# EGEE 520 – Modeling of Rock Structure Changes due to Stress Induced by $CO_2$ Sequestration

By

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## 1. Introduction

Storage of carbon dioxide ($CO_2$) into sedimentary settings, such as deep saline aquifers, depleted oil and gas reservoirs, and coal seams, shows great potential to reduce the emission of greenhouse gases to the atmosphere[1-6]. However, $CO_2$ injection into geological formations may give rise to a variety of unexpected chemical and physical processes[7, 8]. The reservoir permeability, the porosity and the storage capacity, which are reservoir key parameters, can then be highly compromised due to $CO_2$-rock interactions. Consequently, the effects of $CO_2$ injection on fracture aperture must be evaluated with respect to the possibility of induced injectivity losses.

Considerable research on the $CO_2$ geo-sequestration has been done worldwide. Most of the studies focused on the modeling and simulation of the caprock integrity and the possibilities of rock failure and leakage[9-11]. Rutqvist and Stephanson[10] provides a comprehensive overview of models used for hydromechanical coupling at an aquifer level, and a number of well-known empirical approaches to changes in the normal stress across fractured structure. Coupled thermo-hydro-mechanical models with the ability to characterize groundwater flow behavior in fractured aquifers containing thermal sources have been done[12-14]. Additionally, more of the thermo-hydro-mechanical research available are dedicated to the characterization of geothermal reservoirs[15-21]. Some of these studies, with adjustment may be adapted to the geo-sequestration environment. However, this should be done carefully considering the difference in chemical and physical behavior of fluids.

The characterization of fracture aperture variation during $CO_2$ injection has not yet been thoroughly studied. It is believe that the holdback is because of the lack of detailed understanding of the thermo-hydro-mechanical behavior of the sequestration environment and $CO_2$ phase change. During $CO_2$ injection, as a consequence of local or regional cooling, temperature fluctuation can be expected, which in turn may leads to substantial amounts of stress energy release as in the case for underground waste disposal[22]. It can be anticipated that the overall response of the fracture is determined by $CO_2$-rock interaction, $CO_2$ physical characteristics such as density, viscosity, heat capacity, and temperature. According to McDermott[23], within the solid medium, factor such as the elastic response of the structure and in-situ conditions including overburden stress, temperature and pressure play a critical role. The objective of this model is to provide more insight into the key processes determining the closure of a fracture by isolating and quantifying different components contributing to the changes. The result can serve as an input for numerical models linking the effects of changes to the flow and transport parameters of a fractured system.

## 2.

### 2.1. The Physical System and its Governing Equations

In general, modeling the dynamic of the geosequestration environment requires reduction of an extremely complex system to an ideal one, base on simple principles such as the dual porosity concept. Such an idealized approach has already been used for geothermal reservoir characterization[20]. The conceptual model corresponding to an idealized parallel-plate system illustrating a fracture-matrix coupled system is represented in Fig1. A plane strain approximation is used to treat a horizontal section of a vertical fracture. It is assumed that heat flow and fluid loss are one-dimensional occurring perpendicular to the fracture wall (in the y-direction). Also in the approach, we assume the rock displacement resulting from thermoelastic and poroelastic loads is zero in the x-direction (parallel to the fracture). More importantly, the influence of rock matrix deformation on pore pressure is not included.

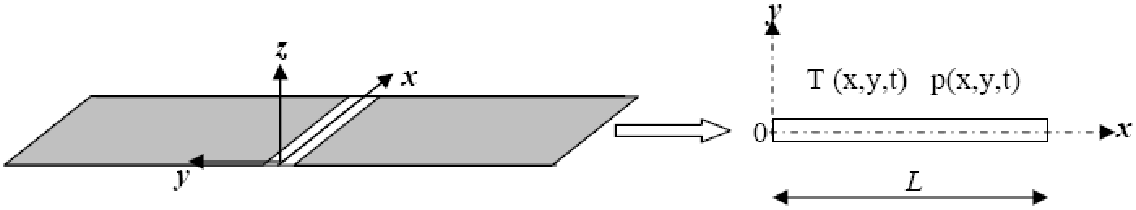

**Figure 1. Geometry for the mathematical model**

***Fluid flow equations***

The flow in a fracture is a result of the applied pressure gradient. Fox and McDonald[24], assuming the lubrication flow theory, described the flow in fracture by:

$$\frac{\partial p^*(x,0,t)}{\partial x} = -\frac{12\mu_f}{w^3(x,t)} q(x,t) \tag{1}$$

