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Coupled Thermal-Hydrodynamic-Mechanical-Chemical (THMC) Processes for CO_2 Geological Sequestration in Deep Saline Aquifers

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Injecting CO_2 into deep saline aquifers is considered as a promising method to reduce the emissions of anthropogenic CO_2 to Earth's atmosphere, which is referred to as CO_2 geological sequestration (CGS). CGS involves coupled thermal-hydrodynamic-mechanical-chemical (THMC) processes, which are important for predicting migration and transformation of injected CO_2, evaluating the reservoir performance, and assessing the risk associated. Based on the Terzaghi consolidation theory, a coupled mechanical module is developed and is incorporated into the existing simulator TOUGHREACT, which is a well-established code for THC processes in subsurface flow systems. We have performed numerical simulations of the coupled THMC processes during and after the CO_2 injection period using the modified simulation tool. Geological and geochemical conditions from the Orods CCS demonstration project are utilized.

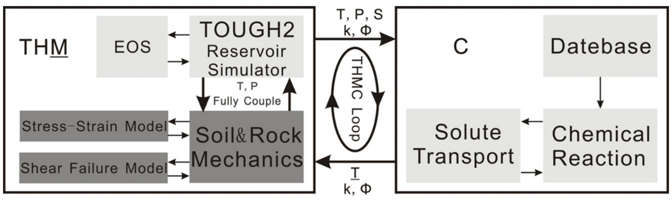

Fig. 1 Approach for coupled THMC processes

The effects caused by variations in temperature, pressure, stress and strain, and rock chemistry have been investigated. The migration and transformation of CO_2 between different forms, effects of injection on reservoir porosity and permeability due to change in temperature and stress and water-rock-gas interaction, and its feedback to injection are analyzed. The results show that pressures increase in the system with more at the top of reservoir resulting from gravity-driven accumulation of CO_2 along the top of reservoir. The maximum pressure occurs in the vicinity of injection well after a few years' injection. The increase in pressure leads to decrease in effective stress, which alters the reservoir porosity and permeability. This stress-dependent permeability changes have a positive effect on the CO_2 injection because it's favorable for pressure dissipation. The reduction in effective stress also would induce possible rock shear-slip failure in the lower part of the caprock. The mechanical effect reduces after the injection period because the CO_2 spread and dissolution into formation water makes the pressure buildup decrease. However, the effect of water-rock interaction on CGS begins to increase with time. Gas trapping decreases, but solubility trapping and mineral trapping increase. The mineral trapping is sensitive to the primary minerals which contain significant Ca, Mg, and

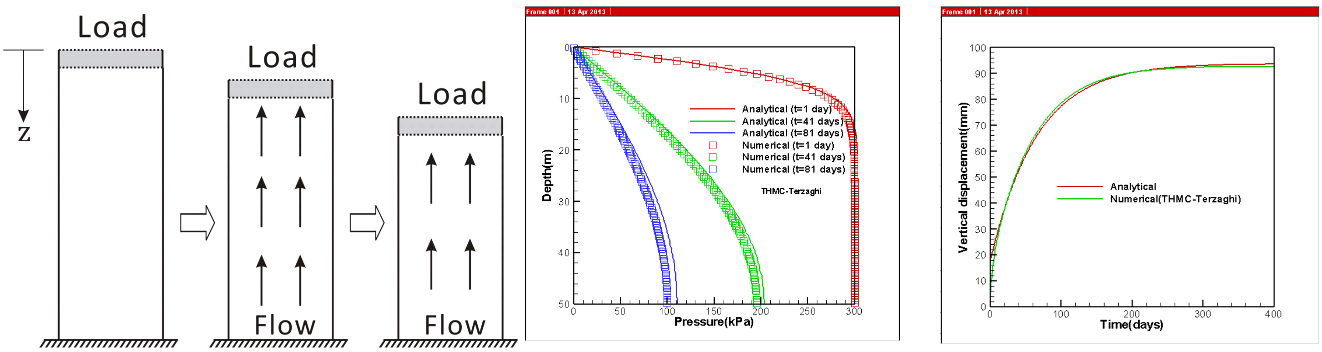

Fig. 2 Conceptual model and results comparison for one-dimension consolidation (a) Pressure (b) Displacement

