A Study of Propagation of Cooled Cracks in a Geothermal Reservoir

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ABSTRACT

Thermal stimulation has been considered as a means of enhancing reservoir permeability. The plausibility and the conditions for success of such approach are investigated by considering the influence of cooling on fractures and their propagation. Interaction of multiple fractures and their trajectory is also considered. Results indicate that under suitable conditions of in-situ stress regime, pore pressure, and cooling, thermal stimulation can lead to significant fracture propagation. The necessary conditions for effective contribution of this process to reservoir permeability are also discussed.

Introduction

The influences of thermal processes on fracture opening have been studied by a number of investigators (Murphy, 1978; Barr, 1980; Perkins and Gonzalez, 1985). These thermoelastic and a poro-thermoelastic analysis (Ghassemi and Zhang, 2006) of a uniformly cooled crack indicate that large thermal stresses develop that can give rise to tensile cracking. Also, experimental work (Finnie et al., 1978) and 3D analysis of injection into fractures (Ghassemi et al., 2007) show the possibility of high tensile stress zones developing in the vicinity of the main fracture, indicating a potential for multiple initiation and propagation events. Cooling induced stresses causes a complete rotation of the stress field such that stress parallel to the secondary cracks becomes the in-plane major principal stress (higher than the component in the normal direction) and may exceed the in-situ stresses of the geothermal reservoir. These cracks can propagate into the rock matrix perpendicular to the main fracture and increase the permeability of the reservoir. The formation and propagation of thermal fractures in response to cooling of their surfaces has been theoretically treated (Bažant and Ohtsubo, 1977; Nemat-Nasser et al., 1978); these analyses predict that many short cracks may appear shortly after cooling, however, only some of them will grow long enough to penetrate deeply into the reservoir matrix (Figure 1). It has been shown that short equidistant cracks will grow simultaneously for some distance until they reach the bifurcation point. At this point the propagation of one crack suppress the propagation of its nearest neighbours and only every second crack will grow further until the next bifurcation point is reached. In our work we explicitly consider the propagation with time of many thermal cracks in a geothermal reservoir matrix that is cooled by cold water injection.

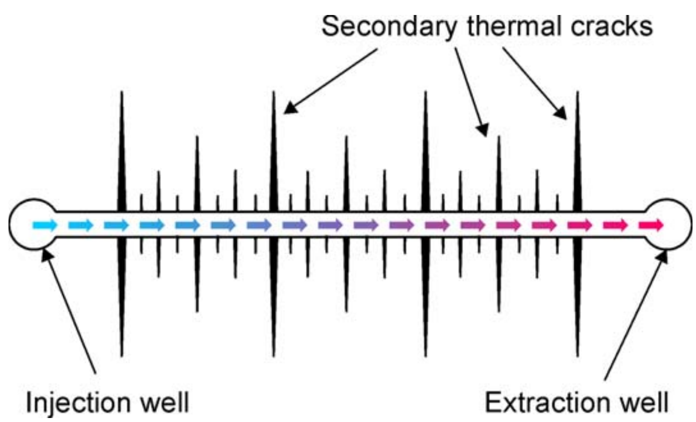

Figure 1. Schematic of a cooled surface in geothermal reservoir with secondary thermal cracks.

Temperature and Thermoelastic Stress

We solve the problem of injection/extraction in a line crack. In deriving the solution for the 2D temperature distribution, we assume that the rock matrix permeability is low and fluid leak-off can be neglected. The secondary thermal fractures that are created upon cooling of the main fracture walls are considered to be small and filled with water having the same temperature as the rock at that location, so that the temperature field is only determined by the cooling of the main crack. We consider the fluid flow inside the secondary fractures to be small and negligible; therefore, the rock is cooled only by the flow in the main fracture. These assumptions are valid as long as the secondary crack opening remain low under cooling and pressurization by fluid and the secondary fractures do not coalesce with other pre-existing natural fractures. With these assumptions, the problem of heat extraction from hot rocks by the injection of the cold water can be solved using the integral formulation in the Laplace domain as described in Cheng et al. (2001). The temperature in the reservoir is found by solving the integral equation on the fracture plane:

$$\tilde{T}(x,y,s) = -\frac{Q\rho_w c_w}{2\pi K_r}\int_0^L \frac{\partial \tilde{T}(x',0,s)}{\partial x'} \mathrm{K}_0(\xi)\,\mathrm{d}x' \quad (1)$$

where $\tilde{T}$ is the normalized temperature in Laplace domain, s is Laplace transform parameter, $\xi = \sqrt{\rho_r c_r s / K_r}\, R$ with R as the distance between the source point and the field point, Q is injection rate, K_r is rock thermal conductivity and ρ_w, c_w, ρ_r and c_r are density and heat capacity of water and rock, respectively. The integration is performed along fracture of length L, the integral equation (1) is solved using a collocation technique. Once the temperature inside the fracture is found, the thermally induced stresses are found using the Green's function for the thermal stresses due to a continuous heat source (Nowacki, 1973):

$$\tilde{\sigma}_{ij}(x,y,s) = -Q\rho_w c_w \int_0^L s\tilde{\sigma}_{ij}^{cs}(R,s)\frac{\partial \tilde{T}(x',0,s)}{\partial x'}\,dx' \quad (2)$$

where the fundamental solution $\tilde{\sigma}^{cs}$ is given as (Nowacki, 1973):

$$\begin{aligned} \tilde{\sigma}_{rr}^{cs} &= \frac{-E\alpha_T}{4\pi(1-\nu)K_r}\frac{1}{s}\left(\frac{2}{\xi^2} - \mathrm{K}_2(\xi) + \mathrm{K}_0(\xi)\right) \\ \tilde{\sigma}_{\theta\theta}^{cs} &= \frac{E\alpha_T}{4\pi(1-\nu)K_r}\frac{1}{s}\left(\frac{2}{\xi^2} - \mathrm{K}_2(\xi) - \mathrm{K}_0(\xi)\right) \end{aligned} \quad (3)$$

where E is Young's modulus, ν is Poisson's ratio, α_T is linear thermal expansion coefficient.

The elastic solution i.e., the solution to the fracture propagation part of the problem is obtained by using the complex variable boundary integral equation of elasticity theory (Linkov, 2002) with thermally induced stresses used as the boundary conditions on the crack faces.

Initiation of Thermal Cracking

Secondary thermal cracks may initiate from sufficiently large pre-existing defects in the rock mass. However, in the absence of such defects, the secondary cracks initiate in unstable (fast, nearly instantaneous crack generation) manner in intact material when strain energy due to thermal load is sufficient to produce number of cracks of certain length. The initial length and spacing between such cracks may be estimated from energy balance between the energy required to generate new surfaces and the strain energy released during formation of new cracks.

The analysis of the minimum possible spacing between thermal cracks forming by the instantaneous uniform cooling of an infinite surface was given by Nemat-Nasser et al. (1978). If all stored energy is relieved by cracking, the crack spacing can be determined from the condition $G_c a = dU_0(a)$, where U_0 is the strain energy per unit length stored in a layer of thickness a, due to the stress acting in the direction normal to the potential crack faces, G_c is critical energy release rate of rock and d is crack spacing. Assuming the crack spacing approximately equals the crack length (as dictated by mechanical crack interference) allows us to estimate the minimal crack length and spacing and the time at which the cracks will appear. Several crack propagation direction criteria have been developed over the years, the most popular is the maximum circumferential stress criterion or the maximum energy release rate criterion. However, for some problems, especially those involving crack growth in the direction of compressive stresses, the application of the maximum circumferential stress criterion leads to an oscillating crack path. To overcome this difficulty we use the method of Stone and Babuška (1998).