Where $p^*$ is the effective pressure, induced in the fracture by injection ($p^* = p(x,0,t) - p_0$) with $p$ as the total pressure and $p_0$ as the initial reservoir pressure, $\mu_f$ is the fluid viscosity, $w$ is the fracture aperture, and $q$ is the flow rate per unit height.

The continuity equation is:

$$\frac{\partial q(x,t)}{\partial x} = -2q_S(x,t) \tag{2}$$

Where $q_S(x,t)$ is the storage or the leak-off velocity, which is multiplied by 2 to account for both fracture walls. The fluid flow in the reservoir due to the one-dimension leak-off is governed by the diffusion equation given as:

$$\frac{\partial^2 p^*(x,y,t)}{\partial y^2} = \frac{1}{C_D}\frac{\partial p^*(x,y,t)}{\partial t} \quad y \succ 0 \tag{3}$$

Where $c_D$ is the fluid diffusivity. The initial and boundary conditions for (1) and (3) are:

$$p^*(x,y,0) = 0 \qquad p^*(L,0,t) = 0 \qquad w(x,0) = w_0 \tag{4}$$

Equations (1), (3), and (4) form the solution system for solving the induced pressure in the fracture and rock.

***Heat flow equations***

Temperature differences drive the heat transfer between the injected fluid in the fracture and the reservoir matrix. The main mechanisms involved are thermal advection, thermal conduction and thermal dispersion within the fracture[25]. Neglecting heat storage and longitudinal dispersion, the heat transport in the fracture becomes[26]:

$$\rho_f c_f q(x,t) \frac{\partial T(x,0,t)}{\partial x} = 2K_r \frac{\partial T(x,y,t)}{\partial y}\Big|_{y=0} \tag{5}$$

Where $\rho_f$ the density of the injection fluid (CO2) is, $c_f$ is the specific heat capacity of the injection fluid, $K_r$ is the rock thermal conductivity (coal), and $T$ is the temperature. One-dimensional heat transport in the rock $(y \succ 0)$ is governed by:

$$\frac{K_r}{\rho_r c_r} \frac{\partial^2 T(x,y,t)}{\partial y^2} = \frac{\partial T(x,y,t)}{\partial t} + q_S(x,t) \frac{\partial T(x,y,t)}{\partial y} \tag{6}$$

The initial and boundary conditions for the system are:

$$T(x,y,0) = T_{r0} \quad T(0,0,t) = T_{f0} \tag{7}$$

Where $T_{r0}$ is the initial rock temperature and $T_{f0}$ is the injection fluid temperature at the injection point.

***Thermo- poroelastic equations***

In the presence of temperature change and poroelastic mechanisms, rock displacement can be described by the following form of the Navier equation:

$$G \nabla^2 \vec{u}(x,y,t) + \frac{G}{1-2\nu} \nabla\left[\nabla \vec{u}(x,y,t)\right] = 3K\alpha_t \nabla T(x,y,t) + \alpha \nabla p(x,y,t) \tag{8}$$

Where $G$ is the shear modulus, $u(x,y,t)$ is the displacement vector, $\nu$ is the Poisson's ratio, $K$ is the drained bulk modulus, $\alpha_T$ is the linear expansion coefficient, and $\alpha$ is Biot's effective stress. We assume that the thermally induced stress is one-dimensional and that rock contraction occurs by normal strain without any shear or horizontal strain. For this simplified approach, Eq. (8) reduces to:

$$\frac{\partial^2 u_y(x,y,t)}{\partial y^2} = \chi \frac{\partial T(x,y,t)}{\partial y} + \frac{\eta}{G} \frac{\partial p(x,y,t)}{\partial y} \tag{9}$$

