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ON THE ROLE OF THERMAL STRESS IN RESERVOIR STIMULATION

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ABSTRACT

The paper presents a numerical study of the role of thermal stress on fracture propagation in the vicinity of a wellbore and on the fracture permeability during injection operations. For the case of wellbore stimulation and considering the regime of relatively long crack growth, the number of initial cracks and the rock fracture toughness have a small influence on the crack length. At times, particularly when the in-situ stress is isotropic or has a weakly anisotropy, the direction of crack growth becomes *unstable* and straight radial cracks start to grow in circumferential direction. In the presence of an anisotropic stress field, the cracks grow in the direction of maximal compressive stress, as expected, but the crack length is controlled by the minimal compressive stress. The influence of thermal stress on fractures and their propagation is considered for the problem of sudden cooling of a rock half-space, injection/extraction process in fractures, and cooling of a wellbore. Interaction of multiple secondary thermal fractures and their trajectory is considered. Results indicate that length of the secondary cracks is mainly determined by the temperature distribution in the geothermal reservoir. In the case of instant cooling of the half-space surface, the cracks length is proportional to the cooling depth *L*. Under suitable conditions of in-situ stress regime and cooling, thermal stimulation can lead to significant fracture propagation. However, a timely increase in reservoir permeability requires pressurization of the thermal cracks.

INTRODUCTION

In-situ stress, pore pressure and temperature variations as well as dissolution/precipitation reactions are some of the major factors responsible for the behavior of discontinuities in the reservoir. The influences of coupled thermal and poroelastic (e.g., McTigue, 1990) processes on fracture opening has been addressed previously (Ghassemi and Zhang, 2004a; Hayashi and Okitsuka, 2004). It has been shown that poroelastic and thermally induced stresses can contribute to fracture width change and permeability variation. These effects are of particular implication and interest in geothermal systems. When rocks are heated/cooled, the bulk solid and pore fluid tend to undergo expansion/contraction. A volumetric expansion can result in significant pressurization of the pore fluid depending on the degree of containment and the thermal and hydraulic properties of the fluid as well as the solid. The net effect is a coupling of thermal and poromechanical processes when developing a geothermal reservoir. These processes occur on various time scales and the significance of their interaction and coupling is dependent upon the problem of interest. In hydraulic fracturing, the fluid-rock mechanics coupling evolves rapidly (on the scale of minutes, hours to possibly a few days) compared to the induced thermal processes, thus the thermal effects may not have a large influence on the fluid-mechanical processes in fracture propagation. However, during a long term injection phase (time scale of months to years), the thermo-mechanical coupling can no longer be neglected.

The influences of thermal processes on fracture opening have been previously addressed (Ghassemi and Zhang, 2004ab). These studies and a poro-thermoelastic stress analysis (Li et al., 1998) around a uniformly cooled crack surfaces indicates that large thermally-induced thermal stresses occur around a cooled geothermal well giving rise to tensile cracking. Also, results of 3D simulations of cold water injection into hot fractures (Ghassemi et al., 2007) predict developing of high tensile stresses in the vicinity of cooled surface, indicating a potential for development of secondary thermal fractures. Cooling induced stresses may exceed the in-situ stresses of the geothermal reservoir, resulting in formation of system of secondary cracks perpendicular to main fracture. These cracks propagate into the rock matrix, increasing the permeability of the reservoir. As a result, thermal stimulation has been suggested as a means of enhancing reservoir permeability. The plausibility and the conditions for success of such approach are numerically investigated by considering the influence of cooling of the wellbore on fracture propagation.

Some aspects of the formation and propagation of thermal fractures from a wellbore in response to cooling of their surfaces has been treated (Dobroskok and Ghassemi, 2005). Murphy (1978) used the simple analytical model of a single crack to estimate the extent of penetration and spacing of thermal cracks. Barr (1980) numerically studied the effect of thermal crack penetration into geothermal reservoir. In this paper, the development and propagation of system of crack from a cooled wellbore, and secondary thermal cracks in geothermal reservoir due to cold water injection is studied. The extent of the thermal fractures and their spacing is estimated using a combination of the real boundary integral equation method for the temperature solution, and the complex variable boundary integral equation for fracture propagation solution.

