PROCEEDINGS, Thirty-Sixth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 31 - February 2, 2011
SGP-TR-191

MODELING OF FLOW AND TRANSPORT IN ENHANCED GEOTHERMAL SYSTEMS

Dimitrios Karvounis and Patrick Jenny

Institute Of Fluid Dynamics, ETH Zurich
Sonneggstrasse 3, ML H 45
Zurich, 8092, Switzerland
e-mail: karvounis@ifd.mavt.ethz.ch, jenny@ifd.mavt.ethz.ch

ABSTRACT

Here, we consider Enhanced Geothermal Systems (EGS), which rely on increased permeability and artificially created fracture networks in the subsurface, thus increasing the efficiency of geothermal power plants. By injecting cold supercritical working fluid (usually H2O or CO2) into the “damaged matrix”, new fractures are created. This dynamically changing fracture system allows the working fluid to flow efficiently through the reservoir and to extract thermal energy at a higher rate.

We present a modeling framework for such geothermal reservoirs, which is based on a hierarchical approach, i.e. a discrete representation is employed to model flow and transport through large fractures and a continuum representation is used for the huge number of small fractures (damaged matrix). In this way, the addition of new fractures during enhancement is computationally inexpensive, since whenever a new fracture is created, a small number of control volumes is added to the existing mesh thus allowing the flow computation for dynamically changing reservoirs. Important criteria are the accurate and efficient coupling between flow and transport calculations, consistent transfer of mass and energy between the continuum and the discrete fracture representations, treatment of heat conduction in the rock and across the interfaces with the fractures, inclusion of the integral effects on the permeability due to geochemistry, and of course a general interface with a geomechanics module. Moreover, the framework has to be suitable for both the creation and production phases.

Here, it is explained how the coupling of flow and transport in the discrete and continuous fracture representations in combination with heat conduction in the rock can be modeled. Various test cases representing scenarios during reservoir creation and production are considered and the resulting pressure and temperature evaluations are discussed.

INTRODUCTION

Geothermal Energy is one of the few carbon free and renewable energy resources that can produce a significant portion of the base load energy production. However, vital geographical restrictions constrain the further development of the current technologies for extracting vast amounts of shallow geothermal energy. One of these novel technologies under development include Enhanced Geothermal System.

Enhanced Geothermal Systems (EGS) rely on increased permeability and artificially created fracture networks in the subsurface, thus increasing the efficiency of geothermal power plants. In particular, EGS exploit the geothermal energy that is stored few kilometers below the surface. By injecting cold working fluid (usually H_2O) into the “damaged matrix” through an injection well, new fractures are created. This dynamically changing fracture system allows the working fluid to flow efficiently through the reservoir and to extract thermal energy at a higher rate. Finally, the hot circulating working fluid is forced out through the production well and at the surface extracted thermal energy is converted into electrical power.

The accurate modeling of the physical phenomena that take place during the operation of an EGS is vital for ensuring financial viability and the further development of the technology. Desired characteristics of an EGS simulator (Sanyal et al. 2000) are i) a discrete fracture representation in two and three dimensions with irregular grids, ii) flow rates influenced by the aperture of the fractures, iii) the ability of simulating multiphase or high Reynolds number flows, iv) tracer and heat transport modeling and v) the accurate simulation of all the important mechanical and chemical procedures that take place during an EGS operation.

For the simulation of mass and energy various approaches have been applied in existing EGS simulators. GEOTH3D (Yamamoto et al.1997) that employs a finite difference method, without allowing discrete fracture modeling, allows for simulations of simple EGS reservoirs. FRACTure (Kohl et al. 1995a, Kohl et al. 1995b), RockFlow (McDermot et al. 2005, McDermot et al. 2006) and FracSim are based on Finite Element Method (FEM) in order to study various scenarios that take place during the long term operation of an EGS power plant, where changes in the geometry of the reservoir occur slowly. Hydrothermal simulators such as FEHM (Bower et al. 1997), a finite element code that uses a dual porosity, and TOUCHREACT (Taron et al. 2009a, Taron et al. 2009b), that uses the dual continuum method, assisted in the simulation of scenarios that include mechanical and chemical effects.

