PROCEEDINGS, Thirty-Seventh Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 30 - February 1, 2012
SGP-TR-194

MODELING OF FLOW AND TRANSPORT FOR EGS COST OPTIMIZATION PROBLEMS

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ABSTRACT

Efficient and accurate direct predicting tools for hydrological, thermal, mechanical and chemical phenomena that take place during the creation and production phases of Enhanced Geothermal Systems (EGS) are essential for optimization of geothermal energy extraction, to increase the life expectancy and to avoid undesired phenomena such as large seismic events or excessive fluid and pressure losses.

Towards that goal, a modeling framework to investigate such geothermal reservoirs has been developed. It is based on a general hierarchical fracture modeling framework that enables the addition of new fractures in a dynamic and computationally inexpensive way. The framework has been coupled with reliable flow and heat transport solvers, where mass and energy are conserved and due to its modular nature, it can be easily coupled with geomechanics and geochemistry modules that enable the simulation of large thermal-hydro-mechanical-chemical systems.

Here, the framework has been applied for a variety of EGS operation scenarios and their performance is presented, analyzed, and compared. More specifically, the impact of the injection temperature on the production history of an EGS power plant is studied and its overall energy production and cost is compared to scenarios, where the working fluid is injected after it has been preheated in a cheap shallow geothermal reservoir.

INTRODUCTION

Geothermal energy is one of the few carbon free resources that can potentially cover a significant portion of the base load energy. However, unexploited geothermal resources at shallow depths are very scarce. Therefore, novel technologies, such as Enhanced Geothermal Systems (EGS) are under development and aim to exploit the heat stored few kilometers below the surface.

Enhanced Geothermal Systems rely on increased permeability and artificially created fracture networks that increase the efficiency of geothermal power plants and enable the production of high enthalpy working fluid (usually H_2O). As the cold working fluid is injected into the “damaged matrix”, new fractures are created and the circulating working fluid extracts heat more efficiently. Finally, the fluid is forced out through a production well and some of the extracted thermal energy is converted into electrical power.

The cost of an EGS is still high compared to the amount of electrical energy it produces. One of the main reasons are the high drilling costs. Additionally, due to the so far uncontrolled microseismicity and due to the unavoidable uncertainty regarding position of large fractures, the risk of creating EGS reservoirs with small life expectance cannot be neglected. Finally, in the range of temperatures where EGS operates, the efficiency of converting thermal to electrical energy is worse for lower production temperatures.

The accurate modeling of the physical phenomena that take place during the operation of an EGS can be an invaluable tool towards making EGS technologies financially competitive. Optimal positions of new wells and reservoirs can be estimated and EGS revenues can be optimized.

Various approaches have been applied for the simulation of mass and energy transfer in EGS. Finite difference methods (Yamamoto et al.1997), finite element method s (Kohl et al. 1995a, Kohl et al. 1995b, McDermot et al. 2006), dual porosity models (Bower et al. 1997) and dual continuum descriptions (Taron et al. 2009a, Taron et al. 2009b) have been applied and assisted in understanding the behavior of EGS under realistic conditions.

We have developed an algorithmic framework for EGS simulations that is based on a hierarchical fracture representation (Hajibeygi et al. 2011). The addition of new fractures during the creation phase is a computationally inexpensive task, which avoids undesired tiny volumes that would increase the computational cost. The resulting software has been coupled with reliable flow and transport solvers that conserve mass and energy.

Here, we study how our software can be used for cost optimization. Initially, the algorithmic framework and its components are presented and discussed. Then, three alternative EGS operation scenarios are described and the simulations of their long-term behaviors is presented and compared to a typical EGS power plant. The aim of this study is to improve the understanding of why and how circulating the fluid in a shallower reservoir reduces the overall cost of an EGS.

GOVERNING EQUATIONS AND MODELING

Governing equations

Mass conservation

Here, we consider incompressible and laminar single phase flows inside a dynamically changing fractured reservoir of compressible rock.

Based on the above and neglecting gravitational effects, the mass conservation equation becomes

$$\frac{\partial \varphi}{\partial t} - \nabla \frac{1}{\mu} \underline{\underline{K}} \nabla p = \frac{q^M}{\rho} \ , \tag{1}$$

where $\underline{\underline{K}}$ is the permeability tensor, φ the porosity of the medium, q^M is a mass source term and p, μ, and ρ are pressure, dynamic viscosity and density of the working fluid, respectively. It should be noted that both permeability and porosity are pressure dependent.