METHOD OF ANALYSIS

In order to study the behavior of fractures around a cooled wellbore, the stress field is represented by a superposition of elastic component (wellbore in a field stress) and the thermal component induced by the transient rock cooling. The elastic portion of the problem is treated using a complex variable boundary integral equation (CV BIE) theory (Linkov, 2002).

The superposition of the mechanical and thermal load must be taken into account within the solid rock, on the crack surfaces and on a borehole wall. Currently, that impact of cracks on the temperature field is not considered. It is assumed that rock matrix permeability is low and fluid leak-off is negligible and that the cool fluid does not enter the crack. For cracks emanating from a wellbore this may correspond to the presence of a filter-cake at the wellbore wall. For secondary facture on the wall of a major natural fracture, the newly formed secondary thermal cracks are small and are filled with fluid of the same temperature as the rock matrix at that location along the main crack, and do not influence the heat conduction. As long as the secondary cracks are not connected to other cracks, the fluid flow inside the secondary cracks is low and can be neglected. Therefore, the rock is cooled by the fluid in the main fracture. If an interconnected fracture network forms, then flow in the secondary fractures should be taken into account.

The temperature distribution for each problem of interest is found by solving the problem of heat extraction from a fracture by cold water injection using the integral equation 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 the rock linear thermal expansion coefficient.

The problem of fracture propagation caused by a thermal field was solved using the same set of equations. To simulate uniform cooling a large injection rate is used. For closed cracks, the penalty method is employed to maintain proper contact of crack faces without penetration.

NUMERICAL RESULTS

First, consider the isothermal problem of a wellbore with multiple micro-cracks emanating from it. Different number and length of initial cracks were used (three different initial configurations with 12, 24 and 48 initial small cracks). The initial crack length is 0.5, 1, and 3 cm. They are equally spaced but the lengths are slightly different (±few percent). The rock is subjected to in-situ stresses but no wellbore pressure is applied to isolate the cooling effect. The following values of elastic constants and stresses were used: E =37.5 GPa, ν = 0.25. Other properties are listed in Table 1.

Table 1. *Input parameters used in simulations.*

Young's modulus, E	37.5 GPa
Poisson's ratio, ν	0.25
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
Linear thermal exp., α_T	8×10^{-6} 1/K
Rock temperature, T_r	220 °C
Water temperature, T_w	20 °C

The fracture toughness of the rock and in-situ stresses were changed and their influence on fracture geometry and the crack length was investigated. A typical propagation pattern for a low stress anisotropy case is shown in Fig. 1.

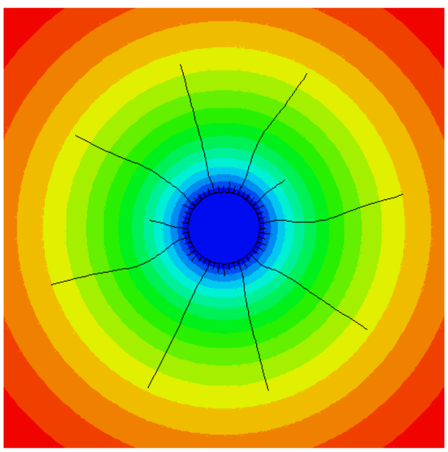
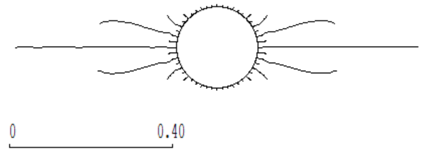


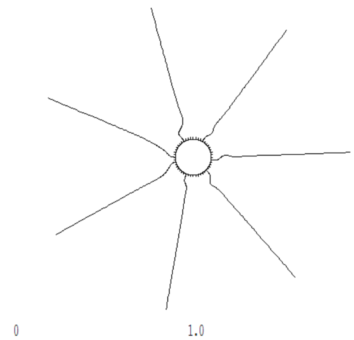
Figure 1: Fracture propagation under cooling.

