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SIMULATION OF GEOMECHANICAL EFFECTS OF CO2 INJECTION IN COLD AQUIFERS WITH POSSIBILITY OF HYDRATE FORMATION

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ABSTRACT

The injection of CO_2 in saline aquifers can have a significant impact on the geochemistry and the geo-mechanics of the reservoirs. Due to this injection, minerals will dissociate in regions with low pH or precipitate in regions with high pH, which imply changes on the stability of the reservoir. Some of the reservoirs in North Sea, and in the Barents Sea, have very low seafloor temperatures. In addition to mineral reactions, CO_2 hydrate formation is also a potential local effect with impact on porosity, permeability and geo-mechanics. In this paper, the geological storage of CO_2 in saline aquifers is studied. A 2D hydro-chemical mechanical model is created which has 3 layers (2 layers with aquifers and 1 layer with cap rock on which two fractures are introduced). A reactive transport reservoir simulator RetrasoCodeBright (RCB) has been used to simulate the storage of CO_2 in this model. Hydrate formation possibility is included in the model. For this purpose hydrate has been added as a pseudo-mineral component and the hydrate phase transition dynamics have been implemented into RetrasoCodeBright. Corrections for effects of porosity changes on permeability are included but so far based on traditional correlations for mineral/fluid. In other parts of the project, these correlations will be reworked for the special case of "hydrate mineral". In both cases, we focus on the implications of the dissociation or precipitation of minerals as well as hydrate formation or dissociation (according to the value of pH) on geo-mechanical properties of the reservoir.

Keywords: geomechanics, CO2 storage, CO2 Hydrate, RetrasoCodeBright.

NOMENCLATURE

E Young's modulus [GPa]
k_0 Zero stress permeability [m2]
P Pore pressure [bar]
P_0 Van Genuchten's gas-entry pressure (at zero stress) [MPa]
Pg Gas pressure [bar]
Pl Liquid pressure [bar]
S_{rg} Irreducible gas and liquid saturation
T Temperature [C]
u Deformation [m]
δ Kronecker symbol
σ Stress [bar]
Φ_0 Zero stress porosity

INTRODUCTION

There has been an increasing interest in studying CO2 storage in saline aquifers during the last decade due to environmental threats of carbon dioxide. The natural CO2 cycling system is not capable of absorbing the current rate of CO2 emissions into the atmosphere, which along with other greenhouse gases will result in global temperature increase. Several functioning sequestration projects are currently running throughout the world such as Sleipner in the North Sea as the oldest project, Snohvit in the Barnet Sea, The Weyburn-Midale CO2 Project in Canada

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considered as the biggest project and In Salah project in Algeria [1]. There are also some others, which will start in the near future in different countries. Saline aquifers are considered as suitable geological formations for CO2 storage and are studied continuously. It is very important that sufficient investigations be performed to insure the sustainability of the process. For this purpose, reservoir simulators have been employed to study CO2 storage in the reservoirs. Beside the multiphase flow and heat transport in porous media which is carried out in reservoir simulators it is important to consider geomechanical modeling also to study the resistance of geological formation against high-pressure conditions of CO2 injection and the possibility of leakage in long terms. The most common approach is to couple a reactive flow simulator to a geo mechanical software in an explicit fashion in order to obtain the necessary stress information for the analysis of geo mechanical stability. Some responses to CO2 injection are fast, like for instance dissolution of carbonates in the low pH region close to injection. In reservoirs containing regions of hydrate formations the responses from hydrate phase transitions are even faster and can be on a scale of seconds. It is therefore unverified whether an explicit scheme with time shifts between evaluation of flow and evaluation of geo mechanical consequences is adequate.

