AAPG/SPE/SEG HEDBERG CONFERENCE
"ENHANCED GEOTHERMAL SYSTEMS"
MARCH 14-18, 2011 – NAPA, CALIFORNIA

Development and Validation of a Stimulation Prediction Model for EGS Reservoir Creation

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The development of Enhanced Geothermal Systems (EGS) will require innovative methods to stimulate low permeability reservoirs through the formation of large induced fractures that will allow injection of large volumes of water required to continuously produce steam for power generation or other heating requirements. Large induced fractures are needed to ensure that injected water is in continuous contact with rock fracture surfaces that are at high temperature. A system of such fractures will ensure that water can circulate through the reservoir and be converted to significant volumes of steam or hot water before being returned to the surface. The most common technique for reservoir stimulation is hydraulic fracturing of the formation from a wellbore, although other methods of fracturing are also available. To ensure that fractures remain conductive, proppants are injected and circulated into the fracture aperture to prevent the fractures from closing.

The hydro-thermal fracturing process in EGS reservoirs is a combination of many complicated physical phenomena, including, fracture opening/closure in poroelastic geologic materials, non-linear behavior of injected slurry and its leak-off into the formation, fracture propagation in the rock mass, proppant transportation and its action to prevent fracture closure, and flow of fluid and heat through the fracture and the surrounding rock. Many of these processes are coupled in that one process affects the other processes. For instance, fracture hydraulic apertures affect fracture flow and fluid pressures. In turn, mechanical response of fracture (closure or opening) is affect by the fracture fluid flow and fluid pressures. Numerical modeling is an effective way of understanding the mechanics and coupling behind each of the phenomenon of hydraulic fracturing.

The fracture geometry greatly affects well stimulation and the productivity of hydraulic fracturing. Fracture designers wish to create fractures in the appropriate directions in the reservoir, and need to know the necessary volumes of injection fluid and pressure. Fracture geometry is governed by the in-situ stresses in the reservoir and the layers above and below the pay zone, material properties of the rocks, fracturing fluid properties, and injection schedule. In the case of a deviated borehole, the axes of the principal stresses are usually not parallel to the borehole direction, and a fracture initiated from perforation between packers will tend to twist and bend perpendicular to the maximum tensile stress axis. However, most of the hydraulic fracturing simulators that have been developed adopt fracturing geometry assumptions such as two-dimensional planar fracture and symmetrical fracture with respect to the borehole. Examples include the classical two-dimensional Perkins-Kern/Nordgren (PKN), Geertsma-DeKlerk (GDK) and other penny shape type fracture geometries (Perkins and Kern, 1961; Geertsma, J. and de Klerk, 1969). Pseudo-3D and planar 3D hydraulic fracturing simulators have been developed, and many proprietary to oil and gas service companies (e.g., MFRAC, FRACPRO, STIM-PLAN and Frac-Cade). Warpinski et al. (1993; 1994) provided a review and comparison of predictions for the available 2D and pseudo-3D simulators. Although there have been several efforts devoted to developing true-3D hydraulic simulators (e.g., Advani et al. 1990; Devloo et al. 2006), so far, as pointed out by Carter et al. (2000), the only available code for true 3D hydraulic simulation is Cornell University's FRANC3D code (Carter et al. 2000).

Planning and design of reservoir stimulation using hydraulic fracturing and fracture propping require advanced computational models and tools. Fracturing simulators are available from the Petroleum Industry, however, these may not be fully suited for use in EGS applications due to the following reasons:

1) *Fracturing and proppant response in EGS will encounter rock types that are different from the mainly porous sedimentary rocks in oil and gas reservoirs.* Hence, different fracture propagation phenomena, and injected fluid and proppant flow/transport behavior will be encountered in EGS. In particular, most EGS will be developed in faulted crystalline rocks which are less porous and permeable than sedimentary hydrocarbon reservoirs.
2) *In EGS, temperature will be an important factor in the fracture propagation process*. Temperature will influence the fluid and rock properties, and thermal stresses will affect fracture propagation and may lead to secondary fracturing (Gutierrez et al. 1997). Secondary fractures will enhance thermal sweep of the reservoir.
3) EGS will require new and different types of proppants from those used in the oil and gas industry. The temperature, stresses, corrosive brine chemistry and high-volume circulation in potential EGS reservoirs would destroy the majority of the most widely used proppants. *New computational tools are needed to simulate the response of future high-strength and temperature-hardened proppants for EGS applications.*
4) *In general, fracturing in EGS applications will have three-dimensional* (*3D*) *geometries*. A new generation of simulation model for the three-dimensional fracturing and proppant flow in heterogeneous formations is urgently required in the EGS industry.

