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Thermal Shock in Reservoir Rock Enhances the Hydraulic Fracturing of Gas Shales

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Summary

Thermal shock occurs when a material's temperature is changed over a short period of time such that constituent parts of the material deform by different amounts. The deformation of material due to thermal load can be manifested through strain and stress. As the temperature diffuses from hydraulic fracture into reservoir, the temperature changes with x coordinate and the stress/strain can be obtained from the Equation (6). Once the stress at any point exceeds the strength of material, the body fails in one of the three modes of tension, compression or shear. A thermal load on rock, results in the creation and extension of cracks, crushing the grains, or sliding the grain interfaces. In this paper we look into the possibility of stimulating the rock matrix beyond hydraulic fracturing stimulation by cooling down the rock. The physics of temperature reduction in a solid dictates that when a solid is laterally fixed and undergoes temperature reduction, a thermal stress gradient is induced in the solid body. In rock, this thermal stress gradient leads to a differential contraction of the rock, which in turn creates openings, referred to as thermal cracks. We numerically solve the nonlinear gas diffusivity equation, using finite element method and show that the thermal cracks in rock have the potential to improve the productivity of wells placed in tight formations by 20%.

Introduction: Thermal fracturing

Injection of cold fluids into reservoir rock, induces thermal cracks. This has been observed in the injection of cold CO2 into reservoir rock for sequestration purposes and from extensive studies of thermal loading on rock properties [6–8]. For successful fracturing of rocks using temperature reduction, the following system[1] properties play a major role:

- Decrease of rock tensile strength by flaws in rock matrix
- Rapid application of thermal load, causing a steep temperature gradient
- Reduction of thermal conductivity of the rock, its fundamental material property.

[1]The system consists of a cylindrical volume of rock around a horizontal wellbore and coolant. The system interface is a no-deformation cylindrical boundary some distance from the wellbore.

- Confinement of rock. Boundary condition plays a major role as the more confined the rock is, the less compliance it exhibits to the load, leading to easier crack initiation.
- Increase of the coefficient of thermal expansion. This is also a fundamental material property and not much can be done to change this coefficient.
- Increase of the Young modulus. This parameter exhibits the efficacy of thermal shock in shale. Some shales are extremely stiff such as the Qiongzhush Shale in China with the modulus of elasticity of 60 Gpa, which is an order of magnitude larger than the Marcellus shale with the modulus of elasticity of 6 Gpa [9]. We will see later that large stiffness can enhance the efficiency of fracturing by cooling down the rock.
- Decrease of toughness. Fracture toughness, exhibits the level of resistance of a material to brittle rupture. The lower the fracture toughness, the closer-to-brittle the fracture could be and the less energy is required for rupturing the rock.

It can be concluded from the above properties of rock that the facility of thermal fracture is mainly proportional to the modulus of elasticity and coefficient of thermal expansion and inversely proportional to the thermal conductivity and tensile strength of rock. Here we are discussing equilibrium fracture and its imposed displacement. We basically impose thermal shrinkage on a solid (rock), which is laterally confined. We are not talking about how fast the fracture propagates, rather we are interested in seeing at what level of temperature reduction the hot reservoir rock starts to develop thermal cracks.

Fracture initiation and propagation

Without loss of generality, many of the concepts of fracture mechanics can be applied to all cases in which an opening in rock extends in size, regardless of applied load. The main types of loads for fracture creation are the internal fracture fluid pressure and the external tensile stress. Here we go over only a few concepts to set the scene for understanding the materials described in this article.

The most important property of a rock relevant to fracturing is toughness. In order to understand what toughness means, one should understand two rock properties, its strength and ductility. Figure 1 explains these three properties. In a tensile experiment, a load T is applied to a component such as a rod of original length L and cross sectional area A and the rod deforms axially to increase the length by ΔL. Strain is defined as $\varepsilon = \Delta L/L$ and stress is defined as $\sigma = T/A$. Ductility is the ability of material to undergo large strains and strength is the ability of material to undergo large strains before failure. Toughness depends on these two properties and it can be calculated as the area under the stress-strain curve or energy dissipated by unit volume of material. Temperature, rate of loading, and existence of voids and cracks could influence the toughness of a material. For example a rock which remains intact under a static load could fracture under a dynamic load.