According to these conditions, it is desirable to develop a reservoir simulator with an implicit coupling between reactive flow and the geo-mechanical analysis [2]. In the work presented here, code RCB (RetrasoCodeBright) has been chosen as the software platform. RCB is the result of coupling two codes: CodeBright and Retraso. CodeBright (COupled DEformation of BRIne Gas and Heat Transport) was designed for the thermo-hydraulicmechanical analysis of three-dimensional multiphase saline media [3]. In other words, CodeBright permits the modeling of deformation, mechanical processes in implicit solution of multiphase mass and heat transport. Retraso (REactive TRAnsport of SOlutes) is a code for solving reactive transport problems [4]. The design of implicit coupling between Retraso and CodeBright makes the code RCB perfect for CO2 injection calculations. Formed hydrate will not be in equilibrium but competing phase transitions of formation and dissociation can be defined as pseudo reactions and as such, the reaction kinetics of competing phase transitions will be handled in similar fashion as competing reactions. This also provides the inherent couplings between geomechanical reactions which involve CO2 and hydrate.

Basically in one time step, which is pre-described by user, CodeBright module first calculates the flow properties, heat transport and geomechanical deformation, then copy all the variables including independent variables, meaning liquid pressure (P_l), gas pressure (P_g), temperature (T) and deformation (u), and dependent variables, like flux of liquid, flux of gas, hydraulic saturation, porosity that will be solved in reactive transport calculations to Retraso module.

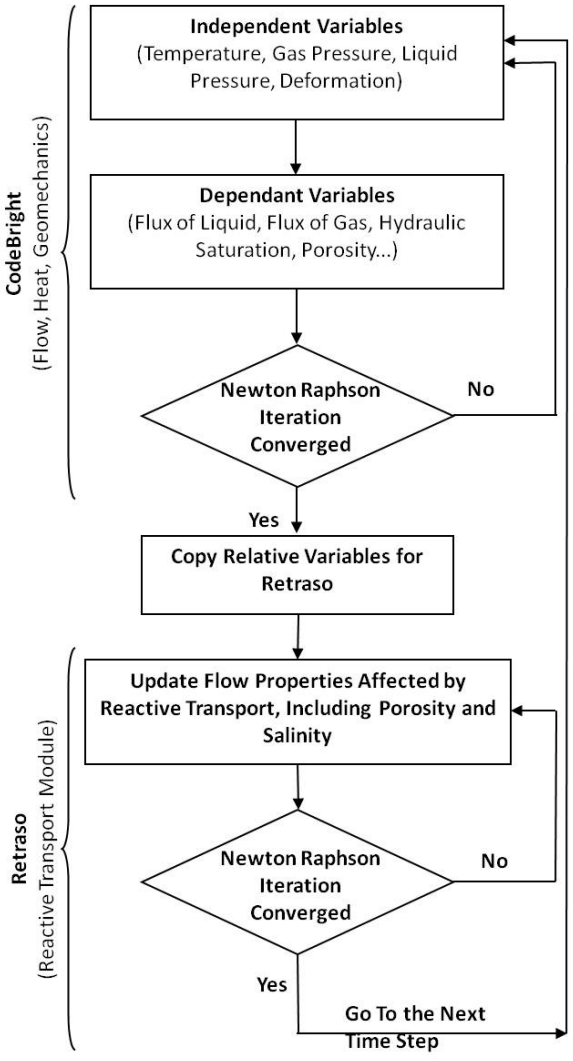

Figure 1. RCB solves the integrated equations sequentially in one time step

Retraso module updates all the flow properties by solving the matrix of concentrations of primary

species and secondary species. When calculations in Retraso part are successfully finished, Retraso module passes all the variables that have been taken part in chemical calculation to CodeBright module to get ready for the next time step. By now the calculations for one time step is completely finished. Both CodeBright module and Retraso module adopt Newton-Raphson iteration method to solve the matrices made up of the governing equations, which will be elaborated later. Figure 1 illustrates this process schematically.

To study geomechanics of the system, effective stress calculation has been implemented into RCB according to Terzaghi's Principle [5]. According to this principle, effective stress controls the mechanical failure of rock and is defined as:

$$\sigma'_{ij} = \sigma_{ij} - P\delta_{ij} \quad (1)$$

Where σ' *is* effective stress, σ is total stress, P is pore pressue and δ is Kronecker symbol ($\delta_{ij} = 0$ if $i \neq j$ and $\delta_{ij} = 1$ if $i = j$).

According to this definition, a tensile fracture will happen if the minimal effective stress is negative and its absolute value is greater than tensile strength of the formation [6].