The highly fractured reservoir of an EGS power plant dramatically increases the complexity of the problem that has to be solved in order to compute flow rates and heat transport in 3D scenarios. This complexity is further increased if resolved fractures must conform with the grid of the surrounding matrix, while certain fracture geometries may lead to computational grids that significantly decrease the time step based on the CFL condition.

Moreover, during the enhancement of an EGS reservoir, new fractures are created and the network of open fractures, through which the working fluid flows, changes constantly. Therefore, the ability to add new fractures to the computational grid in an efficient and consistent way is desired. Other important criteria are the accurate and efficient coupling between flow and transport calculations, consistent transfer of mass and energy between the continuum and the discrete fracture representations, treatment of heat conduction in the rock and across the interfaces with the fractures, inclusion of the integral effects on the permeability due to geochemistry, and of course a general interface with a geomechanics module.

Finally, since most of the flow occurs within the large fractures of the reservoir, resolving all the small fractures is less essential. Therefore, a hierarchical approach that reduces the size of the computational problem without sacrificing accuracy can be employed.

The goal is the development of a modeling framework that is capable of simulating the thermal, hydrologic, chemical and mechanical processes taking place in such a geothermal reservoir that will provide an alternative solution for the above mentioned open issues in large scale simulations.

MODELING FRAMEWORK

The modeling of flow and heat transport should be modular and general to enable coupling with a vast number of different geomechanics and geochemistry modules. The latter is important to account for integral effects on the permeability and the former for computing where and when the rock fails and new fractures are created.

In our suggested approach, the first step consists in a hierarchical discretization of the reservoir. Such a hierarchical fracture representation enables the treatment of dynamically changing geometries in a computationally efficient manner. Once all the required hydraulic and thermal properties are initialized, the main iterative procedure begins. In particular, at each time step hydraulic pressure, mass flux, heat transport between the continuum and the discrete fractures and heat conduction in the rock and across the interfaces with the fractures are calculated. These values are then used by the geomechanics and geochemistry modules that provide all the needed information for updating the network of open fractures, its discretization and all required hydraulic properties.

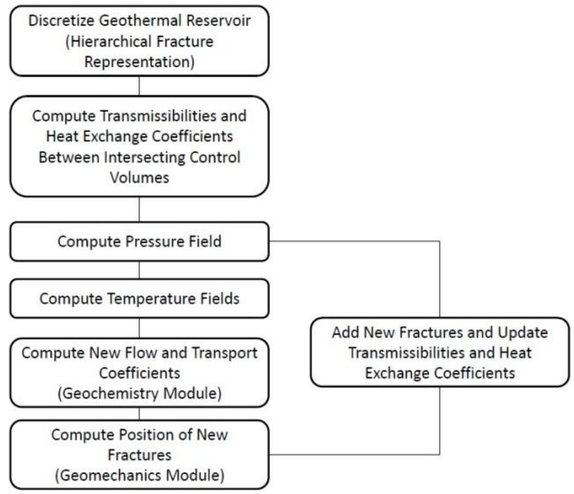

Figure 1: Flow chart of the modeling framework

Here we present our hierarchical fracture representation and the modeling of mass flow and heat transport. The simulator that has been developed is programmed in C++ and much effort has been invested in ensuring a general interface that allows the coupling with other modules.

HIERARCHICAL FRACTURE REPRESENTATION

Many challenges that have to be tackled for the efficient simulation of EGS reservoirs also have to be tackled for efficient simulations of black oil in naturally fractured reservoirs. The high fracture density and the observation that most of the flow occurs within the large fractures led to the development of hierarchical approaches for the modeling of flow (Lee et al. 2001) and to a hybrid finite volume method where only large fractures are resolved and the small and medium sized fractures are modeled by effective permeabilities (Li et al. 2008).

Similarly, due to the huge number of fractures that exist within an EGS reservoir, resolving all of them is not feasible. Therefore the small fractures are upscaled, i.e. their integral effect is captured by effective properties (e.g. an effective permeability is derived) for computations of flow and transport in a continuous "damaged matrix", for which a relatively coarse grid can be employed. For simplifying the programming effort, this grid can be a structured orthogonal grid both in 2D and 3D scenarios and could be aligned to the orientation of the anisotropies inside the reservoir.