The initial cracks strongly interact only at first and as some continue to propagate, a stable configuration is reached where the number of cracks no longer changes.

The numerical simulations show that there are two regimes of the crack growth, one with relatively short cracks (slightly longer than the wellbore radius) and the other with long cracks. For the short crack regime the cracks length is influenced by the wellbore and by the number of initial cracks. For long cracks the wellbore effect is negligible. The latter regime is considered further in this work. However, our results show that for both regimes the crack length is well described by a power law function.



(a)



(b)

Figure 2: Fracture geometry for different stress contrasts. (a) S_h =20, S_H =30 MPa; (b) S_h =S_H =30 MPa. K_{IC}=1 MPa m$^{1/2}$.

An example of the impact of the in-situ stress is shown in Fig. 2, and the results are summarized in Fig. 3. For the anisotropic stress field, the dominant cracks grow in the direction of maximum compressive stress, but the crack length is controlled by the minimal compressive stress. At times the direction of crack growth becomes unstable and straight radial cracks grow in the circumferential direction.

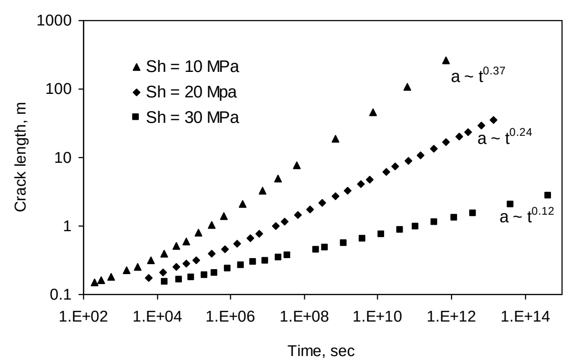


Figure 3: The influence of minimal in-situ stress on the crack length (S_{Hmax} is 30 MPa in all cases). For higher compressive stress the crack length is smaller.

A few other observations resulting from the numerical simulations are worth noting at this time. The number of cracks and the fracture toughness exert a small influence on the crack length. In addition, the direction of crack growth may become unstable and straight radial cracks start to grow in circumferential direction. Symmetric spiral-shaped pattern have also been observed.

SECONDARY CRACK GROWTH IN THE RESERVOIR

This problem is of interest in assessing the evolution of the reservoir permeability during circulation operations. Before presenting numerical examples for injection/extraction operations, however, it is useful to explore the fundamental aspects of the interaction of many cracks extending from the surface of a cooled major crack (Bažant and Ohtsubo, 1977; Nemat-Nasser et al., 1978). This is achieved by considering fracture propagation from the surface of a cooled half-space under in-situ stress (Tarasovs and Ghassemi, 2012). To simulate crack propagation, thermal stresses are calculated using:

$$\sigma^{th} = \alpha_T \Delta T(y) \frac{E}{1-\nu} \qquad (4)$$

and are applied on the crack faces. To simulate the growth and interaction of thermally driven cracks, a number of small cracks are generated at random locations before the simulation. Usually, an array of about 100-200 cracks are used with periodic boundary conditions to simulate infinite array of cracks. The cracks are located at random positions, keeping the average crack spacing, *d*, constant. Results of numerical studies indicate that on average, the initial cracks locations practically do not influence the final crack pattern.

After several time steps, some of the cracks stop growing while the remaining ones continue to grow. This yields a characteristic crack pattern as presented in Fig. 4.

