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REVIEW OF THE STATE-OF-THE-ART OF NUMERICAL SIMULATION OF ENHANCED GEOTHERMAL SYSTEMS

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ABSTRACT

Under the premise that the behavior of enhanced geothermal systems (EGS) will be dominated by fracture flow, this paper reviews the special features that would be required of any practical numerical simulator for EGS. These features, required in addition to the basic features of conventional geothermal simulators, namely, the ability to handle two-phase fluid flow, heat transfer and tracer transport in porous and fractured media, are: explicit representation of fractures, change in fracture aperture due to effective stress and shear, thermo-elastic effects, relation between fracture aperture and conductivity, and channeling of fluid flow within fractures. Chemical reaction between water and rock and coupling of the reservoir model with a wellbore model would also be desirable features. The paper reviews the well-known simulators that have been used or can be used to model EGS (TOUGH2, TETRAD, STAR, GEOCRACK, FEHM, FRACTure, GEOTH3D and FRACSIM-3D) with regard to the features listed above.

While each of the simulators has many of the capabilities listed above, none has all of them; and each simulator has its strengths and weaknesses. A single type of model may not be suitable for all EGS projects or at every stage of a given project. For example, in the early development stage of an EGS project, when available information is limited and the primary need is for reserves estimation and project planning, fracture network-type models may be more practical to use. In a more mature stage of the same project, when reliable information on fractures becomes available, discrete fracture-type models may be preferable for optimizing injection/production strategy. Water/rock interaction or two-phase flow may not be an important issue in some projects. Therefore, the need for developing a single, all-purpose simulator for EGS applications at this time is perhaps less urgent than taking advantage of the strengths of the various available simulators to solve the problem at hand.

1. INTRODUCTION

This paper reviews existing reservoir simulation technology applicable to the analysis of Enhanced Geothermal Systems (EGS), a term that has been adopted to describe geothermal systems which require enhancement to render them commercially feasible for development or continued exploitation. These differ from currently developed hydrothermal systems in that permeability may be too low for commercial exploitation, natural fluids may be absent because of a lack of fractures, or the reservoir may have become fluid-depleted as a result of over-production. However, a vast amount of heat energy remains in such systems; through artificial enhancement of the system, some of this heat can be recovered. The so-called Hot Dry Rock (HDR) projects exemplify one type of EGS development.

Existing hydrothermal simulators cannot accurately model certain aspects of fractures, either artificially created or enhanced, particularly the dynamic aspects. Existing HDR simulators are better at handling the dynamic aspects of fractures but lack certain other critical features (for example, the ability to handle two-phase flow).

For conventional hydrothermal resources (hot water, steam and two-phase reservoirs in porous or fractured rock), reservoir simulation is a routine activity. Although hydrothermal simulators have been used to model complex fracture systems in an approximate way, they have not been used extensively for modeling artificially fractured systems. Much can be learned about modeling EGS reservoirs from the experience gained in modeling of artificially fractured systems in connection with HDR projects, which lie at one extreme of the EGS spectrum. Some of the simulation methods developed for HDR systems have application in the broader area of EGS reservoirs.

This paper reviews the applicability of four hydrothermal and four HDR simulators to EGS developments. The list of simulators reviewed for this paper is by no means exhaustive; there exist other less well-known simulators that may also be applicable to modeling EGS projects.

2. DESIRED FEATURES FOR EGS SIMULATION

It is important to establish a framework to discuss and identify the common characteristics of EGS reservoirs that are important to successful operation. The general concept is a reservoir system consisting of a porous medium, generally with a natural fracture network, perhaps intersected by highly conductive, hydraulically induced artificial fractures. Flow occurs primarily in fractures and is dependent on fracture apertures, which in turn may be functions of fluid pressure and thermal contraction in the adjacent rock. In EGS systems, the main challenges are improving permeability through enhancement of natural fractures or creation of artificial fractures, and optimizing heat recovery through injection. Heat is removed by the sweep of injection fluid through the fracture system.