Dominant large fractures are represented as lower dimensional intersecting manifolds, i.e. we assume apertures which are small relative to the size of the fractures. Each discrete fracture is decomposed into a number of control volumes; where each of these volumes is connected to its neighbors from that fracture, to the intersecting control volumes of the damaged matrix grid and to the intersecting control volumes from other fractures. Obviously the accurate calculation of all the connectivities is crucial and will be explained and discussed later. Again, in an effort to reduce the programming effort and the complexity of the grids, each fracture can be discretized by a structured orthogonal grid, where only volumes whose center is within the fracture remain in the final grid.

As a result of this hierarchical approach, one obtains an unstructured tube network, which can be employed to simulate flow and transport in the whole reservoir. These tubes connect volumes with working fluid, where mass flow and heat exchange occurs. In 2D simulations, each fracture volume is represented by a one-dimensional line that crosses two-dimensional quadrilaterals and in 3D scenarios fracture volumes are represented by two-dimensional quadrilaterals that intersect with three-dimensional hexahedrons. Wells are always represented as one-dimensional lines.

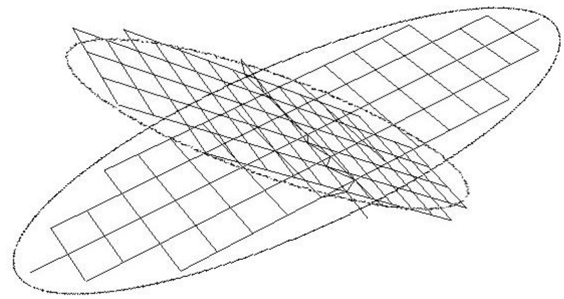

Figure 2: Illustration of the coupling between two discrete large fractures. Fractures have been assumed to have an elliptic shape and only control volumes whose center is within the fracture are considered.

An advantage of the suggested approach is that the computational cost to remesh the reservoir every time a new fracture opens during the creation phase is avoided. Since large fractures do not have to conform to the grid of the surrounding matrix, all that is needed for the addition of a new fracture is its decomposition into a number of control volumes and then to augment the existing grid by adding these control volumes and all the new connections. The rest of the grid remains the same.

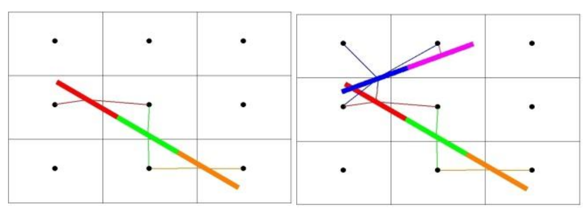

Figure 3: Illustration of coupling between discrete large fractures and the damaged matrix.

Finally, the smallest size allowed for the control volumes can easily be controlled by the user, thus enabling the use of relatively large time steps during heat transport simulations. For further explanations we introduce the set G^{res} of all nodes in that network.

GOVERNING EQUATIONS

Here we consider reservoirs in which the permeability of the fractures is much larger than that of the porous rock. Further we assume that the single fluid phase is incompressible (constant density ρ) and that the Reynolds number is very small everywhere (Re<1→ creeping flow). Therefore, given appropriate transmissibilities C_{ij} for each connection between nodes i and j of the unstructured tube network, according to the Finite Volume Method, one can express mass conservation at any node i as

$$\frac{\partial V_i}{\partial t} + \sum_{\forall j \in G^{res}} C_{ij} \cdot (p_i - p_j) = \frac{Q_i^M}{\rho} \quad (1)$$

where V_i, p_i and 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. The volume flux from node i to node j is

$$u_{ij} = C_{ij} \cdot (p_i - p_j). \quad (2)$$

When the connection is between two damaged matrix volumes or two fracture volumes, the transmissibility C_{ij} is

$$C_{ij} = \frac{\left(\frac{2}{\frac{1}{k_i} + \frac{1}{k_j}}\right)}{\mu \cdot l} \cdot A, \quad (3)$$

where μ is the viscosity of the fluid, A and l are the cross-sectional area and the cross-sectional length between the two volumes i and j and finally, k_i and k_j are the effective permeabilities in the two volumes. When the connection is between a fracture volume and a damaged matrix node, then the transmissibility C_{ij} is

$$C_{ij} = \frac{k_m}{\mu \cdot \langle d \rangle} \cdot A, \quad (4)$$

Where k_m is the effective permeability of the damaged matrix, $\langle d \rangle$ is the average normal distance from the fracture (Li et al.2008) and A is the cross sectional area between the two volumes.

