Coupled simulation of near-wellbore and reservoir models in Horstberg geothermal system

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Abstract

This study presents the simulation of transport phenomena in the Horstberg geothermal system in the North German Basin. The Horstberg geothermal system composed of a subsurface reservoir and a borehole. The borehole was completed in a multilayer sandstone reservoir and an induced hydraulic fracture was created by massive water injection. During reservoir life time, the warm water will be produced from the upper porous layer (Solling formation) and will be injected into the lower porous layer (Detfurth formation). The borehole is similar to a concentric pipe that allows injection through inner pipe (tubing) and production from outer pipe (annulus). The subsurface structural model includes the major faults and induced hydraulic fracture that in turn provides the input geometry into Comsol Multiphysics software. The subsurface and Heat transfer modules were employed in the subsurface model to couple the Darcy's law and solid mechanics, as well as heat transfer in porous media. The second model (borehole model) aims at a simulation of heat transfer and fluid flow in an approximately 4000 meter concentric pipe which acts similar to a counter-current heat exchanger The final goal of this simulation is to couple the subsurface and borehole models to model the performance of the reservoir at different wellbore conditions. The coupled simulator can be used in optimizing production, daily operation, designing well tests, etc.

Keywords: **Heat transfer, Darcy's law, Solid mechanics, Poroelastic material**

Introduction

Modeling geothermal systems requires simulating both reservoir behavior and fluid flow in production and/or injection wells. During circulation of water within borehole and reservoir the pressure, temperature and velocity fields vary during time within the borehole and reservoir. In addition, the production and injection of water from an enhanced geothermal system such as Horstberg, results in pore pressure changes and consequently changing in the stress acting on the reservoir and surrounding as well as effective normal stresses acting on the induced hydraulic fracture. The previous attempts mainly focused on the prediction of the well head pressure without considering either the deformation of the induced fracture or temperature field and they mainly focus on shallow geothermal systems. Thus, the main objective is to provide a tool to evaluate wellbore and reservoir performance while taking into account temperature field as well as rock and fracture deformation.

Borehole heat exchanger (BHE) is often used to exploit shallow geothermal energy. It mainly consists of a pipe or several pipes in a vertical borehole which can have different configurations. A Coaxial heat eXchanger with Centered inlet (CXC) consists of three main components, the inner pipe, the outer pipe and the rock and material surrounding the pipes, so called grout. The water is usually injected through the inner part, i.e. tubing, and flows back through the space between inner and outer pipes, i.e. annulus. Tubing and annulus in CXC configuration are connected at the bottom of the borehole. In contrast, there is no connection between tubing and annulus in a Concentric Tube Heat Exchanger or double pipe heat exchanger and fluid flow can be in co or counter flow directions.

The Horstberg geothermal reservoir is an Enhanced Geothermal System (EGS) where an induced hydraulic fracture was created by massive water injection. The borehole is completed in a multilayer sandstone reservoir, i.e. Buntsandstein formation. During reservoir life time, the warm water will be produced from the upper porous layer (Solling formation) and will be injected into the lower porous layer (Detfurth formation). The borehole is similar to a concentric pipe that allows injection through inner pipe (tubing) and production from outer pipe (annulus). The target production and injection formations, i.e. Solling and Detfurth are relatively low permeability sandstone layers, placed at a measured depth of 3640 to 3930 m. In both formations the static pressure is approximately150 bar higher than the hydrostatic pressure and reservoir temperatures are about 25°C above the average reservoir temperature expected in central Europe as high as 148 °C. Solling and Detfurth reservoir pressures are 584 and 597 bar (Tischner et al., 2010).

Heat transfer in borehole

Borehole heat exchanger BHE and LMTD methods

The previous studies in modeling BHE is based on Eskilson and Claessons's solution (1988). Diersch et al. (2011) developed a thermal resistance and capacity model (TRCM) that approximates BHE as a one-dimensional discretization of nodes in a finite element mesh. An advance numerical strategy is required due to extreme high aspect ratio of the borehole geometry, particularly in deep geothermal reservoirs. A recent study validated and tested the thermal reactions of BHE to thermal oscillation perturbations during an oscillatory injection test (Oberdorfer, 2014). The first law of thermodynamics governs the energy conservation for fluid flow within a pipe where the equation for temperature change can be written as;

$$\rho c_p \frac{\partial T}{\partial t} + \rho c_p \boldsymbol{u} \cdot \nabla T = \nabla.\left(\lambda_f \nabla T\right) + \tau : \nabla u + Q_h$$

where T is temperature, c_p is the fluid heat capacity at constant pressure, λ is thermal conductivity, $\boldsymbol{u}$ is fluid velocity vector, r_c is the characteristic length, ρ is the fluid density, τ is the viscous stress tensor and Q_h contains heat sources other than viscous dissipation. The first term on the left hand side includes the rate of increase in energy per unit volume and second term describes the forced convection heat transport mechanism. The right hand side describes the exchange of heat due to conduction (Fourier's law), viscous forces and sink/source terms.

A common approach to approximate heat transfer in a double-pipe arrangement is to calculate a temperature difference ΔT_m known as Log Mean Temperature Difference (LMTD) and an overall heat transfer coefficient (U).

$$\Delta T_m = \frac{[(T_{h2} - T_{h1}) - (T_{h1} - T_{c1})]}{\ln[(T_{h2} - T_{c2})\,/(T_{h1} - T_{c1})]}$$

The subscripts h and c refer to hot and cold fluid, and the subscripts 1 and 2 refer to inlet and outlet position. LMTD approach involves two main assumptions: (1) the fluid specific heats do not vary with temperature, and (2) the convection heat-transfer coefficients are constant throughout the heat exchanger. The second assumption is more important one because of fluid viscosity, and thermal-conductivity changes, etc.