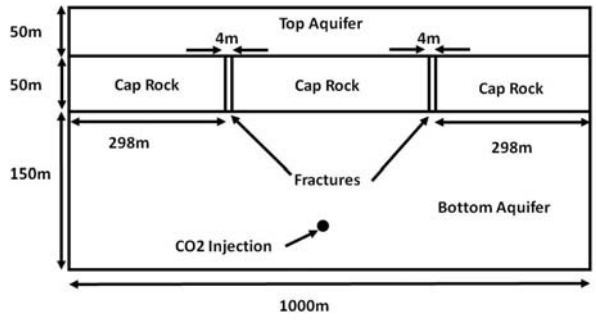

Figure 2. Schematic of the model

Model description

We study the hydro mechanical changes associated with CO2-injection into a brine formation. The geometry of the 2D domain is 1000 m x 250 m rectangle. There are 2 aquifers, 3 cap-rocks and 2 fracture zones in this geometry. The areas in the bottom and top are aquifers. Bottom Aquifer is a 1000 m x 150 m rectangle and top aquifer is 1000 m x 50 m rectangle. The three zones between two aquifers are cap-rocks with dimensions of 298 m x 50 m in both sides and 396 m x 50 in the middle. There are two thin fractures zones, one between left and middle side cap rocks, second between middle and right side cap rocks. These fractures have dimensions 4 m x 50 m each. CO2 is injected at 50 meter height from the bottom in the bottom aquifer as shown in the Figure 2.

Aquifers	**Cap rock and fractures**
Ca+2	Ca+2
H2O	H2O
HCO3-	HCO3-
H+	H+
SiO2(aq)	SiO2(aq)
CaCO3(aq)	CaCO3(aq)
CaH2SiO4(aq)	CaH2SiO4(aq)
CaHCO3+	CaHCO3+
CaOH+	CaOH+
CO2(aq)	CO2(aq)
CO3-2	CO3-2
OH-	OH-
H2SiO4-2	H2SiO4-2
HSiO3-	HSiO3-

Table 1. chemical species (primary and secondary aqueous species) in different formations

	Mineral volume fraction with 11.1% calcite [m3/m3]	**Mineral reactive surface with 11.1% calcite, [m2/m3]**
Aquifers; 10% porosity	Calcite (0.1) Quartz (0.8)	Calcite (100) Quartz (800)
Cap rock; 1% porosity	Calcite (0.1) Quartz (0.89)	Calcite (100) Quartz (890)
Fractures; 5% porosity	Calcite (0.1) Quartz (0.85)	Calcite (100) Quartz (850)

Table 2. Initial composition of minerals

Composition of rocks in each zone is as follows; Aquifers have a porosity of 0.1 and among minerals it has 10% calcite, 80% quartz. Pressure and temperature at each node are defined in one of the input files. In reservoir, pressure gradient is 1.0 MPa/100m and temperature gradient is 3.6 °C/100m. CO2 Injection pressure is 4.6 MPa. Pressure boundaries are also defined at top and bottom of the reservoir. At the top 2.5 MPa and at the bottom 5 MPa pressure boundaries enclose the reservoir.

Zone	Aquifers	Cap rocks	Fractures
Permeability (m^2)	1e-13	1e-17	1e-12
Longitude dispersion factor (*m*)	11	11	11
Molecular diffusion (*m*)	1e-10	1e-10	1e-10

Table 3. Permeability, dispersion and molecular diffusion

Property	Aquifers	Cap rocks	Fractures
Young's modulus, E [GPa]	0.3	0.3	0.3
Poisson's ratio	0.2	0.2	0.2
Porosity	0.1	0.01	0.05
Zero stress porosity, Φ_0	0.1	0.01	0.05
Zero stress permeability, k_0 [m2]	1.0e-13	1.0e-17	1.0e-12
Irreducible gas and liquid saturation, S_{rg}	0	0	0
Van Genuchten's gas-entry pressure, P_0 [MPa], (at zero stress)	0.0196	0.196	0.196
Van Genuchten's exponent [m]	0.457	0.457	0.457

Table 4. Material properties

Pressure boundaries are also defined at top and bottom of the reservoir. At the top 2.5 MPa and at the bottom 5 MPa pressure boundaries enclose the reservoir.The initial stresses are given in absolute values in a range from 5.67 MPa on upper boundary to 11 MPa on the bottom boundary. The summary of this model and properties are presented in tables 1 to 5.