The transmissibility among fracture volumes depends on the aperture of the fracture and on the permeability inside the fracture, if it is filled with porous material. The aperture, however, is a function of hydraulic pressure, thus assuming that the compressibility of a fracture, i.e. $\frac{dV}{dp}$ is known, equation (1) can be approximated as

$$\left.\frac{dV_i}{dp_i}\right|^{\nu} p_i^{\nu+1} + \frac{\Delta t}{\rho} \sum_{\forall j \in G^{res}} C_{ij}^{\ \nu} \cdot \left(p_i^{\nu+1} - p_j^{\nu+1}\right) \quad (5)$$
$$= \frac{\Delta t \cdot Q_i^M}{\rho} + V_i^n - V_i^\nu + \left.\frac{dV_i}{dp_i}\right|^{\nu} p_i^{\ \nu},$$

where the superscript n denotes the previous time step values and ν and ν+1 denote quantities in the current and future iteration step. Upon convergence one obtains

$$p^{\nu+1} = p^\nu = p^{n+1}. \quad (6)$$

During the production phase alterations in the geometry of the reservoir occur significantly less frequently. As a result, equation (1) becomes

$$\sum_{\forall j \in G^{res}} C_{ij} \cdot (p_i - p_j) = \frac{Q_i^M}{\rho}. \quad (7)$$

For the computation of the above pressure distribution, one must solve a sparse symmetric linear system. Algebraic Multigrid Methods can be applied to increase the convergence rate of the linear solver.

ENERGY CONSERVATION

Heat convection from node i to node j is modeled as

$$\frac{\partial (V_i \cdot h_i^{res})}{\partial t} + \sum u_{ij} \cdot h_{ij}^{res} = \frac{Q_i^{E,res}}{\rho}, \quad (8)$$

where h_i^{res} is the average specific enthalpy of the working fluid in the volume associated to node i. The source term $Q_i^{E,res}$ either quantifies thermal energy injected through a well or exchanged with the rock. In the latter case

$$Q_i^{E,res} = \sum_{\forall k \in G^{rock}} C_{ik}^E \cdot \left(T_k^{rock} - T_i^{res}\right), \quad (9)$$

where T_k^{rock} is the mean rock temperature in control volume k of the grid used to solve the discretized heat conduction equation

$$\frac{\partial h^{rock}}{\partial t} = \nabla \cdot \left(\underline{\underline{D}} \cdot \nabla h^{rock}\right) + q^E, \quad (10)$$

where D is the heat conductivity and h^{rock} is the rock enthalpy. 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 and to guarantee energy conservation, the source term $Q_k^{E,rock}$ of control volume k in the discretization of equation (2) is formulated as

$$Q_k^{E,rock} = \sum_{\forall i \in G^{res}} C_{ik}^E \cdot \left(T_i^{res} - T_k^{rock}\right), \quad (11)$$

GEOMECHANICS

The modular framework and the well-defined interfaces allow the coupling of the flow and transport solver, presented here, with various geomechanics modules. The unstructured grid that results from the hierarchical fracture representation enables the flow and transport solver to be coupled with geomechanics modules that employ either a discrete fracture representation or a continuum approach. Those obtain pressure and temperature distributions from the flow and transport simulation and deliver changes of volumes (V_i), transmissibilities (C_{ij}), heat exchange coefficients (C_{ik}^{E}) and the position of new fractures with all specifications.

CREATION PHASE

A particular challenge is the modeling of the creation phase. While the fluid pressure increases, new fractures are created linking existing ones. Thus the permeability of the damaged matrix may significantly increase. In our approach we do not have to prescribe all foreseeable fractures, offering further flexibility to the geomechanics module that will be used. During the simulation the geomechanics module calculates (based on pressure, temperature and shear distribution) where and when new fracture segments are created. These segments are discretized by finite volumes and these volumes with their connections are then added to the computational grid. No further changes need to be made in the existing computational grid. Finally, it is assumed that volume, transmissibility and heat exchange coefficients depend linearly on the aperture of each fracture.

EXEMPLARY SIMULATION RESULTS

Some exemplary artificial test cases are presented below in order to present the capabilities of the presented modeling framework.