Where $\chi = \frac{\alpha_T(1+\nu)}{1-\nu}$, $\eta = \frac{\alpha(1-2\nu)}{2(1-\nu)}$ and assuming $u_y\big|_{y=\infty} = 0$; and $w(x,t) = 2u_y(x,t)$

## 2.2. COMSOL Formulation

Generally, during sequestration operations, $CO_2$ is injected at the liquid state. As the fluid progress in depth, the combination of pressure and temperature gradients lead to the phase changes. A possible direct consequence is the variation of the structural properties of the host rock and its surroundings.

In this study, the mechanical behavior of rock sample is analyzed by means of hydro-mechanical and heat transfer equations. The geometry is simplified through specifying axial symmetry and modeling the phenomena in 2D. The geometry was represented by a 2-D axial symmetry with dimensions of 0.044 meter for the width and 0.22 meter for the height (Figure 2). Physical values for the system were obtained from the literature, or reasonably assumed, and applied to the system. The following physical phenomena are studied:

- Porous flow behavior including a temperature gradient driven contribution.
- Stress-strain behavior including thermal expansion effects and porous flow induced stress. The fundamental Navier's equation states a force equilibrium
- Heat conduction
- Coupling effects between the above mentioned phenomena.

In order to solve the problem using COMSOL Graphical User Interface, mathematical equations describing the problem have been adapted from the following modules:

- Structural mechanic: axial symmetry strain-stress
- Chemical engineering: momentum balance - Darcy law;
- Multiphysics module: Heat transfer by conduction

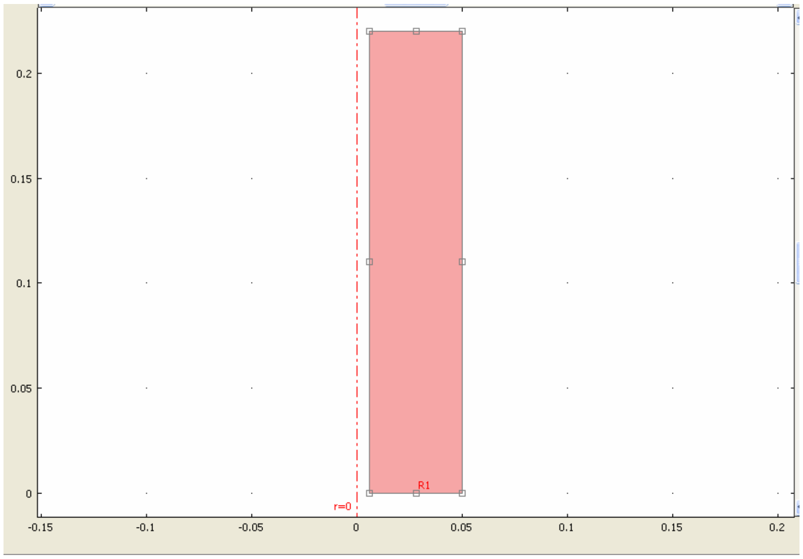

**Figure 2: A geometry modeling in 2D axial symmetry**

## 2.3. Numerical solution

The effects of stress and heat transfer on the structure are represented on the Figures 3, and 4 respectively. Coupling effects are represented on Figure 5. It appear that the host rock swells with gas flow; the extent of the changes is influenced by gas pressure, temperature and in-situ stress (see Figure 5). Volumetric changes are attributed to both rock matrix change and the changes in cleats, fissures and other fractures in the structure.