Parameter	Bottom Boundary	Top Boundary
Pressure, P(MPa)	5	2.5
Mean Stress, σ(MPa)	11	5.67
CO2 initial injection pressure, P_g (MPa)	4.6*	-
CO2 final injection pressure, P_g (MPa)	4.6*	-
Gas and liquid outgoing pressure (MPa)	5	2.5

* at the injection point

Table 5. Initial and boundary conditions

Results and discussion

Simulation results for different time steps are presented in this section. Liquid and gas phase fluxes, porosity and effective stress are the parameters of interest in this study. Each figure shows the results at three time steps: Results for starting day at the top, results after 280 days at the middle and results after 563 days at the bottom, which for effective stress figure it is 320 days.

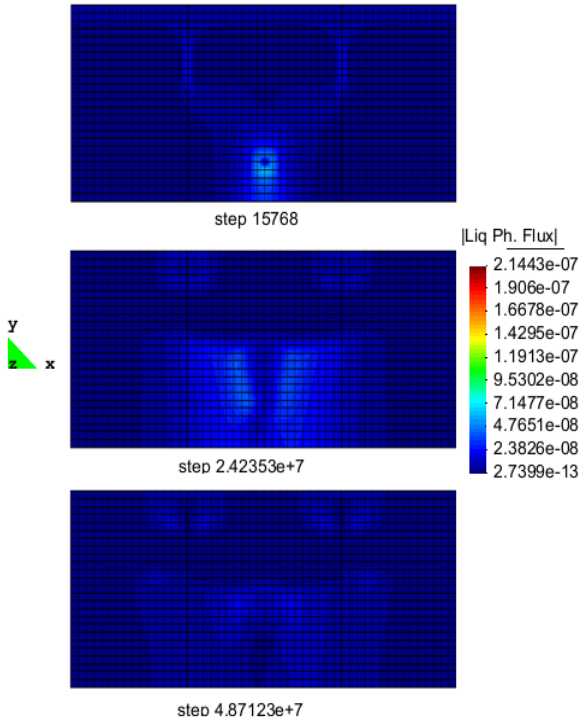

Figure 3. Liquid phase flux(m/s) at starting day (top), after 280 days (middle) and 563 days (bottom).

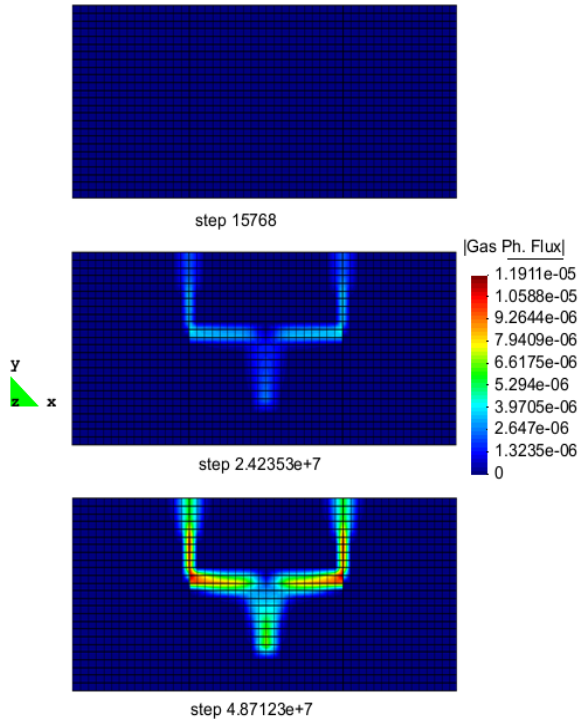

Figure 4. Liquid phase flux (m/s) at starting day (top), after 280 days (middle) and 563 days (bottom).