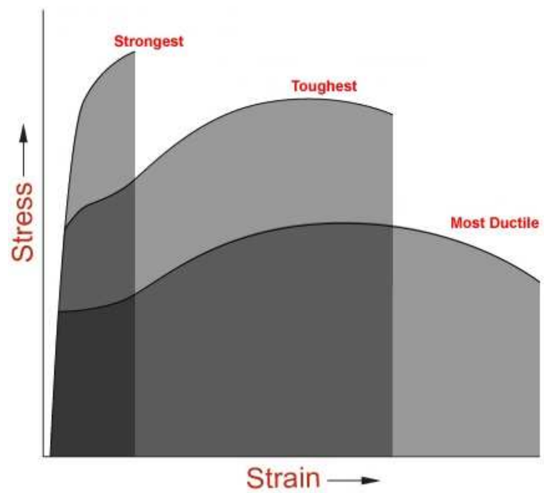


Figure 1: Definition of strength, ductility and toughness

Fracture mechanics started with the works of Inglis [5] and Griffith [2]. Inglis studied stresses around a crack and found out that the stress at the crack tip of an elliptical crack is a function of the curvature of the crack tip and the size of the crack. Griffith showed that when the size of flaws in a solid material increases, the level of stress before failure decreases. Their studies led to the following relation (1) for designing a component which has flaws or cracks.

$$K_I < K_{I_C} \tag{1}$$

in which, K_I is the stress intensity factor which is a function of the applied load and the geometry of crack and K_{I_C} is the fracture toughness which is a function of material properties. As K_I gets closer to K_{I_C}, unstable fracture occurs. The fracture toughness K_{I_C} is in the range of $1 - 5$ MPa$\sqrt{\text{m}}$ for sandstones and about 2 MPa$\sqrt{\text{m}}$ for siltstones and mudstones.

Theory and Method

Injection of cold fracturing fluid into reservoir rock, induces thermal fractures perpendicular to hydraulic fracture. Figure 2 shows the thermal cracks of depth d perpendicular to hydraulic fracture in a horizontal wellbore in a tight formation. Hydraulic fractures tend to grow normal to the minimum horizontal stress, S_{hmin}. As the cold fluid is injected into the fractures, the transient heat diffusion causes the heat to be transferred into the hydraulic fracture as it is colder. This heat transfer, cools down the zone neighboring the fracture and the rock shrinks parallel to hydraulic fracture length. Since the reservoir rock is confined, thermal stresses are created in rock, leading to thermal cracks. Here we are looking at the physics behind this phenomenon and come up with a formulation of a model to obtain the depth d along x-axis, distance b, and width t of thermal cracks.

Figure 2 also shows that the thermal cracks have to open against the maximum in-situ horizontal stress S_{Hmax}. As we see from numerical simulations, these thermal cracks do not extend far from hydraulic fracture face, hence, we can assume these cracks as straight fractures. This observation can justify that as the thermal cracks open, they do not interfere with heat transfer in x-direction.