By further assuming constant fracture geometry and an incompressible medium, Equation (1) results in the steady state mass conservation equation

$$-\nabla \frac{\rho}{\mu} \underline{\underline{K}} \nabla p = q^M . \tag{2}$$

Since laminar flow is assumed, the mean velocity $\underline{u}$ of the fluid is given by

$$\underline{u} = -\frac{1}{\mu} \underline{\underline{K}} \nabla p . \tag{3}$$

Energy conservation

The energy conservation equations for the working fluid and the solid rock, respectively, are

$$\frac{\partial h^{res}}{\partial t} + \nabla \left(h^{res} \cdot \underline{u} \right) = \frac{q^{E,res}}{\rho} \tag{4}$$

and

$$\frac{\partial \left(h^{rock} \right)}{\partial t} - \nabla \underline{\underline{D}} \nabla T^{rock} = \frac{q^{E,rock}}{\rho} , \tag{5}$$

where T is the temperature, h the specific enthalpy, $q^{E,res}$ the rates of energy injected per unit volume, $q^{E,rock}$ the energy extracted from the rock, and $\underline{\underline{D}}$ the heat conduction tensor .

Hierarchical fracture representation

Due to the huge number of fractures within an EGS reservoir, resolving all of them is not feasible. Therefore, a hierarchical fracture representation has been employed. More specifically, each fracture of size larger or approximately equal to the dimensions of a gridblock is treated as a separate lower dimensional continuum and is resolved discretely. The integral effect of the huge number of small fractures is captured by an equivalent medium, called ‘damaged matrix’ (Lee et.al. 2001, Li et. al. 2008). A rather coarse grid can be employed for the discretization of the ‘damage matrix’.

Connections are added among neighboring volumes as well as among intersecting volumes that either belong to different large fractures or a large fracture and the damaged matrix. They connect volumes with working fluid, where mass flow and heat exchange occurs. The result of the above procedure is an unstructured grid of finite volumes and looks like a network of interconnecting tubes (Figure 1).

Modeling flow

Once the domain has been resolved into finer volumes and appropriate initial transmissibilities C_{ij} have been assigned to each connection, the finite volume method can be applied and mass conservation for each node i is expressed as

$$\frac{\partial V_i}{\partial t} + \sum_{\forall j \in G_i^{res}} C_{ij} \cdot \left(p_i - p_j \right) = \frac{Q_i^M}{\rho} , \tag{6}$$

where V_i, p_i, Q_i^M are fluid volume, pressure and mass source, respectively, which are associated with node i. For nodes at a boundary, either Q_i^M or p_i have to be

specified. G_i^{res} is defined as the set of nodes that are connected to node i.

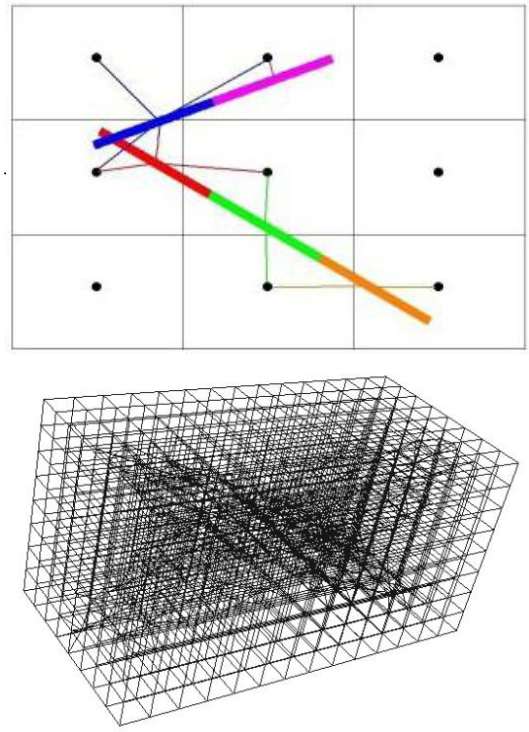

Figure 1: Illustration of the connections among two large fractures and a damaged matrix in a 2D (top) and 3D (bottom) scenario.