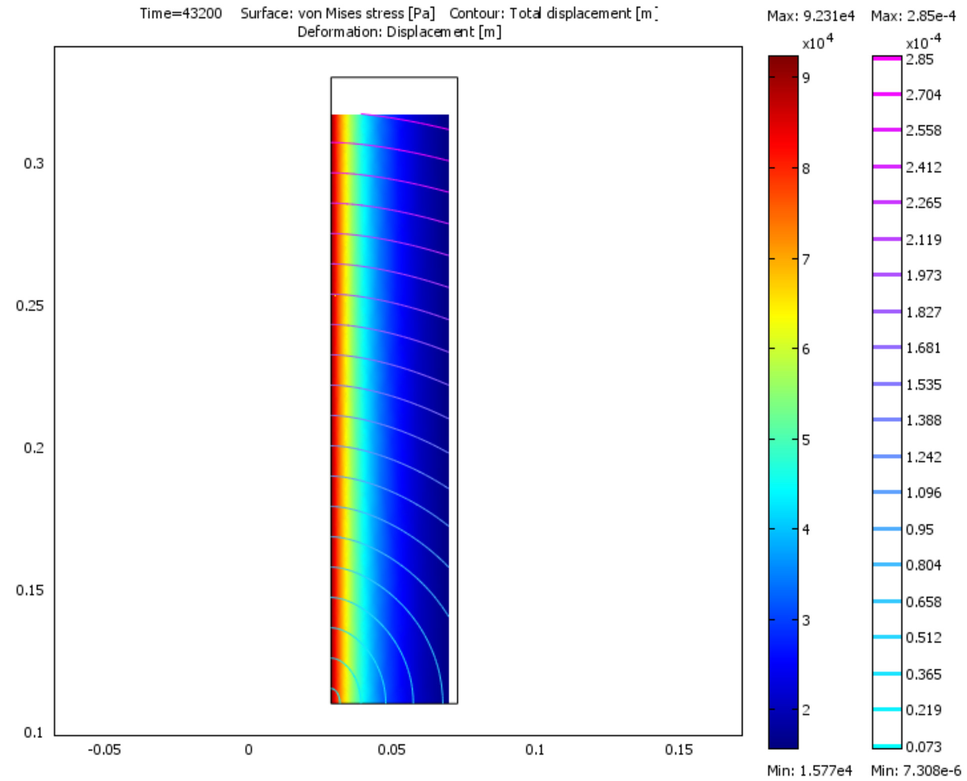

**Figure 3: Effect of stresses on the rock structure**

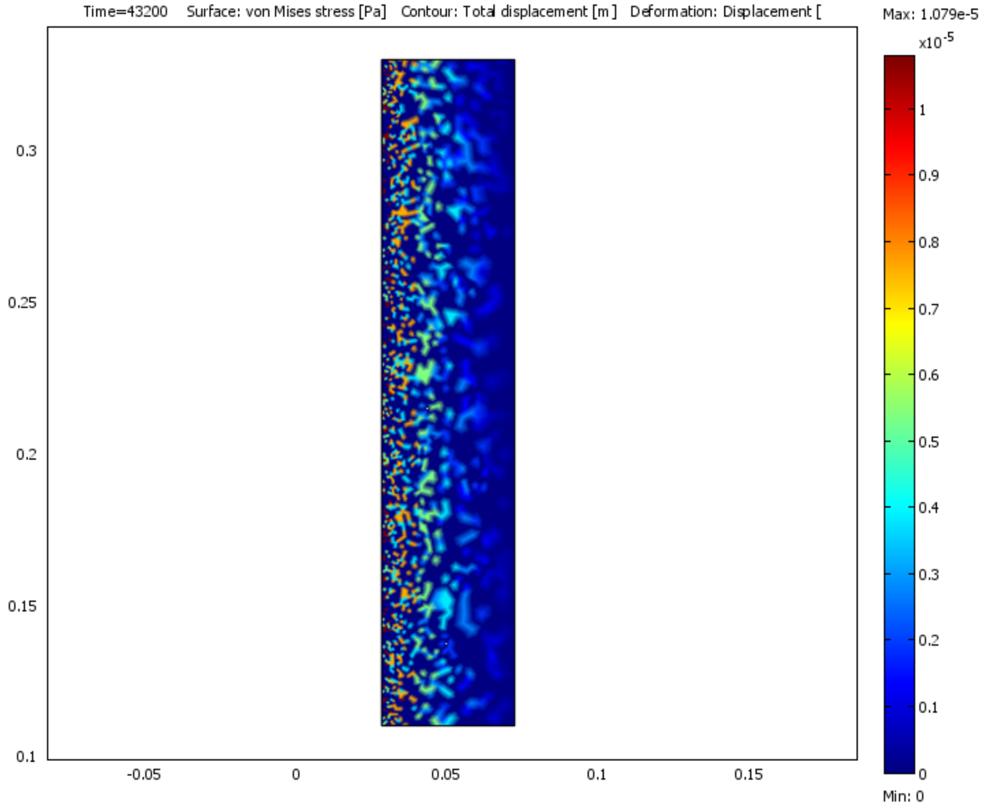

**Figure 4: Effect of temperature on the rock structure**

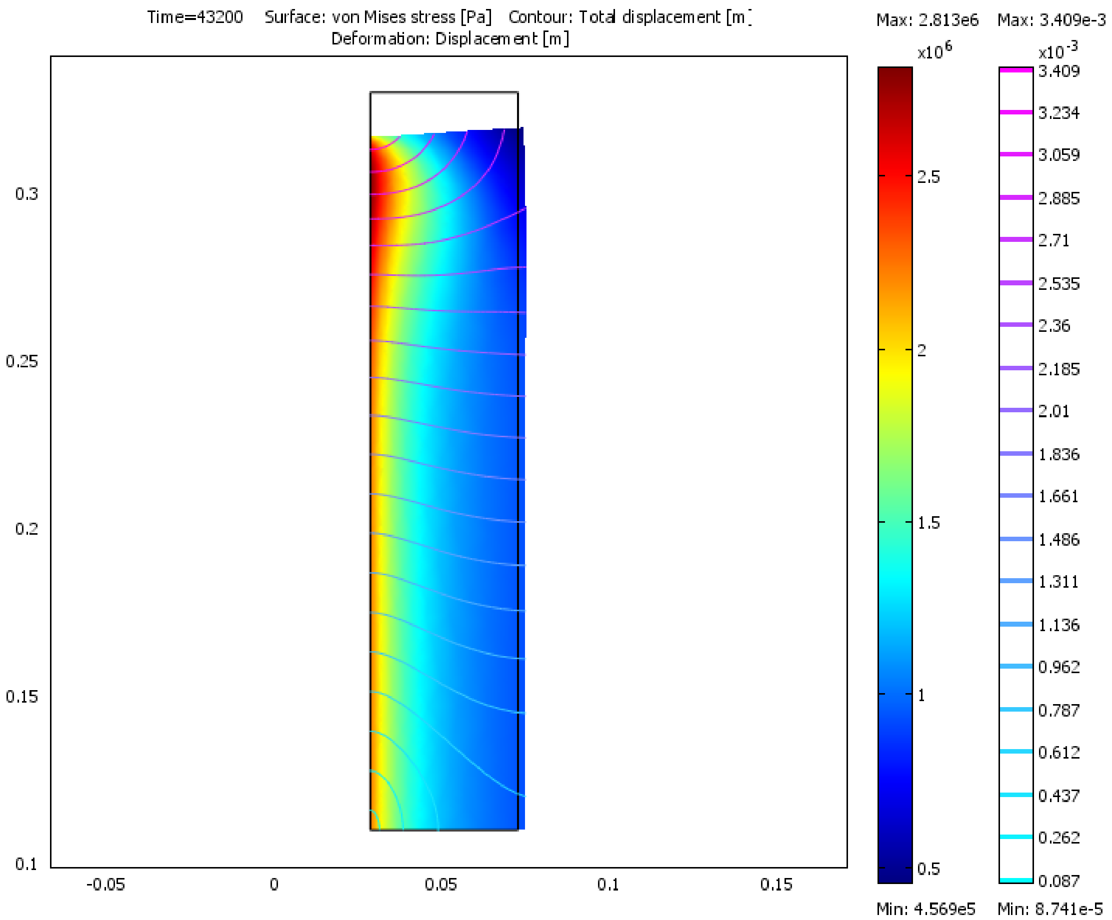

**Figure 5: Combined stress, thermal and flow effects on the rock structure**

## 3. Model Validation

To validate the current model, data from Nygen[27] was used. To indicate the effects of flow-stresses interaction on the rock structur[27]e, total displacement was chosen to be the variable for the validation work. Nygen presented (Figure 6-a) a distribution of normalized fracture width for combined thermo-elastic and poro-elastic effects at various times. This is the result of the fracture closure associated with interactions. Figure 6-b shows the calculated displacement with time from COMSOL along the structure. It can then be noted that, the calculated results exhibits similar trend with Nygen's data. Therefore, the current model provides valid results.