Numerical Examples

Let us consider injection/extraction in a line fracture that is 200 m long. The injected water temperature is 20 °C and the initial temperature of the rock is 220 °C. Other material constants are presented in Table 1. To simulate the growth and interaction of secondary thermal fractures, a number of small, equally spaced perpendicular cracks are initially inserted along the main fracture. The fracture toughness of rock usually is relatively low and thermal fractures can grow into the zone of compressive total stresses (in-situ plus thermally induced stresses). After the crack grows by a finite increment during numerical simulation of crack propagation, the crack tip will be located even further into the compressive zone which may lead to crack closure and even a negative stress intensity factor (if no contact algorithm is implemented). To avoid such situation, very small crack increments are required. In the current study, the fracture toughness used in the simulations was set to a sufficiently high value to reduce the computational time.

In the first problem, we study crack propagation in injection/extraction operation from a major fracture. Seventeen secondary fractures with 2 m half-length, and a spacing of 10 m were used in the simulations. Each fracture was subdivided into 10 segments.

Table 1. Material data used in simulation.

Young's modulus, E	37.5 GPa
Poisson's ratio, ν	0.25
Fracture toughness, K_{Ic}	10 MPa m$^{1/2}$
Rock density, ρ_r	2650 kg / m^3
Water density, ρ_w	1000 kg / m^3
Rock heat capacity, c_r	790 J / kg K
Water heat capacity, c_w	4200 J / kg K
Rock thermal conductivity, K_r	10.7 W / m K
Rock linear thermal expansion, α_T	8e-6 1 / K
Flow rate, Q	5e-5 m^2 / s
In-situ stress, σ_{xx}	35 MPa
In-situ stress, σ_{yy}	50 MPa
Rock temperature, T_r	220 °C
Water temperature, T_w	20 °C

For each time step the induced thermal stresses were calculated for each segment's collocation points and then used as boundary conditions in the elastic analysis. Then, the crack tips for which the propagation criterion is met were moved by some distance (0.4 m in this simulation) and iterative algorithm of Stone and Babuška (1998) was employed to find the propagation direction for which the K_{II} is zero (thermal stresses were updated for each iteration). The size of the time step was chosen such that only several crack tips could propagate during every time step.

Due to high thermal tensile stresses and low tensile strength of rocks, it can be expected that thermal fractures will appear relatively soon after total stresses (in-situ plus thermally induced stresses) in the direction parallel to main fracture become tensile and exceed tensile strength of material. The theoretical analysis of Bažant and Ohtsubo (1977) predicts that typically initial cracks as small as several centimeters could be expected. For the parameters used in this analysis of Bažant predicts an initial thermal crack length equal to 0.2-0.3 m. In the current study we are mostly interested in the long-term behavior of the secondary thermal cracks and the initial depth of fractures was chosen as 2 m, therefore, all smaller fractures that may have grown at earlier times are not considered in this simulation.

The crack located 20 m away from injection well starts to grow after about 2 months of injection. As the thermal front moves along the main fracture, other fractures start to propagate. The thermal front and the length of the secondary fractures after 1 and 6 years of fluid injection are presented in Figure 2. As it is expected, the fractures interact and affect each other when their length is approximately equal to the spacing between them. This interaction leads to instability of fracture growth; the slightly longer fracture suppresses the growth of its neighbor, as shown in Figure 2b. As a result, only every second fracture will grow from this moment on until the next bifurcation point is reached. To correctly catch the instability or bifurcation point by numerical simulation, some care is needed in choosing the crack increment size and time step. For larger increments the cracks may pass instability point and grow longer than they should.