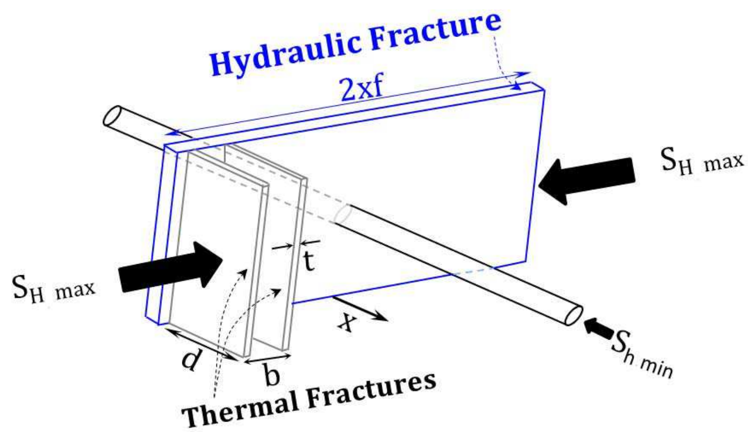


Figure 2: Thermal fractures created perpendicular to the hydraulic fracture

Similar studies [1, 3] on thermal fracturing in ceramic and glass, indicate that the average spacing of thermal cracks is expected to be roughly proportional to their lengths, i.e., $b \propto d$. Figure 3 shows the thermal shock crack pattern on a glass ceramic slab. It can be observed that the length of cracks is roughly proportional to the spacing of cracks, i.e., the smaller the cracks the shorter apart and the larger the cracks, the further apart they are. Due to close material properties of shale and ceramic, we make use of this observation to come up with sized b and t. The material properties reported for ceramic of the test [1] are: Fracture toughness, $K_{IC} = 1.89$ MPa$\sqrt{\text{m}}$; coefficient of thermal expansion, $\alpha = 1.15 \times 10^{-5}$ K^{-1}; and Young's modulus, $E = 60$ GPa. These properties characterize shales; therefore, we expect to see the same pattern of thermal cracks in shale.

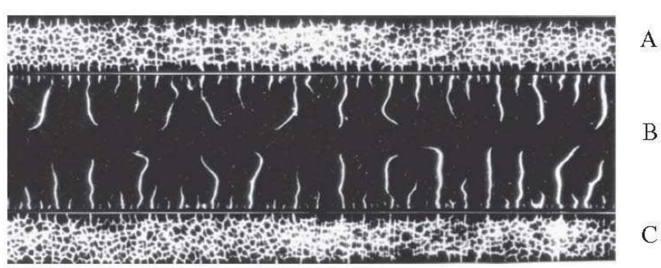


Figure 3: Thermal shock crack pattern on a glass ceramic slab [1]. Faces A and C were quenched at $\Delta T = 300$ K in water while faces B were kept thermally isolated.

To get an insight on the efficiency of the thermal crack creation during hydraulic fracturing, we solve the 1D heat conduction in a semi-infinite solid medium shown in Figure 4, numerically. The results are then compared to analytical heat diffusion solution, Figure 8. We assume that the diffusion of heat from the reservoir to the cold fracturing fluid is conducted along x axis and the fracture side (half-space), is an infinite medium.

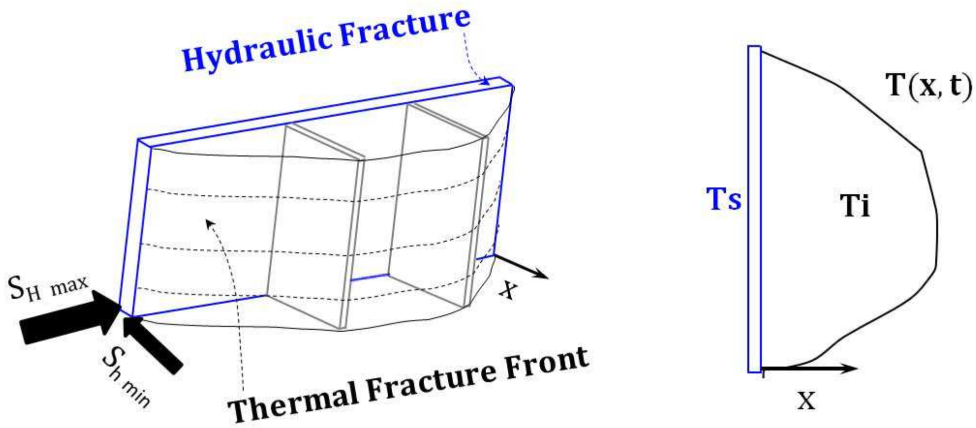


Figure 4: Thermal fracture front changes with time along x axis

The closed-form solution of the problem shown in Figure 4, is given in [4]

$$\frac{T(x,t) - T_s}{T_i - T_s} = \text{erf}\left(\frac{x}{2\sqrt{Dt}}\right) \tag{2}$$

The function "erf" in Equation (2), is the error function and is defined as:

$$\text{erf}(u) = \frac{2}{\sqrt{\pi}} \int_0^u \exp(-t^2) dt \tag{3}$$

Table 1 lists the properties used for both numerical and analytical solutions.

