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Thermo-poroelastic numerical modelling for enhanced geothermal system performance: Case study of the Groß Schönebeck reservoir

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ABSTRACT

Significant pressure and temperature changes can occur within geothermal reservoirs caused by injection and production of fluid which can affect transport properties of the rocks and therefore alter reservoir performance and sustainability. To understand the coupling between transport properties evolution and state variable changes, a complete description of the mechanical behavior of the reservoir is required which should consider thermo- and poroelastic effects. This study aims to integrate transport properties evolution for coupled thermo-hydro-mechanical (THM) process modelling of fluid-bearing reservoirs. This approach is here applied to the geothermal research site of Groß Schönebeck (40 km north of Berlin, Germany) which consists of a doublet system at a target depth of about −4100 m in which both injection and production wells have been hydraulically stimulated. A 3D reservoir model including the main geological units, major natural fault zones and hydraulic fractures is integrated in the finite-element method-based simulator OpenGeoSys for modelling coupled THM processes during geothermal activity. One challenge of this study is to integrate both hydro-geological and physical complexity to better describe the dynamic behavior of the geothermal reservoir. From the results of the simulation, thermal breakthrough is observed after 18 years of injection and life time of the system has been evaluated as 50 years. Furthermore, a 5.5% increase of porosity around the injection well is observed as well as an increase of the anisotropy ratio for permeability (k_z/k_{xy}) of about 2%. These transport properties enhancements lead to a decrease of the thermal breakthrough time (around −8%) and life time of the system (−14%) compared to classic thermo-hydro simulations with constant transport properties. The results presented here provide therefore valuable insights for understanding porosity and permeability distributions and evolutions during injection and production of geothermal fluids and related impacts on reservoir performance.

1. Introduction

Understanding processes controlling transport properties of saturated porous media is of interest for geothermal power production, energy storage or hydrocarbon exploration. Spatial and temporal variations of porosity and permeability can indeed control reservoir productivity and recovery (Walder and Nur, 1984; Raghavan and Chin, 2004; Blöcher et al., 2010; Cacace et al., 2013). Changes of pore pressure, temperature and stress distributions during injection or production of fluid can give rise to porosity and permeability alterations which can be effectively described based on the theories of poroelasticity and thermoelasticity (Fatt and Davis, 1952; Bernabe, 1986; Han and Dusseault, 2003). Correlations between pore pressure and temperature changes as those induced by injection of cold fluid and the in-situ stress field within a reservoir impose strong and non-linear couplings between thermo-hydro-mechanical physical processes (Terzaghi, 1943; Carrol and Katsube, 1983; Soltanzadeh et al., 2009). Quantification of these phenomena at the reservoir scale is difficult due to technical limitations of available methods and tools. Therefore, a common approach in the field of geomechanics is to conduct experiments in laboratory under simple and controlled reference conditions to observe and quantify the phenomena of interest. Based on these results, it is then possible to calibrate and implement these information into mathematical formulations to conduct numerical simulations at the reservoir scale.

In a previous study (Jacquey et al., 2015b), a detailed description of porosity evolution due to hydro-mechanical coupling has been introduced. The theory is based on a strong theoretical background for poroelasticity (Biot, 1956; Biot and Willis, 1957; Zimmerman, 1991). In this contribution, we describe an approach for coupled thermo-hydro-mechanical (THM) processes modelling. The mathematical

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formulations have been integrated in the open-source finite-element method-based software OpenGeoSys (Kolditz et al., 2012) following theory of coupled thermo-poroelasticity (Zimmerman, 2000; McTigue, 1986; Ghabezloo et al., 2008; Ghabezloo and Sulem, 2009). To validate the numerical implementation, in the first stage, the distribution of porosity around an injection well with simple geometry is analyzed and described. This serves as an introductory stage to the non-linear processes which are subsequently analyzed by means of a real case application for the geothermal research doublet of Groß Schönebeck (40 km north of Berlin, Germany).

This research platform, which has been the subject of several studies for the past 13 years (Huenges and Hurther, 2002; Holl et al., 2005; Legarth et al., 2005; Reinicke et al., 2005; Moeck et al., 2009b; Milsch et al., 2009; Zimmermann et al., 2009, 2010) provides a rich geological dataset to analyze the impacts of transport properties evolution models at the reservoir scale. The presence of stress-sensitive structures such as natural faults and induced fractures gives further insights on characterizing fluid flow and mechanical behavior in such a geological setting.

2. Numerical approach

2.1. Balance equations

Modelling coupled THM processes requires solving the governing equations for fluid-flow, heat transport and deformation of the porous medium. These governing equations are derived from balance equations for mass, energy and momentum. In this section the governing equations for THM modelling are presented as they are implemented in the software OpenGeoSys (Kolditz et al., 2012).