The volume flux from node i to node j is

$$u_{ij} = C_{ij} \cdot (p_i - p_j). \tag{7}$$

Transmissibility among volumes of the same continuum is modeled as

$$C_{ij} = \frac{\overline{k_{ij}}}{\mu \cdot l} \cdot A \quad , \tag{8}$$

where A and l are the cross-sectional area and the separation distance, respectively, and $\overline{k_{ij}}$ is the harmonic average of the permeabilities in the two volumes. Permeability for fractures is given by the cubic law, according to which

$$k^f = \frac{b^2}{12 \cdot \mu} \tag{9}$$

Transmissibility for connections between a fracture volume and a damaged matrix node is modeled as

$$C_{ij} = \frac{2 \cdot k_m}{\mu \cdot \left(\frac{d_{min}}{3\sqrt{2}}\right)^2} \cdot A, \tag{10}$$

where k_m is the effective permeability of the damage matrix, A the cross-sectional area between the two volumes, and d_{min} the smallest dimension of the damaged matrix gridblock.

In the case of time dependent problems, where the derivative $\frac{\partial V}{\partial p}$ is known and transmissibility is a pressure dependent quantity, a semi-implicit time integration scheme can be employed and Equation (6) results in

$$\left.\frac{dV_i}{dp_i}\right|^{\nu} p_i^{\nu+1} + \Delta t \sum_{\forall j \in G_i^{res}} C_{ij}^{\nu} \left(p_i^{\nu+1} - p_j^{\nu+1}\right) = \Delta t \frac{Q_i^M}{\rho} + V_i^n - V_i^{\nu} + \left.\frac{dV_i}{dp_i}\right|^{\nu} p_i^{\nu} \quad , \tag{11}$$

where n denotes the time step and ν and ν+1 the current and next iteration steps. Upon convergence one should obtain $p^{\nu+1} = p^{\nu} = p^{n+1}$.

During the production phase, the reservoir geometry and its hydraulic properties alter significantly less frequently, thus steady state flow may be assumed and Equation (6) results in a sparse and symmetric linear system of equations. Algebraic Mutligrid Methods can be applied to increase the convergence rate of the linear solver.

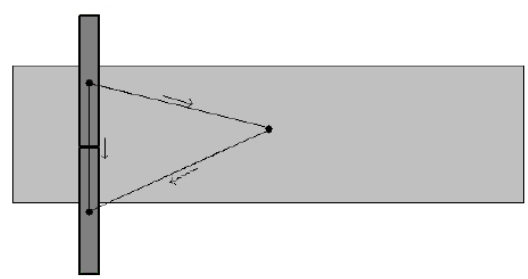

Figure 2: Two neighboring fracture volumes are connected to the same damaged matrix node. Mass flow between the two fracture volumes now also occurs along the iconic parallel path created by their connections with the damaged matrix cell.

Since it is not necessary to conform the grid to the fracture boundaries, a parallel iconic flow path is created whenever two neighboring fracture volumes

are connected to the same damaged matrix cell. This leads to an artificial enhancement of transmissibility along fracture, which might not be negligible in certain scenarios. Thus its equivalent effect should be subtracted from the transmissibility that connects these two volumes (Figure 2).

Modeling heat transport

Heat convection from node i to node j is modeled as

$$\frac{\partial\left(V_i h_i^{res}\right)}{\partial t} + \sum_{\forall j \in G^{res}} u_{ij} \cdot h_i^{res} = \frac{Q_i^{E,res}}{\rho}, \qquad (12)$$

where h_i^{res} is the average specific enthalpy of the working fluid in the volume associated to node i and $Q_i^{E,res}$ the average source term. The exchange with the rock is modeled as

$$Q_i^{E,res} = \rho \sum_{\forall k \in G^{rock}} C_{ik}^{E}\left(T_k^{rock} - T_i^{res}\right), \qquad (13)$$

where T^{Rock} is the mean rock temperature in the control volume k of the grid used to solve the discretized heat conduction Equation (5). The set G^{rock} contains all control volumes k of that grid. Of course the discrete heat exchange coefficients C_{ik}^{E} have to be calculated consistently with $q^{E,rock}$ and to guarantee energy conservation, the source term $Q_k^{E,rock}$ of control volume k in the discretization of Equation (5) is formulated as

$$Q_k^{E,rock} = \frac{1}{\rho} \sum_{\forall i \in G^{res}} C_{ik}^{E}\left(T_i^{res} - T_k^{rock}\right). \qquad (14)$$

FRAMEWORK OF THE SOLUTION ALGORITHM

A synopsis of the desired features for an EGS simulator was given by Sanyal et.al. (2000). Such a simulator should be able work with irregular grids both in 2D and 3D and to employ a discrete fracture representation. The flow of the working fluid should be channeled within fractures and flow rates must be a function of the fracture aperture, which in turn should be a function of shear stress. The porous flow in the matrix and the thermoelastic effects should not be neglected, while the simulation of multi-phase flow, of tracer transport, and of the deposition and dissolution of minerals should be applicable.