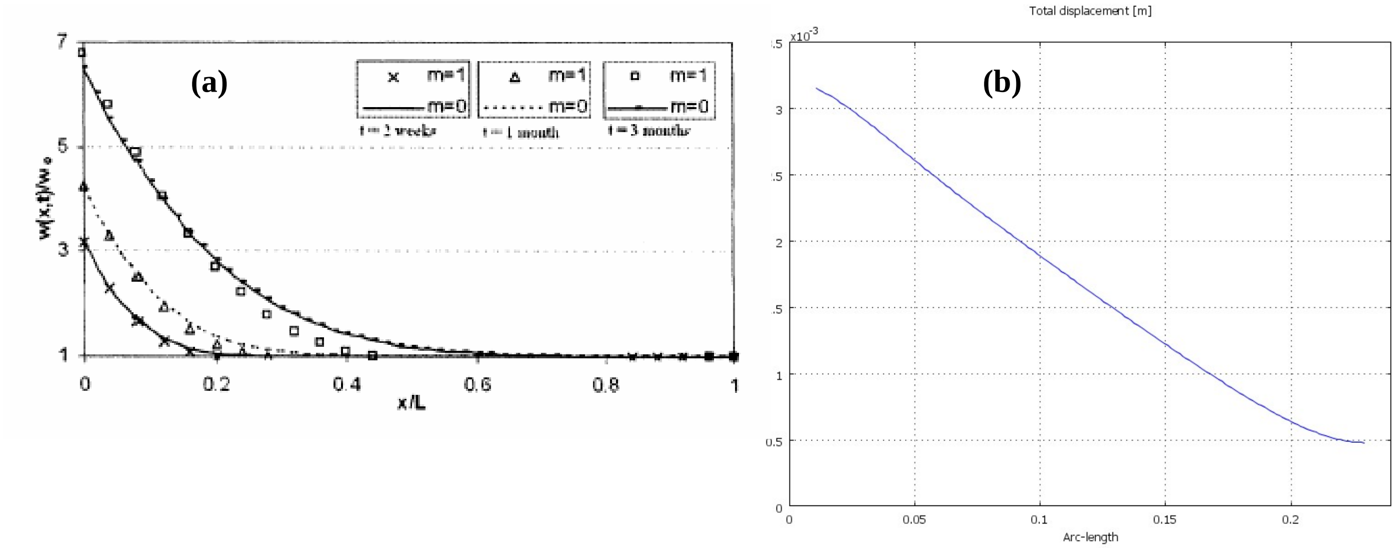

**Figure 6: (a)** Distribution of normalized fracture width for combined thermo-elastic and poro-elastic effects at various times[27]. **(b)** Total displacement along the structure model with COMSOL

To further the validation, it is important to change the mechanical characteristic of the used rock for the current model. Unfortunately, changing the Poisson ratio from 0.33 to 0.5 resulted to the instability of the model. Thus, at this point, we cannot state that the current model is completely valid. However, we should mention that the model provided the expected behavior from the structure under THM influences.

## 4. Parametric Study

To analyze the sensitivity of the model, we vary the initial fluid and host rock temperature. Assuming that the interaction of fluid and rock will bring the temperature of the system (rock + fluid) to around 273 K, the output displayed a physical contraction of the system responding to the freezing of the system (Figure 7).