Parameter	Units
Young's Modulus, E	50 GPa
Thermal expansion coefficient, α	1×10^{-5} K^{-1}
Poisson's ratio, ν	0.22
Minimum horizontal stress, S_{hmin}	2000 psi
Maximum horizontal stress, S_{Hmax}	3000 psi
Reservoir temperature, T_i	125°C
Fracturing fluid temperature, T_s	30°C
Thermal conductivity, k	$2 \frac{\text{W}}{\text{m}^\circ\text{K}}$
Mass density of rock, ρ	$2300 \frac{\text{kg}}{\text{m}^3}$
Specific heat, C	$1380 \frac{\text{J}}{\text{kg}^\circ\text{K}}$
Thermal diffusivity, D	[a]0.63×10^{-6} m^2/s
Simulation time	1 day

Table 1: The properties used for the solution of thermal crack development problem

[a]Thermal diffusivity is calculated as; $D = k/(\rho C)$

The distribution of temperature along x, for several times from 0 to 1 day is shown in Figure 5. It can be seen that, initially, the temperature in reservoir is equal to the reservoir temperature T_i and as the time goes on, the temperature in reservoir decreases and the rock cools down. The temperature at the hydraulic fracture wall is kept at constant value of T_s. In order for the thermal cracks to initiate, the reservoir rock has to undergo contraction due to cooling down the rock. Since the thermal cracks should open against the maximum in-situ stress S_{Hmax}, we can write the condition for critical temperature change ΔT_c at which the cracks initiate.

Thermal strain is proportional to the coefficient of thermal expansion and the change of temperature, in other words,

$$\varepsilon_{thermal} = \alpha \Delta T \tag{4}$$

The deformation of shale is assumed to be linear elastic and the failure is known to be brittle. Also, the component of the normal stress of a solid body due to thermal changes, in a linear elastic material can be calculated as

$$\sigma_{thermal} = E\varepsilon_{thermal} = E\alpha\Delta T \tag{5}$$

The thermal stress at any point x in our 1D semi-infinite heat conduction problem is then

$$\sigma(x,t) = E\alpha[T_i - T(x,t)] \tag{6}$$

Equation (6) is written for the plane stress condition and due to the effect of Poisson's ration, for the plane strain condition, it should be modified to

$$\sigma(x,t) = E(1+\nu)\alpha[T_i - T(x,t)] \tag{7}$$

When the stress in Equation (6) exceeds the maximum in-situ stress S_{Hmax}, thermal cracks develop. Therefore, we can write the following condition for the initiation of thermal cracks:

$$E(1+\nu)\alpha[T_i - T(x,t)] \geqslant S_{Hmax} \tag{8}$$

and the critical cooling down temperature for the initiation of thermal cracks, which is equal to $T_i - T(x,t)$, can be calculated as

$$\Delta T_c \geqslant \frac{S_{Hmax}}{E(1+\nu)\alpha} \tag{9}$$

The value of critical cooling down for the case of the problem we simulated is shown in Figure 5. Equation (6) exhibits an important relation in thermal fracturing of rocks in which the required cooling down for cracks to develop is shown to be a function of rock thermal and strength properties and reservoir condition. It also shows that, the shallower the reservoir, the more efficient the process of thermal fracturing, as ΔT_c will be smaller. One of the great advantages of inducing thermal shock in rocks is that, ΔT_c will be smaller as the modulus of elasticity of rock gets larger. For instance, thermal fracturing could be utilized to create thermal fractures for shales with very large modulus of elasticity, where the fracturing by fluid injection is hard. These openings could serve as seeds for easier and more frequent fracture initiation points as the fluid injection goes on.