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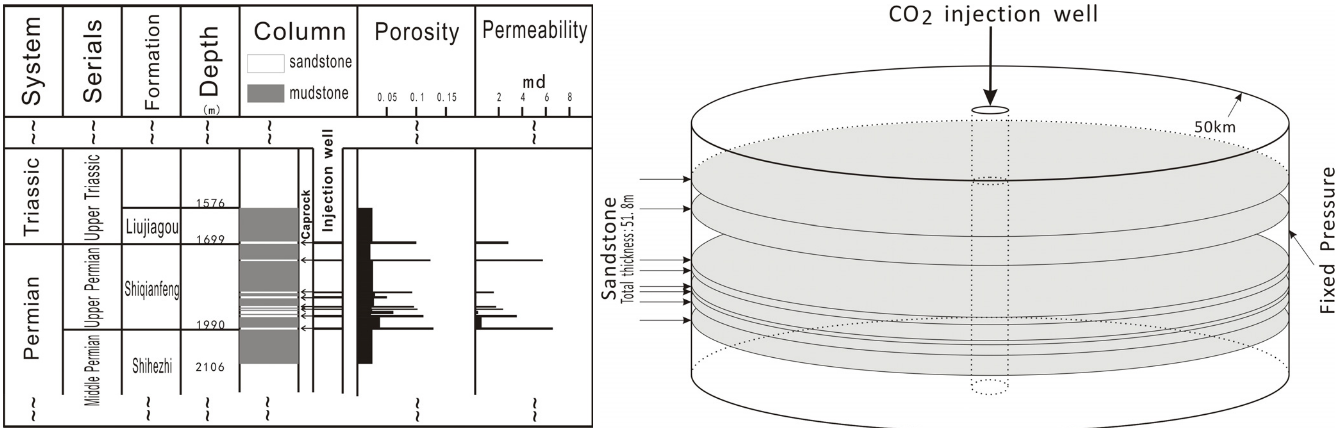

Fig. 3 Characteristic of Shiqianfeng–Liujiagou reservoir-caprock formations and conceptual model for THMC processes (a) Shiqianfeng-Liujiagou reservoir-caprock formations (b) Conceptual model for THMC processes

Table1. **Governing equations for THMC coupled processes**

Description	Main Equations
Multiphase Fluid and Heat Flow (TH)	$\frac{d}{dt}\int_{V_n} M^{\kappa} dV = \int_{\Gamma_n} \mathbf{F}^{\kappa} \bullet \mathbf{n} d\Gamma + \int_{V_n} q^{\kappa} dV$ Left-Hand: $M^{\kappa} = \sum_{\beta=A,G} \phi S_{\beta} \rho_{\beta} X_{\beta}^{\kappa}, \quad \kappa = w, i, g$ $M^{\kappa+1} = (1-\phi)\rho_R C_R T + \sum_{\beta=A,G} \phi S_{\beta} \rho_{\beta} u_{\beta}$ Right-Hand: $\mathbf{F}_{\beta}^{\kappa} = -k \frac{k_{r\beta}\rho_A}{\mu_{\beta}} X_{\beta}^{\kappa}(\nabla P_{\beta} - \rho_{\beta}\mathbf{g}) + \mathbf{J}_{\beta}^{\kappa}, \quad \kappa = w, i, g \quad \mathbf{F}_{\beta}^{\kappa+1} = -\lambda \nabla T + \sum_{\beta} h_{\beta} F_{\beta}$
Mechanics (M)	Change in Effective Stress: $\Delta\sigma_x' = \Delta\sigma_y' = -\frac{v}{1-v}\alpha_P \Delta P + \frac{3K(1-2v)}{1+v}\alpha_T \Delta T$ $\Delta\sigma_z' = -\alpha_p \Delta P$ Change in Average Effective Stress: $\Delta\sigma_M' = \frac{1}{3}\frac{(1+v)}{(1-v)}\alpha_P \Delta P - \frac{2K(1-2v)}{(1+v)}\alpha_T \Delta T$ Vertical Strain: $\varepsilon_z = -\frac{1+v}{1-v}\alpha_T \Delta T - \alpha_P \Delta P \frac{(1+v)}{3K(1-v)}$
Solute Transportation (C)	$\frac{d}{dt}\int_{V_n} M^{\kappa} dV = \int_{\Gamma_n} \mathbf{F}^{\kappa} \bullet \mathbf{n} d\Gamma + \int_{V_n} q^{\kappa} dV$ Left-Hand: $M_j = \phi S_1 C_{j1}$ Right-Hand: $F_j = u_1 C_{j1} - (\tau\phi S_1 D_1)\nabla c_{J1} \quad q_j = q_{j1} + q_{js} + q_{jg}$
Geochemical Reaction (C)	1.Definition of geochemical system: $S_i = \sum_{j=1}^{N_c} v_{ij} S_j$ 2.Conservation of component: $T_j = c_j + \sum_{k=1}^{N_x} v_{kj} c_k + \sum_{m=1}^{N_p} v_{mj} c_m + \sum_{n=1}^{N_q} v_{nj}(c_n^0 - r_n \Delta t_r) = T_j^0$