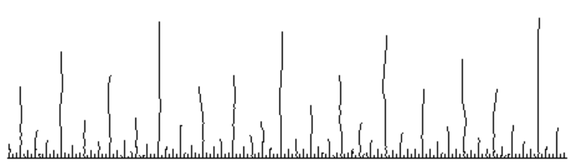


Figure 4: Results of simulation: typical crack pattern (K_{IC}=2 MPa.m$^{1/2}$ *; ΔT=100* °C*).*

The numerically obtained crack patterns were used to estimate the crack length and crack spacing. Several simulations were performed for each combination of parameters and results were averaged for higher accuracy. Fig. 5 presents the numerical results for the crack length for three different compressive in-situ stresses: 20, 35 and 50 MPa. The results show that in the case of instant cooling of a half-space, the cracks length is proportional to the cooling depth $L = \sqrt{4tK_r / c_r \rho_r}$, or proportional to square root of time. The average crack spacing at different depths is presented in Fig. 6 along with a power law fit.

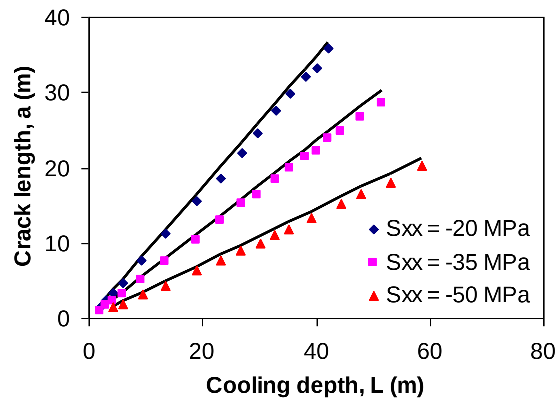


*Figure 5: Crack length as function of cooling depth L. Dots represent results of simulation, lines–analytical approximation (*Tarasovs and Ghassemi, 2011*).*

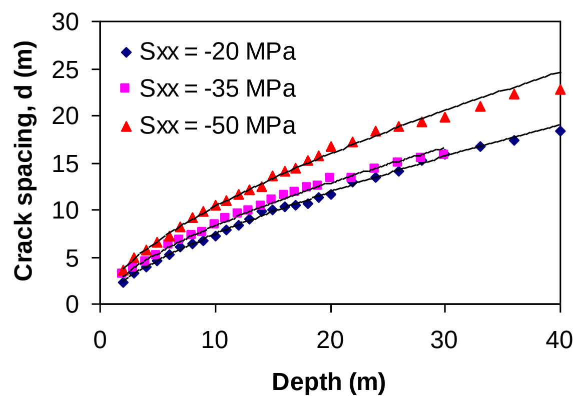


Figure 6: Crack spacing as function of depth. Dots represent results of simulation, curves show a power law fit.

Secondary crack in injection/extraction process

Let us consider a major fracture of length 200 m in a 220 °C rock matrix under a horizontal in-situ stress S_H of 35 MPa, which is cooled by an injected fluid with temperature of 20 °C. The injection rate is 5x10^{-5} m^2 / s. Before the simulation, 50 initial small cracks with half-length 2 m are generated along the main fracture. Each crack is subdivided into 10 segments. For each time step, the induced thermal stresses are calculated for each segment's collocation points and are used as boundary conditions in the elastic analysis. Then, the crack tips for which the propagation criterion is met are moved by some distance (0.4 m in this simulation) and iterative algorithm of Stone and Babuška (1998) is employed to find the propagation direction for which the K_{II} is zero (thermal stresses were updated for each iteration).

Because of 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 et al. (1979) predicts that typically initial cracks as small as several centimeters could be expected. Our analysis which takes into account the compressive in-situ stresses, predicts that the initial crack length and spacing increases with increasing confining stress. However this effect becomes significant only for sub-critical confining stress i.e., when the maximum thermal stresses are only slightly higher than the in-situ stress. For the parameters used in this paper both analyses predict 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.