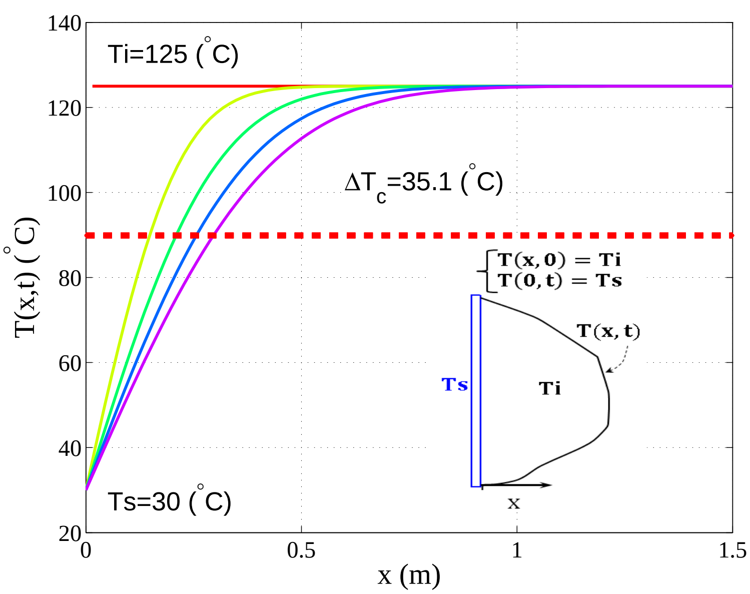


Figure 5: Distribution of temperature in 1D along the x-direction.

Thermal fracture growth

The length of a fracture plays a significant rule in calculation of the stress intensity factor K_I, as a result we are interested to look into the extension of thermal fractures with time. In order to do this, let's add and subtract T_i to the numerator of the Equation (2) and obtain $T_i - T(x,t)$ as

$$T_i - T(x,t) = \left[(T_i - T_s)\text{erfc}\left(\frac{x}{2\sqrt{Dt}}\right)\right] \tag{10}$$

The function "erfc" in Equation (10), is the complementary error function and is defined as:

$$\text{erfc}(u) = 1 - \text{erf}(u) = \frac{2}{\sqrt{\pi}}\int_u^\infty \exp(-t^2)dt \tag{11}$$

Now let's insert $[T_i - T(x,t)]$ from Equation (10) into Equation (8) and change the inequality sign to the equality sign for the onset of crack initiation. By doing this, we get

$$E(1+\nu)\alpha\left[(T_i - T_s)\text{erfc}\left(\frac{d}{2\sqrt{Dt}}\right)\right] = S_{Hmax} \tag{12}$$

Notice that x, the coordinate of crack tip is replaced with d, the thermal crack length. Solving Equation (12) for d and we get

$$d = (2\sqrt{Dt})\text{erfc}^{-1}\left[\frac{S_{Hmax}}{E(1+\nu)\alpha(T_i - T_s)}\right] \tag{13}$$

Figure 6 shows the extension of fracture length with time. It can be seen that the length of cracks are not very large even after 1 day of cooling down, nevertheless, the creation of such cracks, generate weakness notches for hydraulic fracturing.

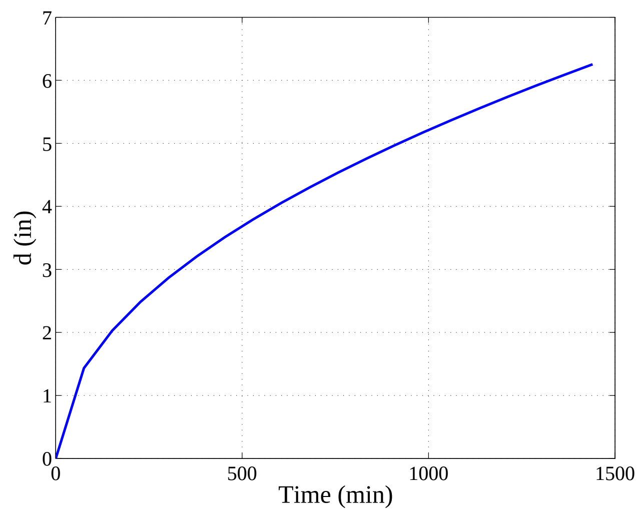


Figure 6: The extension of thermal crack length with time. See Figure 2 for the definition of depth d.