Pruess (1990) discusses when fractures must be represented explicitly and when they can be modeled as an effective continuum. An effective continuum approach can only be justified when matrix and fractures remain in approximate thermodynamic equilibrium; that is, only when there are relatively low temperature gradients in the rock. For a typical situation in which the rock matrix is relatively impermeable, approximate equilibrium is only valid if the active fracture spacing is small (or flow rates are very small), owing to the relatively low hydraulic conductivity of the rock. If thermal equilibration is to occur within a few months, fracture spacing must be less than 2-3 meters. In artificially fractured systems and in many low-permeability systems, the actively flowing fractures are more widely spaced (perhaps ten to a few hundreds of meters apart), so that explicit modeling of fractures is more appropriate. This can be accomplished either by a discrete-fracture formulation or through sufficient grid refinement and application of appropriate permeabilities in a porous-medium model.

A Structured Academic Review of HDR/HWR (Hot Wet Rock) was convened at Tohoku University in 1997. The approximately 70 participants in this review had combined experience with all of the HDR/HWR reservoirs (Rosemanowes, UK; Soultz-sous-Forêts, France; Hijiori, Japan; Fenton Hill, USA; and Ogachi-Akinomiya, Japan). Their experience and conclusions represent a significant cumulative knowledge relevant to EGS reservoirs. Based on their conclusions and our survey of the geothermal developers and operators, we can list the necessary and desirable features to be included in an HDR simulator as follows:

- explicit representation of the fractures;
- fracture opening as a function of effective stress;
- shear deformation and associated jacking of the fractures;
- a relationship between fracture aperture and fracture conductivity, including the potential for turbulent flow in the fractures;
- "channeling," and thermo-elastic effects;
- mineral deposition and dissolution;
- a tracer module; and
- two-phase flow and the consequent complexities of phase change, relative permeabilities, capillary pressure effects, etc.

3. SIMULATORS REVIEWED

3.1 HDR Reservoir Simulators

We have reviewed four well-known simulators that are currently being applied to HDR geothermal systems: FRACTure, GEOTH3D, FRACSIM-3D and Geocrack2D. Willis-Richards and Wallroth (1995) provide an extensive bibliography and a list of simulators available in 1995. Other reviews include those by Bodvarsson *et al.* (1986), Tsang (1991), Pruess (1990) and Hudson (1995).

FRACTure is a discrete-fracture, finite-element code for simulating the coupled hydraulic, thermal and mechanical behavior of fractured media (Kohl and Hopkirk, 1995). The model represents fluid flow through a permeable rock matrix, as well as through discrete fractures. Fluid flow may be modeled using both Darcian and turbulent governing equations. Thermoelastic and poroelastic effects are applied to the porous media, and fracture openings are non-linearly linked to rock stress. Heat transfer includes conduction in the rock and transport in the fluid, and is coupled to the elastic and thermal solutions through thermal expansion and non-linear constitutive relationships.

FRACTure has been used to model a variety of different geological problems, including: radon transport to buildings, space heating, tracer propagation, non-laminar hydraulic behavior at Soultz, and heat extraction during aquifer utilization. It has also been used to compare simulations of HDR reservoirs using single and multiple fractures in both two and three dimensions. It has been used to model the Soultz HDR reservoir using flow in a dominant fracture and a turbulent flow model.

FRACTure's approach and concepts make it applicable to various analyses of reservoir operation. Its strength is the range of physics that has been implemented, with three-dimensional hydraulic, thermal and mechanical coupling. It does not include two-phase flow or a coupling of geochemistry to flow. Channeling is not directly supported, but could probably be modeled using material properties for different elements of a fracture. There is no coupling between fracture shear displacement and aperture.

The GEOTH3D simulator of Yamamoto *et al.* (1997) uses microseismic data as a guide to the permeability distribution and has been applied to the Hijiori, Ogachi, and Fenton Hill reservoirs. GEOTH3D uses a 3-D finite-difference approximation to solve for mass and energy balance based on Darcy's Law. The model can describe both water and heat transport in porous media. When applied to a geothermal reservoir, the available microseismic data are used to define non-uniform porosities in proportion to the microseismic intensity. Thus, the flow is greater in areas of the reservoir where the microseismic activity was most intense during stimulation.