Towards that goal, an algorithmic framework capable to host a large variety of different modules has been developed (Karvounis et al. 2011) and has been coupled with the flow and heat transport solvers, described above. The hierarchical fracture representation is the cornerstone of this framework.

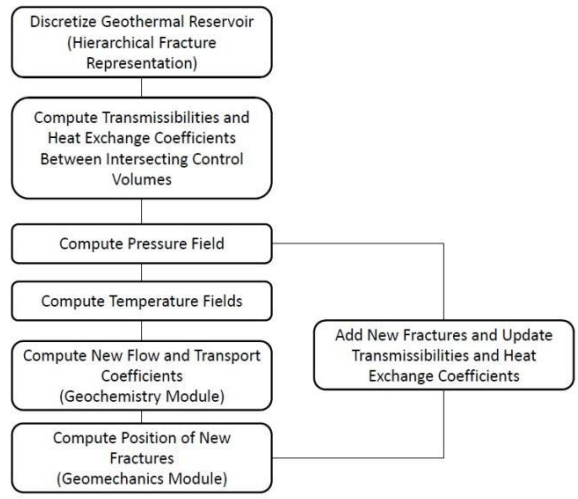

Figure3: Flow chart of the modeling framework.

Once the discretization of the EGS reservoir is accomplished and all the needed connections among intersecting volumes and hydraulic properties have been added and initialized, the main time stepping procedure begins. At each time step, the pressure and the corresponding velocity field are computed. Heat and tracer transport are simulated and the viscosity field is updated (Figure 3).

The framework demonstrates modular behavior and enables its coupling with external geochemistry and geomechanics modules.

The advantages of using the hierarchical fracture representation can be summarized as follows:
First, the use of the finite volumes method ensures mass and energy conservation and consistent discretization schemes are applied. Second, the representation of important large structures is accurate and can be produced at low computational cost. Third, rigorous upscaling of the huge number of fractures represented by the damaged matrix can be performed to reduce the computational cost. Fourth, the addition of new fractures does not require remeshing and finally, undesired tiny volumes that limit the time step size are avoided.

OPTIMIZATION TASK AND COMPUTATIONAL STUDIES

Problem description

For EGS to be competitive, it is vital to reduce associated costs. Drilling costs are considered among the dominant costs. They increase overproportionally with depth and vary according to the morphology of the ground (Huenges 2010).

The total heat extracted by the working fluid equals

$$E = \int_0^{t_l} F \cdot c_h \cdot \left(T_{prod.} - T_{inj.}\right) \cdot dt \,, \qquad (15)$$

where F is the mass flow rate of the working fluid, $T_{prod.}$ the production temperature, $T_{inj.}$ the injection temperature, and t_l is the life expectancy of the EGS.

Life expectancy t_l strongly depends on the evolution of the rock cold temperature front. During the production phase, the area surrounding the injection well exchanges heat at the highest rate and an expanding cold front is created. The faster this cold front approaches the production well, the shorter the reservoir's life expectancy.

The injection flow rate F has an upper bound determined by the impedance and the minimum principal stress of the reservoir. More precisely, the minimum principal stress defines the maximum operating pressure difference, for which seismic events do not occur. Subsequently, the impedance defines the maximum injection flow rate. High values of flow rate result in higher rates of heat exchange with the hot rock, which reduces the life expectancy.

The production temperature $T_{prod.}$ reduces itself as the volume covered by the cold matrix front increases. However, the higher the $T_{prod.}$, the more efficiently is it converted into electrical power due to the higher Carnot efficiency.

Finally, the injection temperature $T_{inj.}$ is usually coupled with optimized conversion cycles on the surface.

Our goal is the minimization of the drilling costs per electrical energy.

Computational studies and cost optimization

Here, we describe four EGS operation scenarios, for which their long-term behavior has been simulated and compared to the one of a typical EGS operation scenario.

It should be noted that for all four scenarios presented here, water injection is constant at 40 l/s. All the reservoirs are hydraulically identical. A permeable homogeneous region that has the shape of a horizontal elliptic cylinder and is penetrated by two parallel horizontal wells at the edges of the major axis, is assumed. The major axis of the elliptic cylinder is 270m, the minor axis is 210 m and the lengths of the wells and of the permeable cylinder are 400m. The size of the matrix surrounding the permeable reservoir is 300x400x300 m^3. The rock's temperature profile is assumed to be 120°C at 1km and increases by 25^{0}C/km after that. All simulations finish, once the production temperature is less than 100°C.

