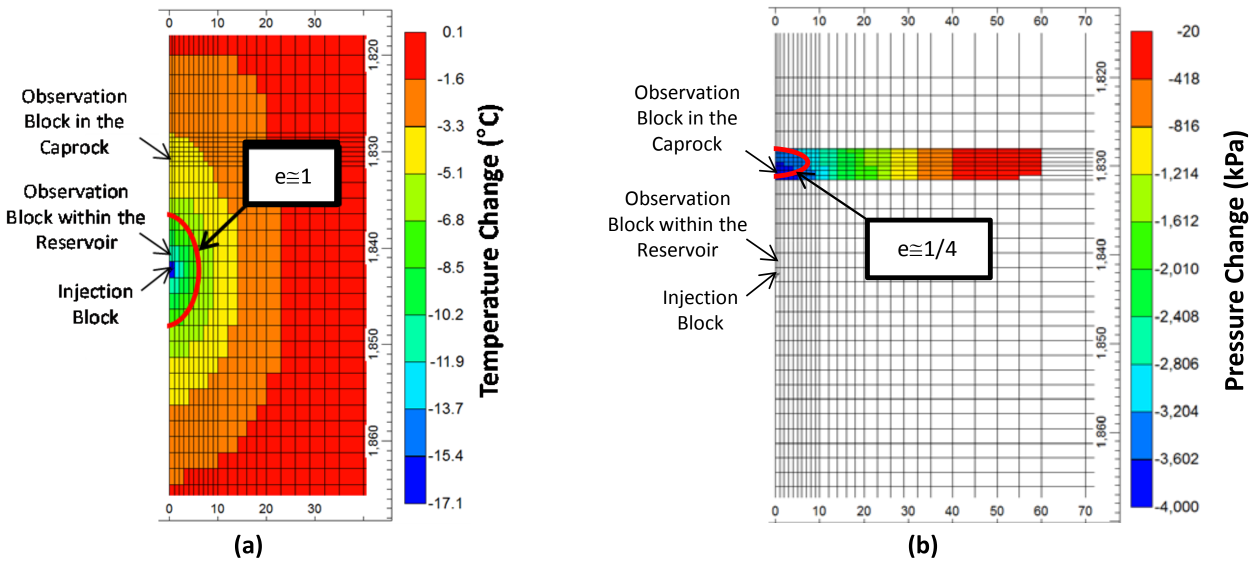

Figure 5. (a) Distribution of temperature change in the field. (b) Distribution of pressure change in the caprock. The parameter, *e*, represents the aspect ratio of the pressure or temperature change regions. Note that the scales of horizontal and vertical axes in these figures are different.

$$\Delta C = \alpha \Delta P \quad \text{for uniform pressure change of } \Delta P; \tag{5}$$

or

$$\Delta C = \frac{E\eta}{1-2\nu}\Delta T \quad \text{for uniform temperature change of } \Delta T; \tag{6}$$

In these equations α and η are Biot's and linear thermal expansion coefficients, respectively. Soltanzadeh et al. (2007) also suggested the following equations to calculate induced stress changes immediately above the elliptical cross-section along its vertical axis of symmetry (i.e., the caprock):

$$\Delta\sigma_V = \frac{1-2\nu}{1-\nu}\frac{e}{1+e}\Delta C \tag{7}$$

$$\Delta\sigma_{H(in-plane)} = \frac{1-2\nu}{1-\nu}\frac{-e}{1+e}\Delta C \tag{8}$$

$$\Delta\sigma_{H(out-of-plane)} = 0 \tag{9}$$

These equations can be used for quantitative evaluation of the modeling results. As discussed in the previous section, for the isothermal scenario with geomechanics, the pressure change distribution has an aspect ratio close to zero. Equations (2) to (6) may be utilized to calculate the induced total stress changes at the observation point within the aquifer. Table 1 includes the total stress changes calculated using these equations compared to the numerical modeling results after 10 years of CO_2 injection. This table shows a very good consistency between these results. Equations (5) to (9) may be used to assess the induced stress changes in the caprock in the isothermal scenario. These equations result in zero stress changes in the caprock, which are comparable to the insignificant values of stress changes predicted by the numerical model (Table 1).

For the thermal scenario with geomechanics, since the model behaves elastically and the equations are linear, the effects of pressure and temperature change on the *in-situ* stresses may be calculated separately and superimposed. In this scenario, within the aquifer, the pressure increase induces compressive total stress changes, while the temperature decrease induces extensile total stress changes. Nevertheless, in the caprock, both pressure and temperature decrease simultaneously and induce extensile total stress changes. Therefore, Equations (2) to (6) may be used to estimate stress changes within the aquifer and in the caprock as shown in Table 1. According to this table, the estimated values are reasonably close to the values predicted by the numerical model. This is an interesting observation considering the simplicity of the implemented equations and their underlying physics. The analytically estimated induced stress changes in Table 1 may be used to evaluate the respective shares of heat and fluid flow in the geomechanical response of the aquifer and the caprock to low-temperature CO_2 injection.

Table 1. Comparison between the total stress changes calculated by the analytical solutions and the developed numerical model. The parameter, *e*, represents the aspect ratio of the pressure or temperature change regions.