Fe such as chlorite.

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Key words: Thermal-Hydrodynamic-Mechanical-

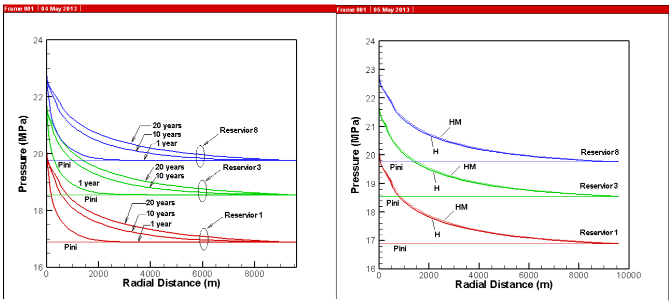

Fig. 4 Change in pressure induced by CO_2 injection

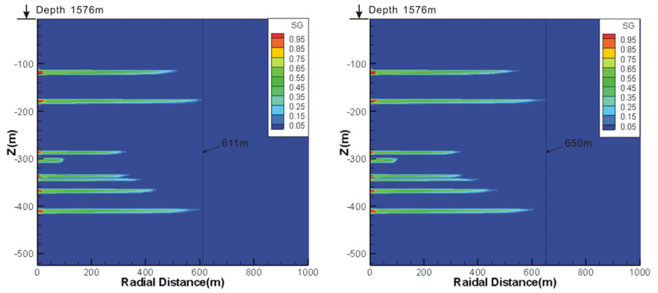

Fig. 5 Gas saturation after 20 years' CO_2 injection (a) Not considering Mechanical effect (b) Considering Mechanical effect

Chemical Processes, CO_2 Geological Sequestration, Numerical Simulation

References

Antonio, P.R., Rutqvist, J., 2013. Modeling of deep fracture zone opening and transient ground surface uplift at KB-502 CO_2 injection well, In Salah, Algeria. International Journal of Greenhouse Gas Control, 12: 155-167.

Cappa, F., Rutqvist, J., 2011. Modeling of coupled deformation and permeability evolution during fault reactivation induced by deep underground injection of CO_2. International Journal of Greenhouse Gas Control, 5: 336-346.

Feng, X., Pan, P., Ding, W., Hudson, J., Hui, Z., 2008. Thermo-Hydro-Mechano-Chemical coupling studies on excavation damage zone in crystalline rocks. Chinese Journal of Rock Mechanics and Engineering, 27(4): 654-663. (In Chinese)

Hou, Z., Gou, Y., Taron, J., Gorke, U.J., Kolditz, O., 2012. Thermo-hydro-mechanical modeling of carbon dioxide injection for enhanced gas-recovery (CO_2-EGR): a benchmarking study for code comparison. Environ Earth Sci, 67: 549-561.