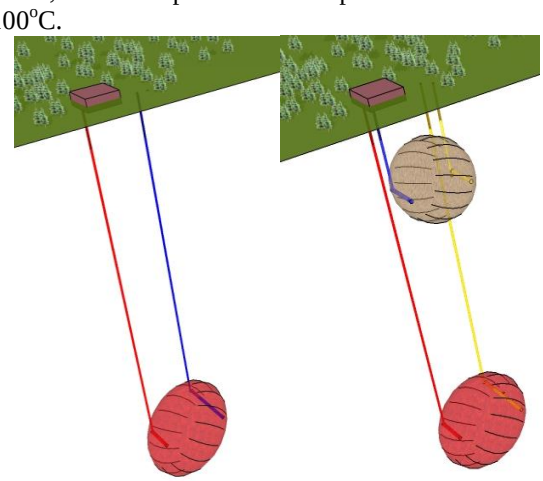

Figure 4: Typical EGS operation scenario (on the left) and an alternative EGS operation scenario for increased recovery of high enthalpy working fluid (right).

The first EGS operation scenario to be studied here, which is the most common one, is made up by a single deep reservoir at 5.35km depth. Water is injected into it at a constant temperature of 60°C and is pushed through the production well.

For the second scenario the same deep reservoir is assumed, but now 80°C water is injected (Figure 4). Such a temperature increase can be performed quite cheaply, e.g. if the EGS is combined with a nearby conventional power plant or by using solar heaters.

The simulated life expectancy of the first scenario is approximately 11 years. The production temperature decreases rapidly until it reaches the region where it asymptotically starts approaching the injection temperature. The simulation results of the second scenario indicate life expectancy of 36% more, whereas the same flow rate was applied (Figure 5).

For the third and the fourth scenarios the same deep reservoir at 5.35km is considered, but the working fluid now is preheated in a shallower reservoir at

2.35km (preheater). For simplicity, this preheater is assumed to be hydraulically identical to the deep one. The cold working fluid is injected into the preheater, where it warms up and then it is redirected into the hot rock, where it gains the rest of the heat needed. The 40 l/s of water are injected to the preheater at 60°C in the third scenario and at 80°C in the fourth one.

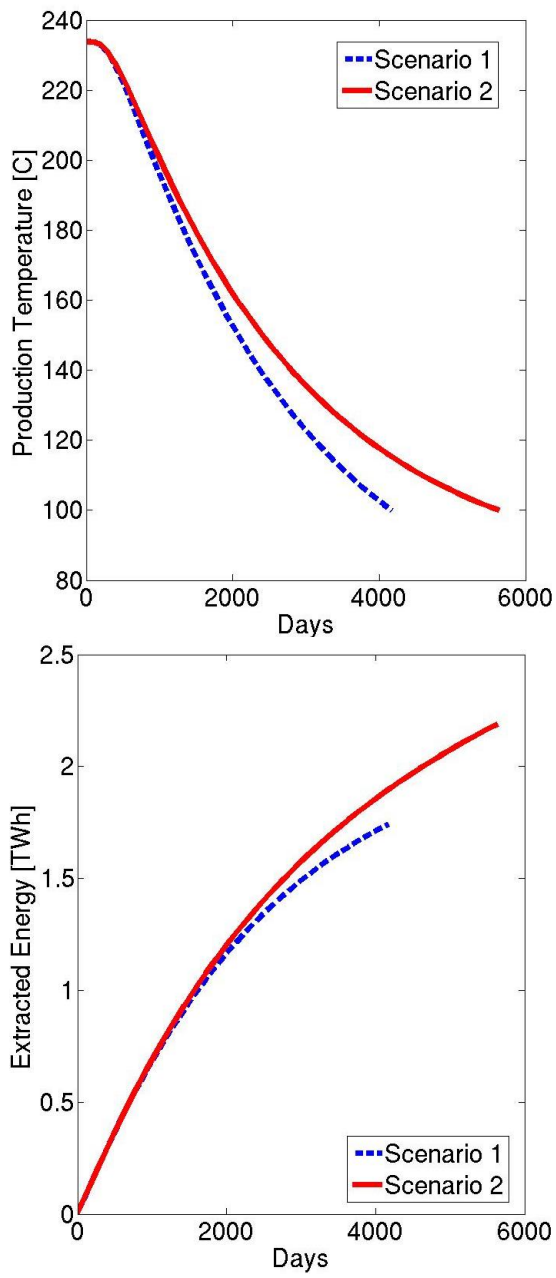

Figure 5: Histories for scenarios 1 and 2: production temperature (top) and accumulated produced thermal energy (bottom).