A typical application of GEOTH3D is described by Eguchi *et al.* (1998) for the Ogachi HDR reservoir. The GEOTH3D code was applied to a thirty-day circulation test conducted at the Ogachi site in 1995. The measured pressures at the injection and production wells were used as boundary conditions and the resulting computed flow rates compared well with measured data. The model was then used to examine two alternate reservoir designs to improve recovery rates.

GEOTH3D is appealing in its use of the microseismic data obtained during stimulation to make a non-uniform porous-medium model. The model does not include discrete fractures, and, in general, porous-medium models tend to be somewhat optimistic with respect to energy production. This is because porous-medium models usually do not capture the sharp local temperature gradients and cooling that can occur in a fracture and do not represent changes in aperture due to stress or thermo-elastic effects.

The FRACSIM-3D code, a fracture network model that includes fluid flow and heat transfer, has been used to model the Hijiori and Soultz reservoirs. As described in Jing (1998) and in Jing *et al.* (1998), this model is an extension of the 2-D fracture simulator FRACSIM-2D. A similar model has been developed by Tezuka *et al.* (1998). The model focuses on the following reservoir effects: 1) fracture shear and dilation during stimulation and circulation; 2) thermo-elasticity during circulation; and 3) chemical dissolution and precipitation during circulation.

FRACSIM-3D can be used for analyzing both stimulation and reservoir testing operations, including tracer analysis and a simple chemical dissolution model. In the Hijiori model, the correlation between the microseismic volume and the predicted simulation volume is quite good. A statistical flow calculation was then performed. Depending on the generated fracture distribution, different flow rates between the injection and production wells were obtained; however, the mean values for the wells matched the observed flows quite well. Good matches were also obtained for the tracer calculations. The best-fit flow and tracer model was then used to predict reservoir behavior during a 30-day test and during long-term production and injection.

FRACSIM-3D can analyze both the enhancement of the reservoir (well stimulation) as well as the operation of the reservoir once it has been developed. The stimulation analysis appears to be quite strong, including shear dilation (based on a single global stress). Reported stimulation results show good correlation with the observed microseismic data. However, there is an active debate on the exact meaning of microseismic events, especially at Hijiori, where the best connections to the fracture system occur in relatively aseismic regions. FRACSIM-3D maps the fractures to form a non-uniform porous-medium model. Unavoidably, this results in smearing of local gradients near a fracture and can lead to optimistic predictions of reservoir life. The inclusion of simple chemical dissolution and deposition is a useful feature.

Geocrack2D is a finite-element-based simulator developed by Swenson and Hardeman (1997) that focuses on flow in fractures and has been used to model the Fenton Hill and Hijiori reservoirs. The code can solve coupled thermal, hydraulic and mechanical problems where the flow is in fractures (Swenson, 1997). A Geocrack2D model consists of rock blocks with nonlinear contact and discrete fluid paths between the blocks. Heat transfer occurs by conduction in the rock blocks and transport in the fluid. A tracer model is also included that uses particle tracking with thermal decay, diffusion, and adsorption of the tracer. The user interactively defines the finite-element mesh, the material properties, boundary conditions, and solution controls.

Geocrack2D's discrete-fracture approach is similar to that used in FRACTure. The fracture aperture is a function of effective stress, flow is calculated using the cubic law, thermo-elastic effects are included in the model, and tracers are calculated using a particle-tracking algorithm. The model does not include coupling of fracture aperture to shear displacement, and there is no porous-medium flow. The program is interactive, with graphical feedback to the user in all phases. At the present time the implementation is 2-D; however, a three-dimensional version is under development (Hardeman and Swenson, 1998).

3.2 Hydrothermal Reservoir Simulators

We have reviewed four simulators that are currently used to model hydrothermal reservoirs: TOUGH2, TETRAD, STAR and FEHM.