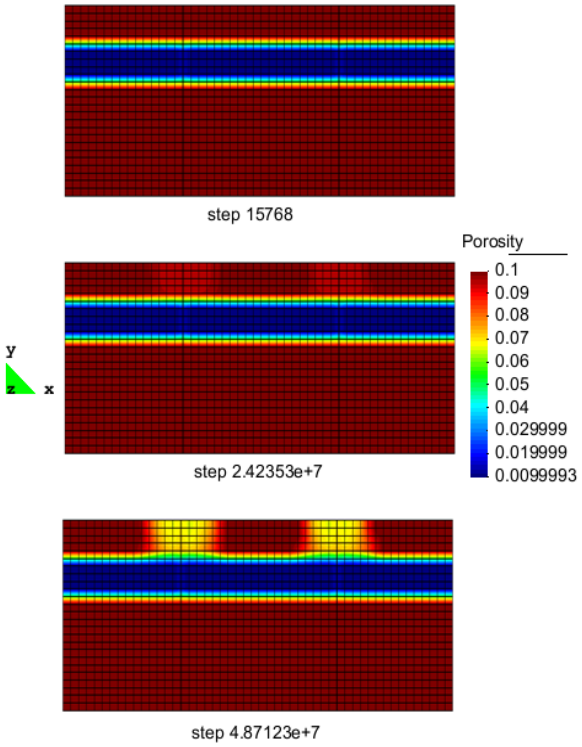

Figure 5. Porosity changes at starting day (top), after 280 days (middle) and 563 days (bottom).

Figure 3 and 4 shows the liquid and gas phase fluxes respectively. These figures clearly show that because of the fractures flow will reach the upper aquifer in a relatively short time. As soon as CO2 reaches the top aquifer, it will start forming hydrate due to suitable temperature and pressure conditions as shown in figure 5.

Figure 6 shows the effective stress in yy direction in the reservoir. According to this figure, minimum effective stress is -4.9074 MPa. A comparison between tensile strength of sand stone in the literature [7] and the minimum effective stress in this simulation suggests that it might be in the range of tensile strength for similar material.

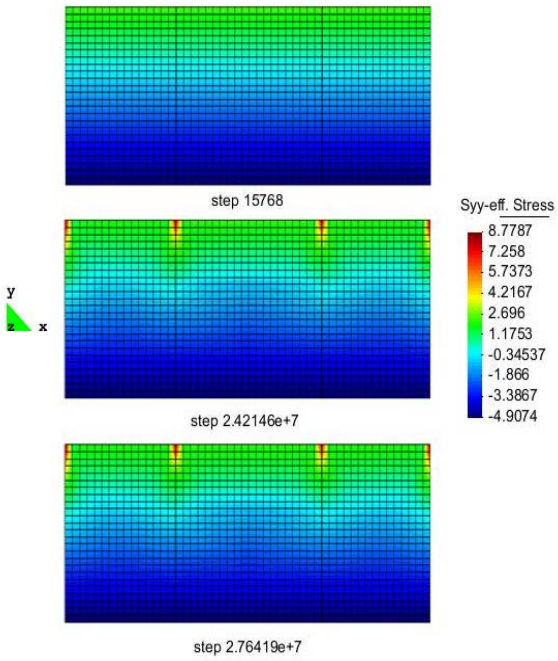

Figure 6. Effective stress at starting day (top), after 280 days (middle) and 320 days (bottom).

Conclusion

A reactive transport simulator has been modified to account for hydrate phase transition in the reservoir. The phase transitions are handled as pseudo reactions to ensure the logistics of competing phase transitions in a non-equilibrium system. It also logically and automatically links the couplings between chemical reactions that consumes or releases CO2. Due to implicit calculation of geomechanics along with flow equations it is possible to study the effects of hydrate formation and dissociation on geomechanics of the reservoir in the same time step as transport calculations are done. This allows

for geo mechanical analysis in every elements of the reservoir for every time step during the simulation. The extended RetrasoCodeBright have been applied to a simplified example with a cap rock penetrated by two fractures and a top section in hydrate stability zone. As expected the hydrate grows outward from the fractures and results in increased stress out from the fractures and towards the top of the formation.

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- FME-SUCCESS, project number: 804831.
- PETROMAKS, "CO2 injection for extra production", Research Council of Norway, project number: 801445.

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