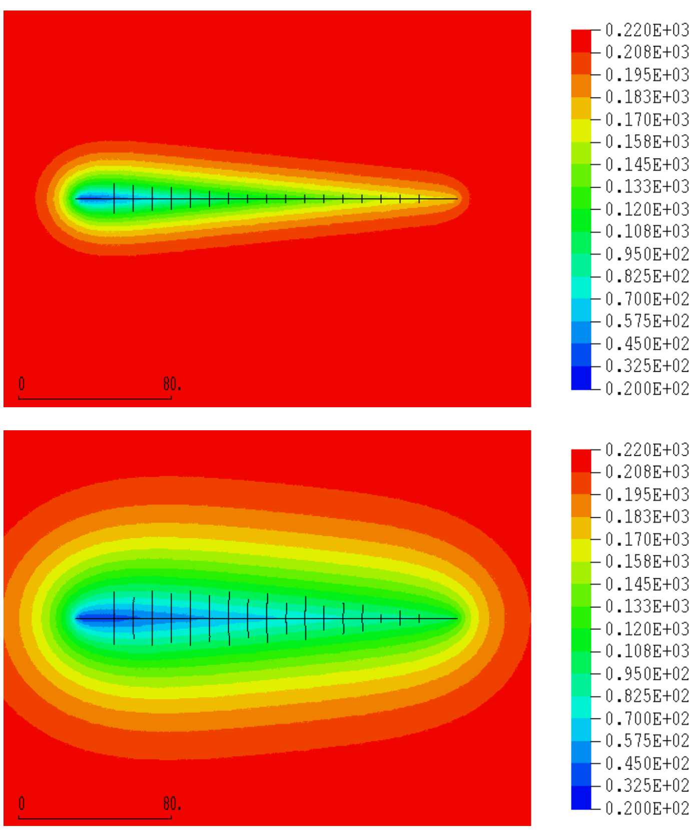

Figure 2. The temperature field in the rock matrix after (top) one and (bottom) six years of injection/extraction. Black vertical lines are thermally induced cracks.

Figure 3 shows the total σ_{xx} stress component and the secondary thermal fracture geometry after 30 years of injection/extraction. All thermal fractures are located inside the zone of tensile total stresses with their tips grown to edge of the compressive stress zone. The length of the longest secondary fractures is about 25 m. The opening of the longest cracks after 30 years is about 8 mm whereas the shorter cracks have an opening of nearly 1.5 mm.

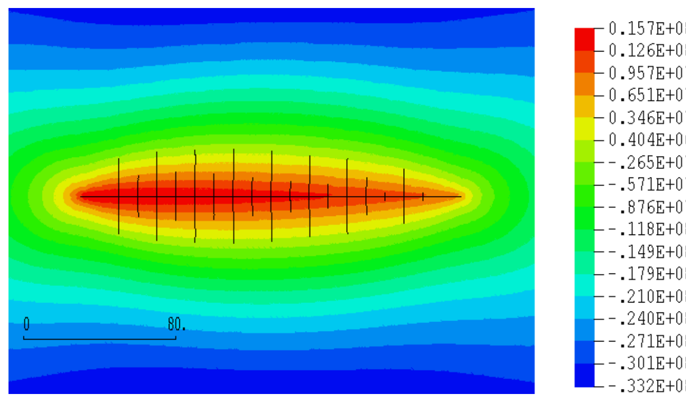

Figure 3. Distribution of the total stress, σ_{xx} (MPa), and secondary fractures in the reservoir rock matrix after 30 years of operation.

As a second example we consider thermal cracks formed by the sudden and uniform cooling of the major fracture surface (thermal shock). To simulate the instant cooling we use a very high flow rate per unit fracture height in the calculations, about 1 m^2 / s, and the fracture length is 600 m; all other parameters are the same as for the injection/extraction example. For such high flow rate the fracture surface is cooled within 1 min and for longer periods this approximately corresponds to instant cooling. The average crack spacing for the problem of instant uniform surface cooling was estimated using numerical simulations with 65 randomly distributed small cracks with initial half-lengths of 0.5 m and an average spacing between of 1 m. The position of each thermal crack along the main cooled fracture, P_i, was determined as $P_i = i*d \pm \mathrm{RND}(\Delta d)$, where d is average spacing between cracks and RND(Δd) is random number in range between 0 and Δd.