IPCC (Intergovernmental Panel on Climate Change, 2005. Carbon Dioxide Capture and Storage[R], Cambridge University Press, UK and New York.

IPCC (Intergovernmental Panel on Climate Change). Climate change 2007[R], 2007.The physical science basis. Fourth assessment report. IPCC, Secretariat, Geneva, Switzerland.

Jing, L., Feng, X., 2003. Numerical modeling for coupled thermo-hydro-mechanical and chemical processes (THMC) of geological media-international and Chinese experiences. Chinese Journal of Rock Mechanics and Engineering, 22(10): 1704-1715.

Masakazu, C., Borgesson, L., Fujita, T., Jussila, P., Nguyen, S., Rutqvist, J., Jing, L., 2009. Model development and calibration for the coupled thermal, hydraulic and mechanical phenomena of the bentonite. Environ. Geol., 57: 1255-1261.

Olden, P., Pickup, G., Jin, M., Machay, E., Hamilton, S., Somerville, J., Todd, A., 2012. Use of rock mechanics laboratory data in geomechanical modeling to increase confidence in CO_2 geological storage. International Journal of Greenhouse Gas Control, 11: 304-315.

Pruess K, García J, Kovscek T, et al., 2004. Code intercomparison builds confidence in numerical simulation models for geological disposal of CO_2. Energy, 29: 1431- 1444.

Pruess K, Curt O, and George M.,1999. TOUGH2 USER'S GUIDE, VERSION 2.0[R]. Earth Science Division, Lawrence Berkeley National Laboratory, University of California, Berkeley.

Rutqvist, J., Wu, Y.S., Tsang, C.F., and et al., 2002. A modeling approach for analysis of coupled multiphase fluid flow, heat transfer, and deformation in fractured porous rock. International Journal of Rock Mechanics & Mining Sciences, 39: 429-442.

Rutqvist J, Tsang CF., 2002. A study of caprock hydromechanical changes associated with CO_2-injection into a brine formation. Environmental Geology, 42:296-305.

Rutqvist J, Birkholzer J, Cappa F, Tsang CF., 2007. Estimating maximum sustainable injection pressure during geological sequestration of CO_2 using coupled fluid flow and geomechanical fault-slip analysis. Energy Conversion and Management, 48:1798-1807.

Rutqvist J, 2011. Status of the TOUGH-FLAC simulator and recent applications related to coupled fluid and crustal deformations. Computers & Geosciences, 37:739-750.

Taron, J., Elsworth, D., Min, K.B., 2009. Numerical simulation of thermal-hydrologic-mechanical-chemical processes in deformable, fractured media. International Journal of Rock Mechanics & Mining Sciences, 46: 842-854.

Vilarrasa, V., Silva, O., Carrera, J., and Olivella, S., 2013. Liquid CO_2 injection for geological storage in deep saline aquifers. International Journal of Greenhouse Gas Control, 14: 84-96.

Wan YY. Migration and Transformation of CO_2 in CO_2 Geological Sequestration Process of Shiqianfeng Saline Aquifers in Orods Basin [D]. Changchun: Jilin University, 2012.

Wu, Y., Kazemi, H., Xu, T., and et al. Development of Advanced Thermal-hydrological-Mechanical-Chemical (THMC) Modeling Capabilities for Enhanced Geothermal Systems: Progress Report of Year 2. Colorado School of Mines, 2011.

Xu, T., Sonnenthal, E., Spycher, N., and et al., 2006. TOUGHREACT User's Guide: A Simulation Program for Non-isothermal Multiphase Reactive Geochemical Transport in Variably Saturated Geologic Media. Earth Science Division, Lawrence Berkeley National Laboratory, University of California, Berkeley.

Yin, S., Dusseault, M.B., Rothenburg, L., 2012. Coupled THMC modeling of CO_2 injection by finite element methods. Journal of Petroleum Science and Engineering, 80: 53-60.