From the conservation of mass, flow in a porous medium is described by:

$$\frac{S_s}{\rho_f g}\frac{\partial p_f}{\partial t} + \nabla \cdot \mathbf{q_f} = Q_f \tag{1}$$

where S_s is the specific storage of the medium; ρ_f, the fluid density; p_f, the pore pressure; $\mathbf{q_f}$, the specific discharge and Q_f, a source/sink term. The specific discharge $\mathbf{q_f}$ can be expressed from the conservation of momentum as:

$$\mathbf{q_f} = -\frac{\mathbf{k}}{\mu_f}\left(\nabla p_f - \rho_f \mathbf{g}\right) \tag{2}$$

where $\mathbf{k}$ is the permeability tensor and μ the dynamic viscosity of the fluid. The equation governing heat transport is derived from heat balance under thermal equilibrium conditions between solid and fluid phase. Diffusive as well as advective heat transport processes are considered in saturated porous media:

$$(\rho c)_b \frac{\partial T}{\partial t} + (\rho c)_f \mathbf{q_f} \nabla T - \nabla \cdot (\lambda_b \nabla T) = Q_T \tag{3}$$

where ρc denotes heat storage (density times heat capacity); T, the temperature field; $\boldsymbol{q_f}$, the specific discharge; λ_b, the bulk thermal conductivity and Q_T, the heat source/sink term. Underscript b stands for bulk, f for fluid and s for solid with the following bulk mixing rule: $(\rho c)_b = \phi(\rho c)_f + (1-\phi)(\rho c)_s$.

Deformation of a fully saturated porous medium is described by the momentum balance equation which can be written in terms of effective stress as:

$$\nabla \cdot \left(\sigma' - \alpha p_f \mathbf{I}\right) + \rho_s \mathbf{g} = 0 \tag{4}$$

where σ' is the effective stress tensor, a main variable of the poroelastic theory here defined after Carrol and Katsube (1983) depending on the total Cauchy's stress tensor σ, the Biot's coefficient α and pore pressure p_f (note the sign convention of positive fluid pressure p_f but negative compressive normal stress for the solid):

$$\sigma' = \sigma + \alpha p_f \mathbf{I}. \tag{5}$$

The terms in Eq. (5) illustrate how deformation is coupled with the fluid flow. The primary variable solved for deformation of the porous medium is the displacement vector $\boldsymbol{u}$ which can be linked to the effective stress tensor σ' via the constitutive law for stress–strain behavior as follow:

$$\Delta\sigma' = \mathbb{C}\left(\Delta\varepsilon - \frac{1}{3}\beta_d \Delta T \mathbf{I}\right) \tag{6}$$

$$\epsilon = \frac{1}{2}\left(\nabla \boldsymbol{u} + (\nabla \boldsymbol{u})^T\right) \tag{7}$$

where $\mathbb{C}$ is the elastic material tensor; ϵ, the strain; β_d, the volumetric drained thermal expansion coefficient and ΔT, the temperature change. The subscript T means the transpose of the matrix. In this work, only isotropic elastic deformation is considered, though non-isothermal. Therefore, linear elasticity can be fully described via the generalized Hooke's law as:

$$\mathbb{C} = \lambda \delta_{ij}\delta_{kl} + 2\mu \delta_{ik}\delta_{jl} \tag{8}$$

where δ is the Kronecker delta; μ, the shear modulus and λ, the Lamé constant defined as $\lambda = \frac{2\mu\nu}{(1-2\nu)}$ with ν the Poisson's ratio. Eq. (6) can also be expressed in terms of elastic strain via the Hookes's law of linear elasticity extended to non-isothermal cases (Eqs. (9) to (11)):

$$\epsilon_{xx} = \frac{1}{E_d}\left(\sigma'_{xx} - \nu\left(\sigma'_{yy} + \sigma'_{zz}\right)\right) + \frac{1}{3}\beta_d \Delta T \tag{9}$$

$$\epsilon_{yy} = \frac{1}{E_d}\left(\sigma'_{yy} - \nu(\sigma'_{xx} + \sigma'_{zz})\right) + \frac{1}{3}\beta_d \Delta T \tag{10}$$

$$\epsilon_{zz} = \frac{1}{E_d}\left(\sigma'_{zz} - \nu\left(\sigma'_{xx} + \sigma'_{yy}\right)\right) + \frac{1}{3}\beta_d \Delta T \tag{11}$$

where E_d is the drained Young's modulus and ν, the Poisson's ratio. Eqs. (1) to (4) describe the governing equations for solving coupled THM processes as they are implemented in OpenGeoSys. Fluid flow, described by Eqs. (1) and (2), is therefore coupled with heat transport and deformation through dependent transport properties (porosity and permeability) and the dependent fluid properties (density and dynamic viscosity). In the next sections, the model for the modified Hooke's law used for mechanical behavior of porous medium as well as models for evolution of transport properties (porosity and permeability) is presented.

2.2. Mechanical behavior of porous media

The typical response of porous materials shows a non-linear stress–strain behavior at low effective stress (below 30 MPa) (Biot, 1973; Zimmerman, 1991; Blöcher et al., 2013. Therefore, Hooke's law (which follows a linear stress–strain relations) cannot be applied under these conditions. In this section, a model for stress-dependent material matrix is presented to reproduce numerically the typical non-linear stress–strain relation of porous media by making use of concepts derived from poroelasticity (Terzaghi, 1943; Biot, 1956, 1973) and crack closure theory (Morlier, 1971).

For a continuous non-porous material, applied stress only induces elastic changes of its volume. The latter can be described by one elastic modulus, the bulk modulus. In the context of deformation of a porous medium, effective stress and pore pressure can change, and both can induce changes in pore and bulk volumes (Zimmerman, 1991). Four