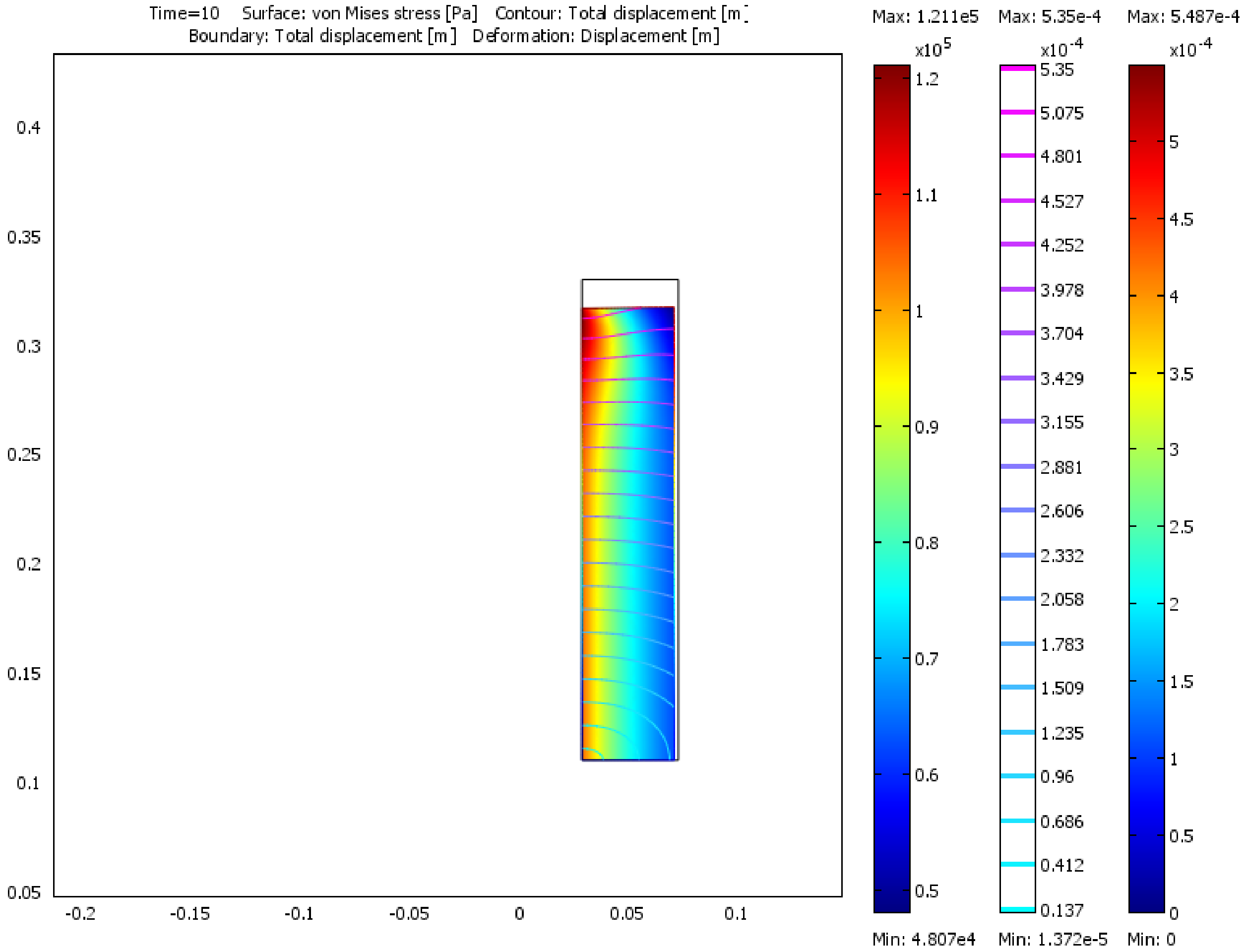

**Figure 7:** Behavior of the rock-fluid interaction and freezing temperature

## 5. Conclusions

Understanding and prediction of rock structure behavior is a critical issue for geological extraction or storage. The model developed for this study qualitatively described the behavior of the rock due to THM interactions as expected. Our results are qualitatively similar to Nygren[27] work. However, we should stress that, most of the physical parameters used in this study, although realistic, were chosen arbitrary. It is important to use specific rock parameter in order to access the stability of the model.

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