First Test Case

A highly heterogeneous porous medium is used to represent the equivalent porous medium that one could have obtained by upscaling the small fractures. The position, the length and the aperture of each of the large fractures is chosen according to a stochastic process and these fractures can have only certain pre-decided orientations. The resulting computational grid and the corresponding transmissibilities are computed (Fig.4).

Initially, the fictional reservoir is filled with hot working fluid and constant pressure difference is applied between the left and right sides of the reservoir. The geometry and the fracture volumes are considered constant and gravitational effects are neglected. The pressure distribution is calculated, allowing hence the computation of the corresponding fluxes. These fluxes stay constant though the whole simulation of heat transport.

Cold working fluid is injected into the reservoir (left bound) and forces out the pre-existing hot working fluid (right bound). In this scenario, heat transfer from the hot rock to the cold working fluid has been neglected. Inside the impermeable region mass is transferred almost solely through the large fractures.

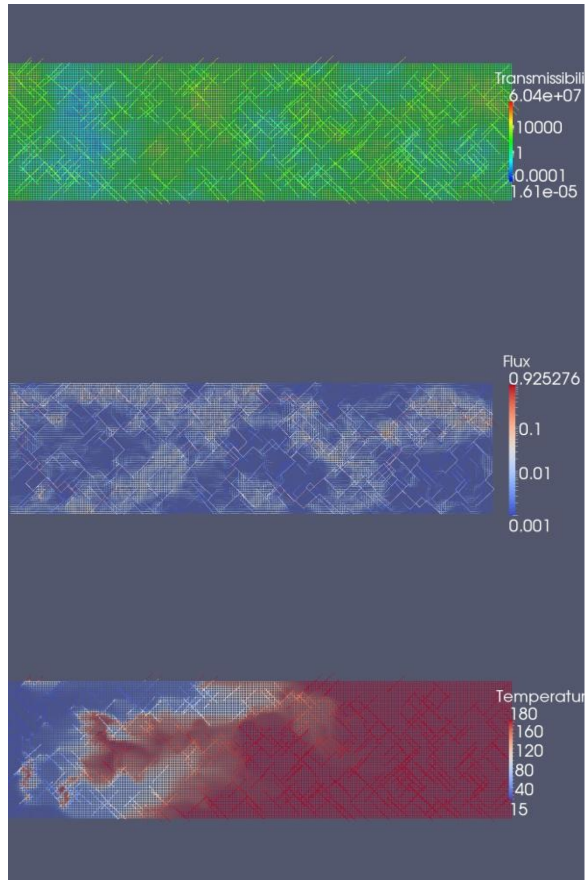

Figure 4: Logarithm of transmissibility and flux and reservoir temperature for an artificial test case.

Second Test Case

In the second test case the damaged matrix is represented by a slightly heterogeneous porous medium and the fracture network consists of only two large fractures. Working fluid is injected at the top left corner and is extracted from the bottom right corner. A constant pressure difference is applied between these two volumes.

For the simulation of an imaginary creation phase, a time marching procedure begins where at various prescribed moments new fractures are created and added to the computational grid. The simulation of this scenario ends once the network of open fractures intersects both the injection and production volumes.

A certain pressure range has been highlighted making more visible the propagation of the pressure front as new fractures are created (Fig. 5). This pressure front moves towards the production well. The pressure drop is higher in the non-fractured areas and once the fracture network connects both wells, the pressure front moves backwards and stabilizes.

The addition of new fractures was performed whenever and wherever predicted by the employed geomechanics proxy.

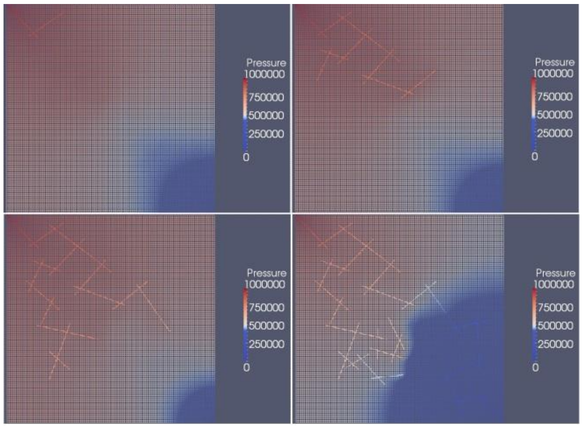

Figure 5: Pressure distribution at various timesteps during the creation phase. The reservoir is heterogeneous and the simulation ends once a large fracture intersects the production well.