The TOUGH2 simulator is used extensively in hydrothermal reservoir simulation, nuclear waste isolation and groundwater modeling. It is a general-purpose numerical simulation program for multi-phase, multi-component fluid and heat flow in porous and fractured media (Pruess, 1991) developed at Lawrence Berkeley National Laboratory of the U.S. Department of Energy (DOE). The space discretization is made directly from the integral form of the governing equations. This method avoids any reference to a global system of coordinates and allows irregular discretization of the considered domain.

TOUGH2 allows the simulation of 1-D, 2-D, and 3-D geometry of porous or fractured media. Heat and mass transfer processes are fully coupled. Tracer transport with adsorption and radioactive decay is accounted for. The treatment of gas in the code is extensive, with the inclusion of all the major gas species normally present in a geothermal reservoir. For dissolved solids, the effects of precipitation and dissolution of NaCl on porosity and permeability are included. One of the more important features of TOUGH2 is the Multiple Interactive Continua or "MINC" method. In an EGS or HDR system, there normally exists a high temperature gradient between the host rock and the circulating fluid. MINC allows sequential partitioning of the rock matrix, and hence, the pressure and temperature transients between the host rock and the injected fluid can be simulated. Discrete fractures can be easily handled as TOUGH2 allows the grid to be highly irregular. Caution must be exercised when using an irregular grid, as the accuracy of the solutions depends upon the accuracy with which the various interface parameters in the flux equations can be expressed in terms of the average conditions in the grid blocks (Pruess, 1991). A prototype interface between TOUGH2 and Golder Associates' FracMan discrete fracture generator has been developed. Flow-channeling effects, and discrete-fracture aperture change due to stress or thermo-elastic effects are not accounted for. Effects of pressure and temperature on porosity and permeability are simulated by the use of rock compressibility and expansivity constant coefficients.

The TETRAD simulator, developed by the Computer Modeling Group of Calgary, Alberta, Canada, is a finite-difference numerical simulator that has been used extensively in hydrothermal, oil, and natural-gas reservoir simulation. Conservation equations are expressed in conventional differential equation forms and then discretized. These equations are fully coupled, and the simulator can be used to model 1-D, 2-D, and 3-D heat and mass flow in porous or fractured media. Fractures can be specified via the use of the double-porosity/permeability option. Each matrix or fracture block is assumed to be in local thermodynamic equilibrium. Interaction between the matrix and fractures is described using the Warren and Root formulation. This simulator allows selective partitioning of the considered reservoir domain through the use of the "local grid refinement" option. This feature permits sections of the base grid to be partitioned, allowing selective portions of the simulated area to have higher grid block resolution. This local grid refinement is, however, not analogous to the MINC method used in TOUGH2 and cannot be applied to model the pressure and temperature transients within a matrix block.

TETRAD contains all the features necessary for reservoir studies. The non-reacting tracer package is comprehensive. Discrete fractures can be modeled, but aperture changes due to stress or thermo-elastic effects have not been included. Flow-channeling effects are not considered. Documentation is extensive, and TETRAD is considered one of the more user-friendly simulators in the industry.

The STAR simulator, developed by Maxwell Technologies of San Diego, California, has been used for hydrothermal, oil, and natural-gas reservoir simulation (including heavy-oil thermal recovery). It employs the finite-differencing scheme in the discretization of the governing equations. It is a 1-D, 2-D, or 3-D simulator and contains all the features commonly found in hydrothermal reservoir simulators, including a tracer module, deposition and dissolution of NaCl, and non-condensible gases. Standard treatment of rock compaction is included in the simulator with the use of a user- prescribed rock-compressibility factor. Changes in pressure and temperature result in changes of rock porosity and permeability.