Results

As we continue to develop this model, we will be using the closed-form solution to come up with the geometry of thermal cracks. To make sure about the accuracy of the model, we compare the analytical model with the numerical solution.

The governing equations of heat transfer in rock are:

1. Equilibrium of forces:

$$\nabla \cdot \sigma = 0 \tag{14}$$

as deformation along x does not affect the heat diffusion in the x-direction, the boundary conditions for the force equilibrium equation are fixed.

2. Heat transfer equation: In absence of convection and source term, the heat transfer equation is

$$\rho C_p \frac{\partial T}{\partial t} = \nabla \cdot (k \nabla T) \tag{15}$$

We have solved the coupled system of Equations (14) and (15) using a finite element method and Figure 7 shows the results of heat diffusion after 1 day. It can be seen that the rock cools down to the depth of 0.5m from the face of hydraulic fracture. However, to find the rock volume affected by thermal shock, we need to find the depth at which temperature decreases by the critical value ΔT_c. This is what we did in Figure 5, where we show that to attain ΔT_c, we should find the coordinate x at the intersection of the temperature profiles and the horizontal dashed line, which is the locus of points where the temperature has dropped to $T_i - \Delta T_c$. Figure 7 shows the numerical solution of Equations (14) and (15).

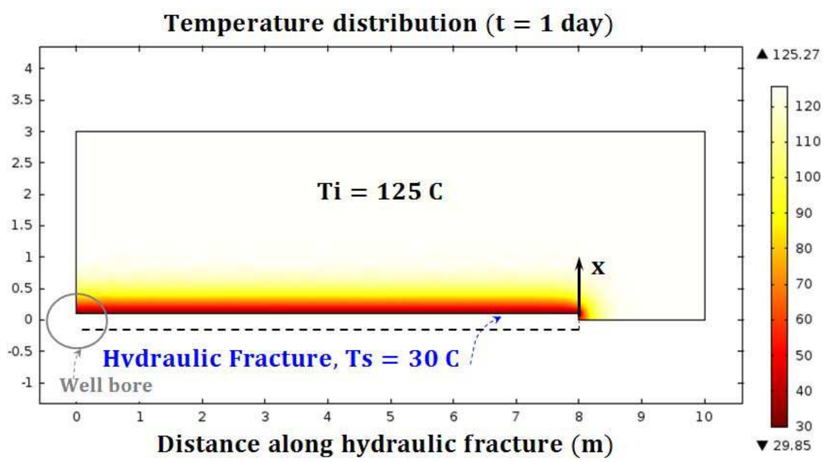


Figure 7: The numerical solution of temperature distribution in 1D.

Now, let's compare the numerical result with the closed-form solution. It can be seen that numerical simulation of this coupled heat transfer process in rock is in agreement with mathematical closed-form solution. Therefore, we continue to obtain the other parameters of thermal crack, b and t, using the closed-form solution and whenever need arises to confirm the accuracy of solution, we use numerical simulation. Figure 8 shows the comparison between closed-form and numerical solution.