Third Test Case

The production phase of a fictional EGS reservoir is simulated. It consists of 50 large fractures with random position, size, aperture and orientation.

A heterogeneous porous medium with impermeable boundaries represents the damaged matrix (Fig. 6). The permeable and heterogeneous region within the reservoir has the shape of an ellipse, outside which the damaged matrix is considered totally impermeable.

An injection and a production well have been added to the reservoir and their permeability has been set equal to a very large value. Initially the reservoir is considered to be filled with hot working fluid of 180^{o}C and the temperature of the injected working fluid is assumed to be equal to 15^{o}C. Constant pressure difference is applied between the two wells forcing the cold working fluid to circulate through the reservoir. The hydraulic properties, the geometry of the large fracture network and their volumes are considered constant.

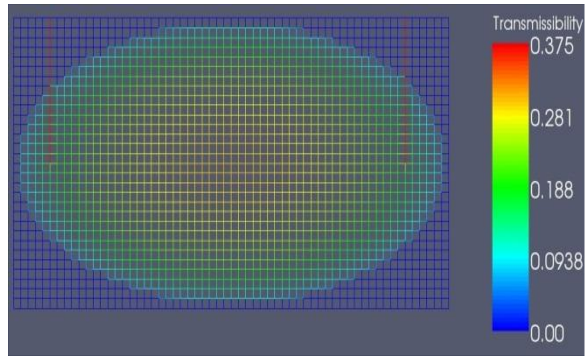

Figure 6: Transmissibility distribution of the connections between damaged matrix and well volumes.

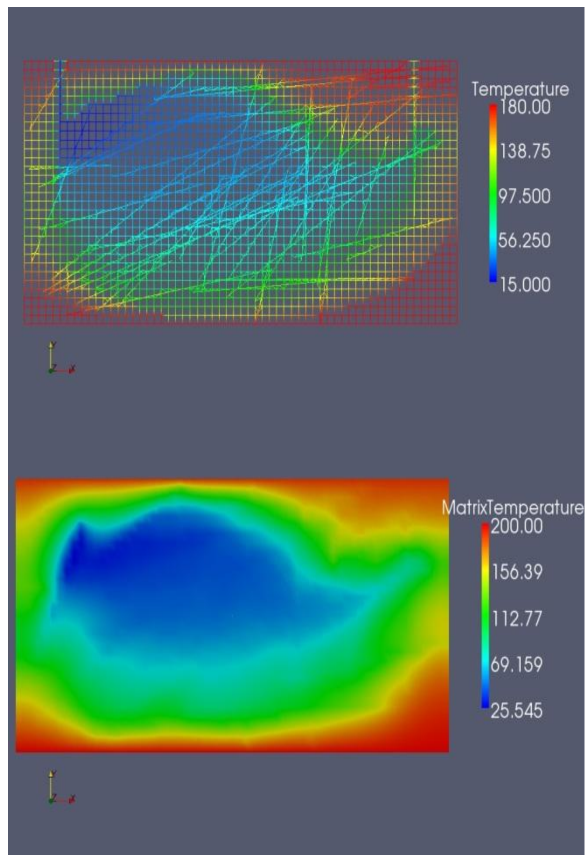

Figure 7: Reservoir and rock temperature for an artificial test case with 50 large fractures.

The surrounding hot matrix is discretized by an orthogonal structured grid identical to the one used for the damaged matrix. At the left and to right boundaries of the reservoir zero heat flux in x-direction was applied and constant temperatures of 200^{o}C and 190^{o}C have been assumed at the bottom and top boundaries respectively. Linear interpolation was applied to initialize the rock temperature in the rest of the domain.

As expected, the cold working fluid enters the reservoir through the injection well, flows through the permeable regions, mass transfer mostly occurs via large fractures and thermal energy is extracted from the hot rock (Fig. 7). Finally, working fluid of increased temperature and enthalpy is forced out through the production well.

The temperature of the rock decreases at a much faster rate in the neighborhood of the injection well. The fact that the working fluid in this region is of low temperature results in low rock temperatures.

FUTURE STEPS

As one can see, the problems that have been solved are dimensionless. No special effort was made in building a test case with real numbers and real properties, since studying the behavior of a real EGS reservoir was not the immediate target of this work. The main aim of the presented test cases was to investigate and demonstrate the potential of this modeling framework.