STAR has been used to perform simulation studies in hydrothermal, natural-gas, and heavy-oil thermal-recovery projects (Pritchett, 1995). It is a typical reservoir simulator with all the necessary features for conducting hydrothermal reservoir simulation studies. The "permeable matrix" option can be used to model the pressure and temperature transients between fractures and matrix rock arranged in a rectangular grid system. A comprehensive non-reacting tracer package is included in the simulator. Flow-channeling effects are not considered, nor are the effects of stress on fracture aperture.

FEHM (Finite-Element Heat and Mass Transfer), developed at Los Alamos National Laboratory, has been used for simulation of hydrothermal, oil, and natural-gas reservoirs, nuclear-waste isolation, and groundwater modeling, as well as for the HDR reservoir at Fenton Hill reservoir (Zyvoloski *et al.*, 1995; Bower, 1996). It simulates non-isothermal, multi-phase, multi-component flow in porous media. The equations of heat and mass transfer for multi-phase flow in porous and permeable media are solved using the control-volume finite-element method. The permeability and porosity of the medium are allowed to depend on pressure and temperature. The code also has provisions for movable air and water phases and non-coupled tracers (that is, tracer solutions that do not affect the heat- and mass-transfer solutions). The tracers can be passive or reactive.

FEHM can simulate 2-D, 2-D radial, or 3-D geometries. Using either double-porosity/double-permeability or dual-porosity models, FEHM can simulate flow that is dominated in many areas by fracture and fault flow. The code can handle coupled heat- and mass-transfer effects, such as boiling, dry-out, and condensation, and can incorporate various adsorption mechanisms, ranging from simple linear relations to nonlinear isotherms.

FEHM is a strong two-phase porous-medium model and also has good tracer capabilities, with multiple reacting tracers. The formulation is rigorous and well documented, with extensive verification. FEHM can model movement of both water and steam phases and the movement of heat through convection and conduction, making it well-suited for EGS simulation. FEHM combines 3-D volume elements with 2-D plate elements, allowing integration with discrete-fracture network (DFN) generators. The 3-D version (the official release) does not include elastic deformation, discrete fractures, or aperture changes due to stress or thermo-elastic effects. These have only been included in the 2-D version and have not been extensively used. A prototype interface between FEHM and Golder Associates' FracMan discrete fracture network generator has been developed. FEHM does not provide mechanical coupling, but it does have tracer-test modeling interfaces, facilitating model calibration.

4. OBSERVATIONS AND DISCUSSION

4.1 Current Capabilities Relative to Desired EGS Features

Tables 1 and 2 summarize the capabilities of the HDR and hydrothermal simulators, respectively, with reference to the following features:

Explicit representation of fractures: All simulators can be used to simulate fractures at some level; the mathematical formulation that describes the fractures and the ease with which fractures can be represented may differ from one simulator to the next.

Fracture opening as a function of effective stress: This will be important in reservoirs in which the natural permeability is low or when permeability enhancements are being modeled. Many of the models include approximations of this, either through permeabilities that are a function of stress or by discrete-fracture modeling.

Shear deformation and associated jacking of the fractures: This feature is similar to the previous one and is also subject to similar limitations.

Relationship between fracture aperture and fracture conductivity: This feature requires the fluid flow in the fracture to be a function of the fracture aperture. Practically speaking, all reviewed simulators have this feature. In discrete-fracture models, the fluid flow in the fractures is described by the cubic law; and in porous-flow models, fluid flow in the fracture is described by Darcy's Law. Hence it can be said that the above equations are practically equivalent with $a^3/12$ equal to Akk_r, where a is the fracture aperture, A is cross-section to the flow, k is the permeability and k_r is the relative permeability. If the cubic law is used, only single-phase fluid flow can be accounted for because this analytical solution ceases to be applicable in the presence of multi-phase fluid. In the second equation, such restriction is not present, and the equation is applicable for all phases.

Channeling in fractures: Obtaining sufficient detailed knowledge to successfully identify when channeling is occurring will require input from other technologies, such as tracers and other fracture-detection methods. These technologies are under development, but may not be achievable in the near future. As indicated in Table 1, only one simulator (FRACTure) can handle this (approximately, with user-define material properties).