Typical geometry of the growing cracks is presented in Figure 4. Because we use a finite number of cracks in the calculations, the two end cracks grow slightly longer than the others and have distinct shielding effect on the neighbour cracks within a zone approximately equal to the half-length of the end cracks. Therefore, only the middle part of the model was used to estimate the average crack spacing.

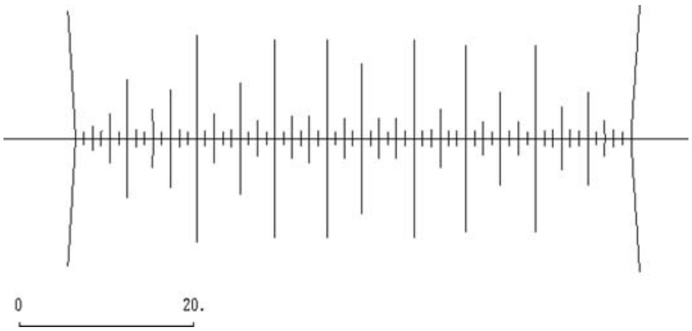

Figure 4. Geometry of the secondary thermal cracks for uniform cooling of the main fracture.

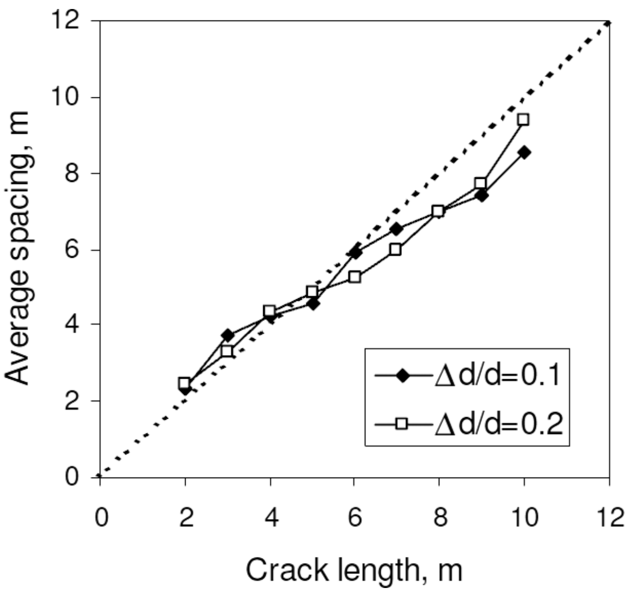

Figure 5. Average crack spacing for the uniform cooling problem.

Two degrees of randomness in the initial cracks distribution were used, with $\Delta d/d$ equal 0.1 and 0.2 (here d is spacing between cracks and Δd is the random shift in cracks position). Figure 5 shows results of the calculations, the average spacing between cracks whose lengths exceed a chosen value (spacing between cracks that are longer than X meters, then longer than Y meters, etc.). Each point on this plot is the average of three independent simulations (the initial crack distribution is random), and the dash line corresponds to the case when the average spacing equals the crack length. The results show that for a random distribution of initial cracks that are non-interacting (size and spacing), the long time average spacing when the cracks start to interact is approximately equal to the crack length.

Conclusions

In the present work the growth and interaction of many thermal fractures in a geothermal reservoir were simulated using the boundary element method. The thermal field caused by the cold water injection was calculated using an integral equation in the Laplace domain. It was found that for typical rock materials, the secondary thermal fractures would be formed inside a cooled zone with tensile total (in-situ plus thermally induced) stresses. If not pressurized, the crack tips probably do not penetrate far into the compressive zone. As expected from previous theoretical analyses, the average spacing between secondary fractures approximately equals their length. It has been shown that by utilizing sufficiently small crack increments and time steps, the theoretically predicted crack growth instability can be numerically simulated with the model which considers many growing and interacting cracks.

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