Numerical methods must normally be employed to correct for these effects.

Heat transfer and fluid flow in a deformable porous media

The conservation of energy is governed by the first law of thermodynamics. The following equation describes the heat transfer in porous media (Bear and Bachmat, 2012):

$$(\boldsymbol{\rho\, C_p})_{\boldsymbol{eff}}\frac{\boldsymbol{\partial T}}{\boldsymbol{\partial t}} + \boldsymbol{\nabla}\cdot(\boldsymbol{\rho C_p v T}) + \boldsymbol{\nabla}\cdot\boldsymbol{q} = \boldsymbol{Q_h}$$

where $\boldsymbol{C_p}$ is the fluid heat capacity at constant pressure, $(\boldsymbol{\rho\, C_p})_{\boldsymbol{eff}}$is the effective volumetric heat capacity at a constant pressure, $\boldsymbol{v}$ is the Darcy velocity, $\boldsymbol{q} = \boldsymbol{-\lambda\nabla T}$ is the conductive heat flux.

The generalized governing equations for fluid flow in a deformable porous media is governed by Darcy's law and Biot poroelastic constitutive equations (COMSOL, 2017);

$$\frac{\boldsymbol{\partial(\rho\phi)}}{\boldsymbol{\partial t}} + \boldsymbol{\nabla}\cdot\boldsymbol{\rho}\left[-\frac{\boldsymbol{k}}{\boldsymbol{\mu}}(\boldsymbol{\nabla p} + \boldsymbol{\rho g z})\right] = \boldsymbol{Q_m}$$

Where $\boldsymbol{\rho}$ is the fluid density, $\boldsymbol{\phi}$ is the porosity, $\boldsymbol{k}$ is the permeability, $\boldsymbol{\mu}$ is the viscosity, p is the pore pressure, $\boldsymbol{g}$ is the magnitude of gravitational acceleration and z is the vertical coordinate.
Two constitutive equations govern the coupling between elastic deformation of porous solid and pore fluid (Biot 1962):

$$\boldsymbol{\sigma} = \boldsymbol{C\,\varepsilon} - \boldsymbol{\alpha\, pI}$$
$$\boldsymbol{p} = \boldsymbol{M}(\boldsymbol{\zeta} - \boldsymbol{\alpha\varepsilon_v})$$

The governing equation for the poroelastic material model is

$$-\boldsymbol{\nabla}\cdot\boldsymbol{\sigma} = \boldsymbol{\rho}\quad\boldsymbol{g}$$

Simulation methods

The final simulation includes different physics mainly recognized as transport phenomena, i.e. mass transport, heat transfer and momentum transfer. This physics are governed by Heat Transfer Module and Subsurface Flow Module that includes part of Structural Mechanics Module. Two different models are built in COMSOL Multiphysics, a poroelastic reservoir model and a borehole model. The Poroelasticity interface combines a transient formulation of Darcy's law to a linear elastic solid mechanics of the porous media matrix. The poroelasticity coupling means that the fluid flow affects the compressibility of the porous medium, while changes in volumetric strains will in turn affect the momentum, material, and heat transport. This interface includes an expression of the stress tensor, as a function of the strain tensor and the Biot-Willis coefficient. The borehole model solves for laminar fluid flow and heat transfer. The coupling aims at transferring data between two models while updating boundary conditions as follow:

(1) Run the full-field reservoir model from time t_0 to t_1.
(2) Update boundary conditions for the near-wellbore model from t_0 to t_1 using the full-field simulation results.
(3) Run the near-wellbore model from t_0 to t_1 with the updated boundary conditions.
(4) Update temperature for the full field model
(5) Check the convergence and repeat step 1 to 5 for the next time step

Simulation Results and Outlook

The final goal is to couple wellbore and reservoir model together in order to better evaluate short term transitional response during injection and production of brine (saline water) using measured wellhead pressure and temperature. Figure 1 presents the wellbore schematic at bottom hole and Figure 2 indicates the reservoir model and applied boundary conditions. The coupled simulator can be used in optimizing production, daily operation, designing well tests, etc.

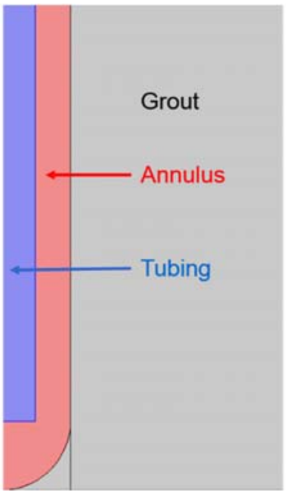

Figure 1. A cross section of wellbore at bottom hole. Three main components are the inner pipe (Tubing), the outer

pipe (Annulus) and the rock and material surrounding the pipes, so called grout.

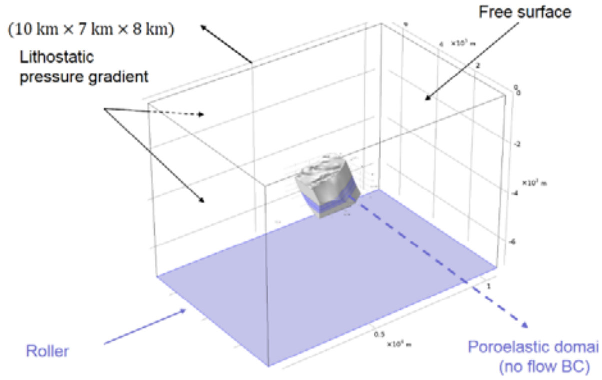

Figure 2. There are two computational domains, a mechanical and a poroelastic domain. To save the computational time fluid flow is only calculated in poroelastic domain.

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