Parameter		Isothermal Case*				Thermal Case*			
		Within the aquifer		In the caprock		Within the aquifer		In the caprock	
		Analytical	Numerical	Analytical	Numerical	Analytical	Numerical	Analytical	Numerical
ΔP (kPa)		8359 (e≅0)		0		8334 (e≅0)		-3800 (e≅1/4)	
ΔT (°C)		-		-		-11.3 (e≅1)		-3.8 (e≅1)	
$\Delta\sigma_V$ (kPa)	Effect of ΔP	0	-	0	-	0	-	-520	-
	Effect of ΔT	-	-	-	-	-5164	-	-1315	-
	Total	**0**	**28**	**0**	**13**	**-5164**	**-5322**	**-1835**	**-2200**
$\Delta\sigma_{H(in-Plane)}$ (kPa)	Effect of ΔP	5719	-	0	-	5700	-	-2080	-
	Effect of ΔT	-	-	-	-	-5164	-	-1315	-
	Total	**5719**	**5602**	**0**	**-81**	**536**	**787**	**-3395**	**-2944**
$\Delta\sigma_{H(out-of-Plane)}$ (kPa)	Effect of ΔP	5719	-	0	-	5700	-	-2600	-
	Effect of ΔT	-	-	-	-	-10330	-	-2630	-
	Total	**5719**	**5698**	**0**	**-16**	**-4630**	**-4902**	**-5230**	**-5198**

* *The linear thermal expansion coefficients for both of the caprock and the aquifer are $1x10^{-5}$ /°C. The Poisson's ratio and Biot's Coefficient for both of these geomechanical units are 0.24 and 1.0, respectively. The Young's modulus of the caprock and the aquifer are 52.6 GPa and 69.5 GPa, respectively.*

3.3. Effective Stress Changes in the Aquifer and Caprock

Effective stresses may be considered as the most important output of geomechanical analysis since they are directly used in rock failure criteria to identify geomechanical risks such as induced shear and tensile fracturing. In their general form, effective stresses (σ') are defined as:

$$\sigma' = \sigma - \alpha P \tag{10}$$

Figures 4e and 4f show the induced effective stress changes for both of the isothermal and thermal scenarios with geomechanics at the observation points located within the aquifer and in the caprock, respectively. According to Figure 4e, injecting low-temperature CO_2 has a considerable influence on the effective stresses within the aquifer and, consequently, may increase the risk of tensile failure. The potential of tensile fracturing in this region also depends on the initial values of *in-situ* stresses and rock strength properties. However, Figure 4f shows that this influence, although still significant, is smaller for the caprock since, in contrast to the aquifer, pore pressure in the caprock decreases during injection of low-temperature CO_2. Changes in effective stresses within the aquifer and caprock may be analytically estimated using Equations (2) to (10) as shown in Table 2. According to this table, there is a reasonable agreement between the effective stresses calculated using analytical solutions and the results of the developed numerical model.

4. Data Uncertainty and Sensitivity Analysis

Uncertainty in the modeling input data is a major concern in reservoir geomechanics. To enhance the confidence in modeling results, it is necessary to address these uncertainties by analyzing the sensitivity of the modeling response to the variations in uncertain input parameters. Sensitivity analyses were conducted in this study for several sets of data including rock mechanical properties (i.e., Poisson's ratio and Young's modulus), rock thermal properties (i.e., heat capacity, thermal conductivity, and thermal expansion coefficient), temperature of injected CO_2, location of injection well, relative permeability of the aquifer, and permeability of the underburden. In these sensitivity analyses, the effects of variations in these parameters on effective stresses in the caprock, as the major parameters for caprock integrity assessment, were studied. The results of these sensitivity analyses are summarized in the following.

Uncertainties in rock elastic properties can be a major challenge in geomechanical modeling. The results of sensitivity analyses in this study show that a variation of ±0.05 in the values of Poisson's ratio of the geomechanical units in the model has a relatively modest influence on the induced effective stresses in the caprock while ±20% variation in Young's modulus has a considerable influence on the effective stresses in the caprock. This can be explained by remembering that Young's modulus has a direct linear effect on thermally-induced stresses in the field (see Equation (6)). Other common uncertain properties in thermo-poro-mechanical modeling are rock thermal properties including thermal conductivity, heat capacity, and the thermal expansion coefficient. Therefore, a series of sensitivity analyses were conducted to investigate the extent which the variation in these properties may affect the results of modeling. In these sensitivity analyses, effects of ±30% variation in each of these parameters on the value of *in-situ* stresses in the caprock were studied. The results show that while variations in thermal conductivity and heat capacity have modest effects on the values of effective stresses in the caprock, variation in the thermal expansion coefficient has a significant effect on these stresses. Similar to Young's modulus, the considerable effect of the thermal expansion coefficient is due to its direct linear effect on induced thermal stresses in the caprock (see Equation (6)).

Table 2. Comparison between the effective stress changes calculated by the analytical solutions and the developed numerical model. *e* represents the aspect ratio of the plume.