The fluid losses into the porous space are not accounted for yet. Furthermore, the existing EGS simulator needs to be coupled with geomechanics and geochemistry modules. Further, the code should be optimized for massive parallel computing such that large scale thermal-hydrologic-mechanical-chemical (THMC) EGS simulations can be performed efficiently.

CONCLUSION

A modeling framework has been developed which represents the geometry of an EGS reservoir using a hierarchical approach that ensures flexibility and consistency. The suggested framework is modular and has been coupled with single phase flow and heat transport solvers. Initially, an unstructured grid is created, where all major fractures are explicitely represented and the cloud of small fractures is upscaled and represented by a continuous damaged matrix. Connections between intersecting volumes are added and flux and temperature distributions can be computed in the rock and in the reservoir.

With the proposed method, the addition of new fractures during the creation phase is computationally inexpensive. The expensive task of remeshing the whole reservoir for the addition of new fractures can be avoided, which enables efficient simulation of dynamically changing EGS reservoirs. The resulting software handles both 2D and 3D problems and its general interface enable its coupling with various modules e.g. for geomechanics and chemistry.

REFERENCES

Bower K. M. and Zyvoloski G. (1997), "A Numerical Model for Thermo-Hydro-Mechanical Coupling in Fractured Rock” *International Journal of Rock Mechanics and Mining Sciences*, **Volume 34, Issue 8,** 1201-1211.

Kohl T., and Hopkirk R. J. (1995a), "FRACTure – A Simulation Code for Forced Fluid Flow and Transport in Fractured, Porous Rock” *Geothermics*, **Volume 24, Issue 3,** 333-343.

Kohl T., Evans K. F., Hopkirk R. J. and Rybach L. (1995b), "Coupled Hydraulic, Thermal and Mechanical Considerations for the Simulation of Hot Dry Rock Reservoirs” *Geothermics*, **Volume 24, Issue 3,** 345-359.

Lee S. H., Lough M. F. and Jensen C. L. (2001), "Hierarchical Modeling of Flow in Naturally Fractured Formations with Multiple Length Scales” *Water Resources Research*, **Volume 37, Number 3,** 443-455.

Li L. and Lee S. H. (2008), "Efficient Field-Scale Simulation of Black Oil in a Naturally Fractured Reservoir Through Discrete Fracture Networks and Homogenized Media” *SPE Reservoir Evaluation & Engineering*, **Volume 11, Number 4,** 750-758.

McDermott, C.I., Randriamanjatosoa, A.L., Tenzer, H., Sauter, M. and Kolditz, O. (2005) "Pressure Dependent Hydraulic Flow, Heat Transport and Geo-thermo-mechanical Deformation in HDR Crystalline Geothermal Systems: Preliminary Application to Identify Energy Recovery Schemes at Urach Spa.” *Proceedings World Geothermal Congress 2005*, Antalya, Turkey

McDermott, C.I., Randriamanjatosoa, A.L., Tenzer, and Kolditz, O. (2006) "Simulation of Heat Extraction from Crystalline Rocks: The Influence of Coupled Processes on Differential Reservoir Cooling” *Geothermics*, **Volume 35, Issue 3,** 321-344.

Sanyal S. K., Butler S. J. and Hardeman B. (2000) "Review of the State-Of-The-Art of Numerical Simulation Of Enhanced Geothermal Systems” *Proceedings of the World Geothermal Congress, Kyushu-Tohoku, Japan*, 3853-3858.

Taron J., Elsworth D. and Min Ki-Bok (2009a) "Numerical Simulation of Thermal-Hydrologic-Mechanical-Chemical Processes in Deformable, Fractured Porous Media” *International Journal of Rock Mechanics and Mining Sciences*, **Volume 46, Issue 5,** 842-854.

Taron J. and Elsworth D. (2009b) "Thermal-Hydrologic-Mechanical-Chemical Processes in the Evolution of Engineered Geothermal Reservoirs" *International Journal of Rock Mechanics and Mining Sciences*, **Volume 46, Issue 5,** 855-864.

Yamamoto T., Kitano K., Fujimitsu Y. and Ohnishi H. (1997) "Application of Simulation Code, GEOTH3d, on the Ogachi HDR Site" *Stanford Geothermal Workshop 1997*