The presentation will cover the development and validation of true 3D hydraulic fracturing and proppant flow/transport simulator that is particularly suited for planning and designing stimulation strategies for EGS applications. The following are the envisioned innovative components of the proposed new EGS stimulation model:

1) The model is *truly three-dimensional* and able to deal with three-dimensional fracture propagation including bending and twisting of the fracture in accordance with the local in situ stress situation, and the presence of heterogeneities (e.g., fractures, bedding planes, joints, etc.) in the rock mass. A 3D Displacement Discontinuity (DD) formulation for an elastic medium is used to model the relationship of fracture aperture and stress around the fracture.
2) The simulator accounts for the *coupled hydro-thermo-mechanical processes involved in fracturing*, including fracture opening and propagation, injected fluid flow/transport, and heat flow and transport.
3) The model *incorporates thermally induced stresses and temperature-dependent fluid and rock properties* in the fracture propagation process. Temperature-induced secondary fracturing is modeled in the simulator.

4) The simulation tool is *able deal with the entire process of hydraulic fracturing* including the post-shut-in process, proppant flow and transport, fluid leak-off and second breakthrough. Fracturing processes including the post-shut-in process are calculated so as to satisfy the equilibrium of injected fluid volume, fracture volume and leak-off volume.
5) The simulator is able to *deal with layered formations* with different rock mass conditions in each layer. Three-dimensional in-situ stresses are defined and affect the fracture formation. Leak-off coefficient and fracture toughness are also defined in each layer.
6) *Deviated boreholes with arbitrary deviation angles are considered in the unsymmetrical formation of fractures*. The initial fracture, which is formed along the perforation zone of the borehole, is assumed to be elliptical. One wing or two wings of the fracture can be considered.
7) *Non-Newtonian rheological behavior of the fracturing fluid and proppants is considered*. The property of the injected fluid is assumed to be uniform throughout the injection schedule. However, the viscosity of the fluid inside of the fracture is affected by the concentration of proppant.
8) *Injection rate, proppant concentration in the injected fluid and time step interval are defined along with pump time*. Shut-in and flow-back are considered as the cessation of the pumping and negative injection rate, respectively.

To show the validity of the proposed techniques, the 3D hydraulic fracturing simulator will be validated against the results of scale model tests and data from field case histories of EGS reservation. The first set of validation will be through the use of laboratory scale model tests of hydraulic fracturing in rocks. A drawback of laboratory tests is that only small-scale models can be tested and it will be necessary to extrapolate results and observations to field scale. However, laboratory tests can be carried out under prescribed and well-controlled conditions, and the results can be directly used in validation of computer models. As such, model tests are easier to replicate and simulate using computer models than field scale tests. The scale model tests will be carried using a cost-effective polyaxial rig that is able to load a 35x35x35 cm^3 block of a rock sample (or an analogue rock material) under three-dimensional stress conditions. The polyaxial rig will be built from a thick-walled steel cylinder. The cubical rock sample will be loaded on its six faces by flatjacks which are pressurized by hand pumps. The flatjack pressures will be controlled to achieve triaxial stress conditions with different magnitudes of overburden stress σ_v, maximum horizontal stress σ_H, and minimum horizontal stress σ_h. The rock sample will be kept at a high temperature during testing by inserting heating elements between the flatjacks and the rock sample.

The second set of validation studies will use data from case histories of EGS creation to show that the model can be used in real EGS projects. Two EGS case histories from Japan, the Ogachi EGS Test Site and Hijiori HDR (Hot Dry Rock) Test Site, will be used. Both EGS projects involved the creation of engineered reservoirs through hydraulic fracturing to produce geothermal energy, and both projects generated large amounts of data during the stimulation stages. More importantly, the two projects experienced very contrasting degrees of success in geothermal energy production, and the experience can be valuable in learning about the role of stimulation in EGS projects.

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