Parameter		Isothermal Case				Thermal Case			
		Within the aquifer		In the caprock		Within the aquifer		In the caprock	
		Analytical	Numerical	Analytical	Numerical	Analytical	Numerical	Analytical	Numerical
ΔP (kPa)		8359 (e≈0)		0		8334 (e≈0)		-3800 (e≈1/4)	
ΔT (°C)		-		-		-11.3 (e≈1)		-3.8 (e≈1)	
$\Delta\sigma'_V$ (kPa)	Effect of ΔP	-8359	-	0	-	-8334	-	3280	-
	Effect of ΔT	-	-	-	-	-5164	-	-1315	-
	Total	**-8359**	**-8330**	**0**	**14**	**-13498**	**-13654**	**1965**	**1596**
$\Delta\sigma'_{H(in-Plane)}$ (kPa)	Effect of ΔP	-2640	-	0	-	-2634		1720	-
	Effect of ΔT	-	-	-	-	-5164		-1315	-
	Total	**-2640**	**-2756**	**0**	**-81**	**-7798**	**-7545**	**405**	**852**
$\Delta\sigma'_{H(out-of-Plane)}$ (kPa)	Effect of ΔP	-2640	-	0	-	-2634		1200	-
	Effect of ΔT	-	-	-	-	-10330		-2630	-
	Total	**-2640**	**-2660**	**0**	**-16**	**-12964**	**-13234**	**-1430**	**-1402**

As discussed before, the results of the analyses show that the low-temperature of injected CO_2 within the aquifer has a critical effect on the geomechanical response of the model. A set of sensitivity analyses were performed to study the effect of the temperature of injected CO_2 on effective stresses in the caprock. In these analyses, different bottomhole temperatures (i.e., 15, 30, 50 and 65°C) were assumed for the injected CO_2. Since the initial temperature of the field is assumed to be 65°C, the injection temperature of 65°C corresponds to an isothermal scenario. These analyses, again, confirm that the effect of low-temperature of injected CO_2 on the induced stresses in the caprock is significant. According to these analyses, injecting CO_2 with a temperature closer to the aquifer temperature reduces the potential for tensile fracturing in the caprock. A higher difference between the temperatures of the injected fluid and the aquifer leads to greater changes in effective stresses in the caprock. In the isothermal scenario, in the absence of such a difference, the effective stresses in the caprock remain almost unchanged (see Figures 4b, 4d, and 4f). Sensitivity studies showed that, if possible, it is preferred to inject low-temperature CO_2 through a well that is located as far away as possible from the caprock and deeper within the aquifer. This will reduce the adverse effects of injected low-temperature CO_2 on the caprock integrity by decreasing the temperature drop in the caprock.

Sensitivity analyses were also performed to study the effect of relative permeability of the CO_2 phase on the effective stresses developed in the caprock. The results show that, by increasing the relative permeability, the injectivity of the aquifer is improved to a large extent, though it does not have a considerable influence on the induced stress changes in the caprock. Analyses also show that the effective stress changes in the caprock are not very sensitive to the permeability of the underburden as the temperature change in the caprock is not considerably affected by this parameter due to CO_2 bouyancy and its tendency to accumulate below the caprock. It is important to mention that the initial values of *in-situ* stresses in the caprock have a critical importance in determining the potential of induced fracturing in the caprock due to their direct role in any failure criterion.

5. Summary and Conclusion

A thermo-poro-mechanical model for a synthetic CO_2 storage case was developed to study the effect of low-temperature CO_2 injection on the geomechanical response of the field. A detailed study was conducted to characterize the behaviour of this model and to identify the mechanisms of interaction between the fluid flow, heat transfer, and geomechanical effects on the modeling results. It was observed that the low temperature of CO_2 has a major influence on the geomechanical response of the model. The results showed that pressure and temperature distributions in the model are dissimilar and, consequently, their effects on the geomechanical response of the model are significantly different. It was observed that the low temperature of CO_2 has a dominant effecton the geomechanical response of the model. In general, a temperature decrease can lead to severe reduction in the values of *in-situ* stresses and, consequently, it increases in the potential of induced fracturing in the aquifer and the caprock. Nevertheless, this potential is smaller in the caprock than in the aquifer as a result of lower temperature decrease in the caprock. This contrast is accentuated by pore pressure drop caused by temperature decrease in the low-permeability caprock. It was also shown the behaviour of the model may be approximated by using analytical solutions. To address the existing uncertainty in data, a series of analyses were conducted to evaluate the sensitivity of tensile fracturing potential in the caprock to several different parameters. These sensitivity analyses showed that changes in some parameters such as Poisson's ratio, heat capacity, thermal conductivity, relative permeability, and permeability of the underburden have modest effects on the value of effective stresses in the caprock, while changes in Young's modulus and the thermal expansion coefficient can significantly affect these stresses to an extent that tensile fractures form in the caprock, leading to an increase on the potential of tensile fracturing. Sensitivity analyses showed that injection of CO_2 with a temperature closer to the temperature of the aquifer reduces the potential for tensile fracturing in the caprock and aquifer to a great extent. This potential is also highly reduced by injecting CO_2 at greater depths within the aquifer and farther away from the caprock.

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