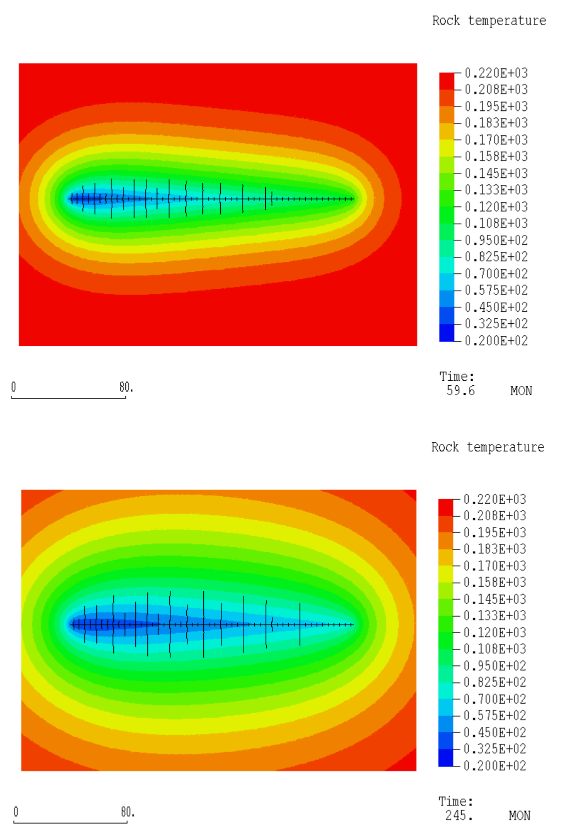


Figure 7: The temperature field in the rock matrix after (top) five and (bottom) twenty years of injection/extraction. Black vertical lines are thermally induced cracks.

The initial cracks located near the injection well start to propagate few days after 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 5 and 20 years of fluid injection are presented in Fig. 7. As expected, for injection problem the cracks are significantly shorter and have length only about 20 m after 10 years of injection. Fig. 8 shows the results of a similar simulation for three parallel fractures with a spacing of 50 m. Much longer secondary cracks can be expected in the inner cooler zone, however cracks growing in the outer zones have lengths similar to the single major fracture case (Fig. 7a).

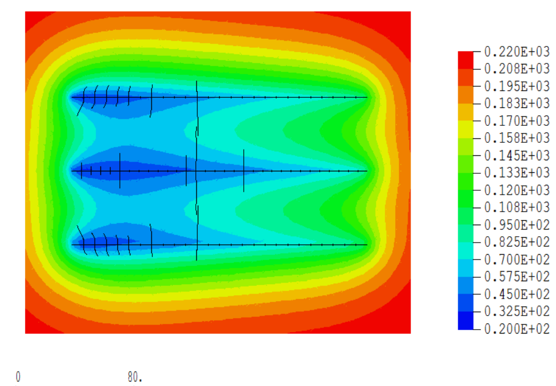


Figure 8: The temperature field in the rock matrix after 5 years of operation involving three fractures. Black vertical lines are thermally induced cracks.

All thermal fractures are located inside the zone of tensile total stress with their tips grown to the edge of the compressive stress zone.

CONCLUSIONS

The role of thermal stress on fracture propagation from a wellbore, and in the reservoir has been numerically studied. Results show that cooling of a borehole can lead to propagation of a crack emanating from a wellbore. For the case of wellbore stimulation and considering the regime of relatively long crack growth, the number of initial cracks and the rock fracture toughness have a small influence on the crack length. At times, particularly when the in-situ stress is isotropic or has a weak anisotropy, the direction of crack growth becomes *unstable* and straight radial cracks start to grow in circumferential direction. For strong stress anisotropy, the cracks tend to be aligned with the maximum principal stress. The higher the ratio of the least to maximum stress S_h/S_H, the longer the time needed to propagate the cracks from the wellbore.

Numerical examples of secondary fracture interactions during injection/extraction show that a fracture network can be generated by thermal shock of the reservoir rock. However, results indicate that in the presence of high compressive in-situ stress, the growth rate of the length of the secondary fractures is rather slow when solely driven by cold water circulation.

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