Thermo-elastic effects: The stress in the rock due to temperature change, in addition to the fluid-pressure stress, can alter the fracture aperture, which changes the fluid flow in the fracture. Since the aperture can not be measured directly, it must be inferred through the transient and steady-state flow simulation and by comparison with tracer data. Once such inferences are made, two of the HDR simulators are equipped to handle thermo-elastic effect around individual fractures, while a third handles this using a global stress (Table 1).

Mineral deposition/dissolution: Reactive chemical transport simulation in geothermal reservoirs is a major topic, particularly if all typical chemical species are included. Work in coupling the reactive chemical transport module to TOUGH2 is in progress, and the preliminary results appear promising (Table 2). FRACSIM-3D includes a simple chemical dissolution and deposition feature.

Tracer module: All simulators reviewed here provide tracer modules.

Multi-phase flow: All of the hydrothermal simulators provide multi-phase flow capability; none of the HDR simulators have this feature.

4.2 Concluding Remarks

Tables 1 and 2 and the above discussion illustrate that, while each of the simulators has many of the capabilities listed above, none has all of them; that is, each simulator has its strengths and weaknesses. A single type of model may not be suitable for all EGS projects or at every stage of a given project. For example, in the early development stage of an EGS project, when available information is limited and the primary need is for reserves estimation and project planning, porous-media or fracture-network models may be more practical to use. In a more mature stage of the same project, when reliable information on fractures becomes available, discrete-fracture models may become preferable for optimizing the injection/production strategy. Therefore, the need for developing a single, all-purpose simulator for EGS applications at this time is less urgent than further developing existing approaches.

As part of this review, the opinions of experts engaged in both HDR and hydrothermal projects were sought. While useful, these discussions also highlighted the lack of experience with the conditions of EGS systems. Thus, many of the evaluations of required EGS features are statements of opinion, not fact based on experience. At this time, the EGS experience base does not exist to rationally commit to one particular simulator or approach. As such, it is premature to identify a particular type of simulator as the primary focus of development. Instead, developing an EGS simulation experience base should be the highest priority. Reservoir modeling and simulator development cannot be done in the abstract; feedback is necessary from active participants in the development and operation of a reservoir. Only through such active interaction with realistic problems can the appropriate simulation needs be identified and skills developed to apply to other reservoirs. Therefore, active simulation of real EGS reservoirs is critically important.

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Table 1: Features of HDR Simulators Potentially Applicable to EGS

Capability	FRACTure	GEOTH3D	FRACSIM-3D	GEOCRACK
Discrete fractures	•		1	•
Aperture function of normal stress	•		2	•
Aperture function of shear			•	
Flow rate as function of aperture	• (4)		•	•
Channeling	• (5)			3
Porous flow in matrix	•	•		3
Thermo-elastic effects	•		2	•
Tracer transport	•		•	•
Multi-Phase flow				
3D	•	•	•	3
Irregular grid			•	•
Mineral deposition/dissolution			•	

1) Discrete fractures during stimulation, converted to equivalent porous media for operation analysis
2) Based on global stress, no local elasticity solution
3) Under development
4) Includes laminar and turbulent flow laws
5) Possible with user defined material properties
6) Being tested

Table 2: Features of Hydrothermal Simulators Potentially Applicable to EGS

Capability	FEHM	STAR	TEDRAD	TOUGH2
Discrete fractures	•	•	•	•
Aperture function of normal stress				
Aperture function of shear				
Flow rate function of aperture				
Channeling				
Porous flow in matrix	•	•	•	•
Thermo-elastic effects	•	•	•	•
Tracer transport	•	•	•	•
Multi-Phase flow	•	•	•	•
3D	•	•	•	•
Irregular grid	•			•
Mineral deposition/dissolution				3

1) Discrete fractures during stimulation, converted to equivalent porous media for operation analysis
2) Based on global stress, no local elasticity solution
3) Under development
4) Includes laminar and turbulent flow laws
5) Possible with user defined material properties