The increase of the life expectancy and of the amount of heat recovered in these two scenarios can be seen in Figure 6. Comparing these two scenarios to our initial scenario, a considerable increase of the life expectancy is witnessed. More precisely, life expectancy is increased by 60% in the third scenario and almost doubled in the fourth one.

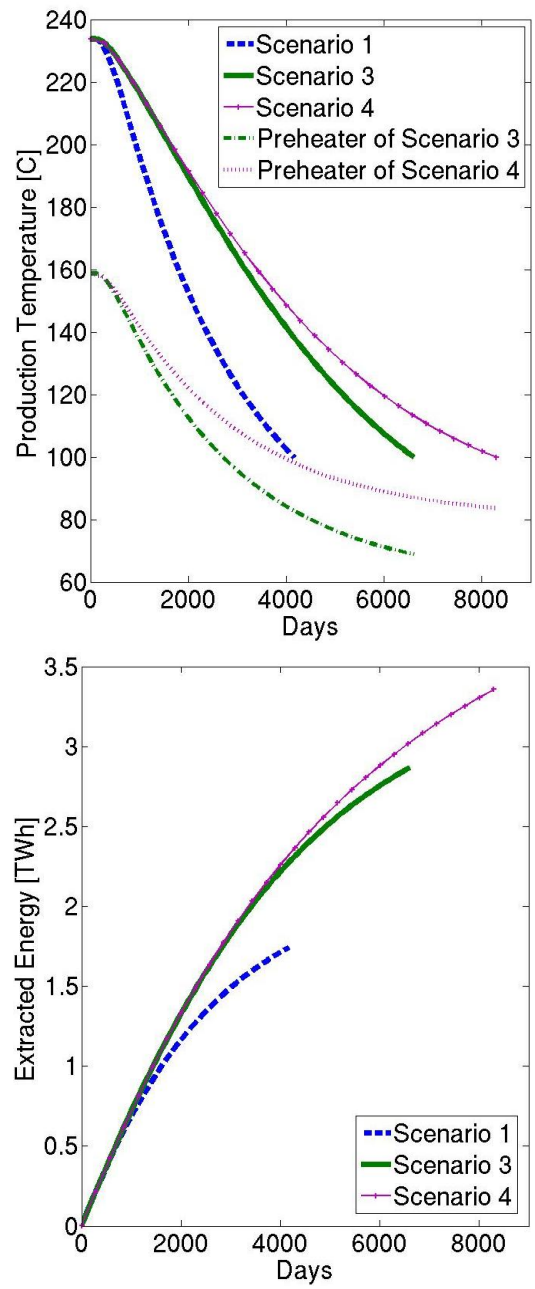

Figure 6: Histories for scenarios 1, 3, and 4: production temperature from deep and shallow reservoirs (top) and accumulated produced thermal energy (bottom).

Moreover, the heat recovered by the preheater causes an increase of the working fluid production at

temperatures with high energy conversion efficiency. Heat is extracted at a lower rate from the deep reservoir, thus its temperature drops at a lower rate. Until the production temperature drops to 160°C, 70% more heat has been extracted than in the first scenario.

Finally, the additional drilling cost for the described preheater is approximately 20% of that for the deep one (Huenges 2010), which has to be related to the 70% more extracted energy. As a result, the third EGS operation cycle leads to approximately 29% lower drilling costs per energy unit, compared to scenario 1.

CONCLUSION

A software that models the geometry of an EGS reservoir in a flexible, consistent, and user friendly manner has been developed. It is coupled with reliable flow and transport solvers that conserve mass and energy, and can be coupled with geomechanical and geochemical modules. The flow and heat transport solvers of the framework have been used to study the effect of the injection temperature on the long term behavior of an EGS power plant and its cost. It was found that dramatic cost reduction may be achieved by employing a shallower EGS in series as a preheater.

ACKNOWLEDGEMENTS

The work was performed as part of the GEOTHERM project that is funded by the Competence Centre for Environment and Sustainability of the ETH-Domain, and by the Swiss Federal Office of Energy under contract 154278.

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