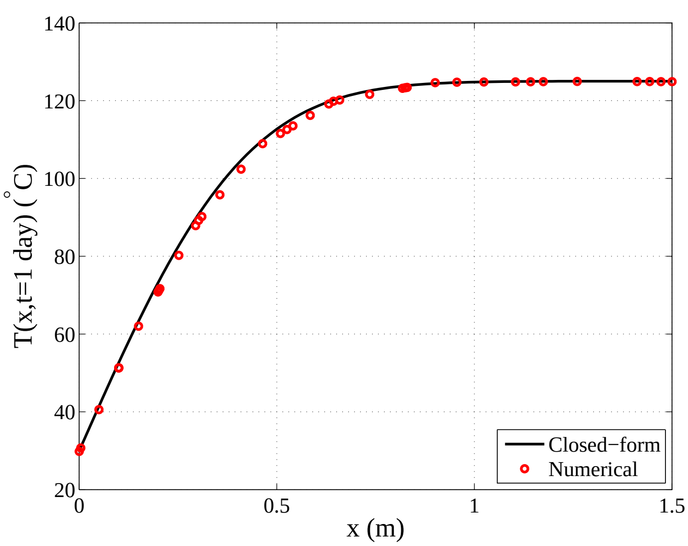


Figure 8: The comparison between closed-form and numerical solution of temperature distribution in 1D

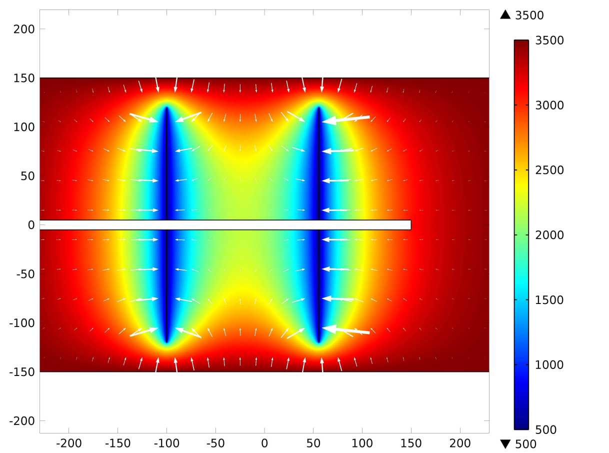
Application

Production from the low permeability formations relies on connectivity of flow pathways. Therefore any process that increases this connectivity, also enhances productivity. Thermal shock is one such method for increasing connectivity by extending thermal cracks and connecting them to a network of natural fractures. The simulations show that thermal shock initiates thermal cracks, which open against the maximum in-situ horizontal stress. These cracks do not initially extend far from the face of the hydraulic fractures; however, they can be extended as the fracturing fluid is injected into them. How far the thermal cracks extend, is a function of the strength of rock, flow properties of reservoir rock and the rate of loading. We are studying the propagation of thermal cracks and the results will be presented in the future.

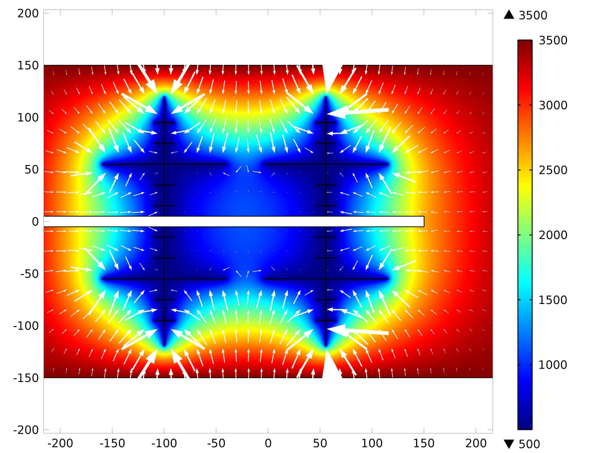
We have simulated gas flow in a fractured horizontal well placed in a low permeability formation. The hydraulic fractures are further stimulated by thermal shocks induced by injection of a cold fracturing fluid. Initially many small thermal cracks are created, however only a few of them can grow far away from the hydraulic fracture. In our simulations, we have assumed that only one of the thermal cracks extends far enough to intersect natural fractures. In the absence of an analytical solution for flow through the complicated geometry of fractures, numerical simulation is used to obtain the cumulative recovery.

We assume a single phase gas flow in a 1 μd permeability formation. The boundary and well pressures are 3500 and 500 psi and production is simulated for 30 years. Figure 9 are the plan views of the pressure distribution after 5 years for the case of no thermal cracks (a) and the case of with thermal cracks (b). The pressures are in psi and the dimensions of reservoir and fractures are shown in meters. The white arrows depict the Darcy's velocity vectors.

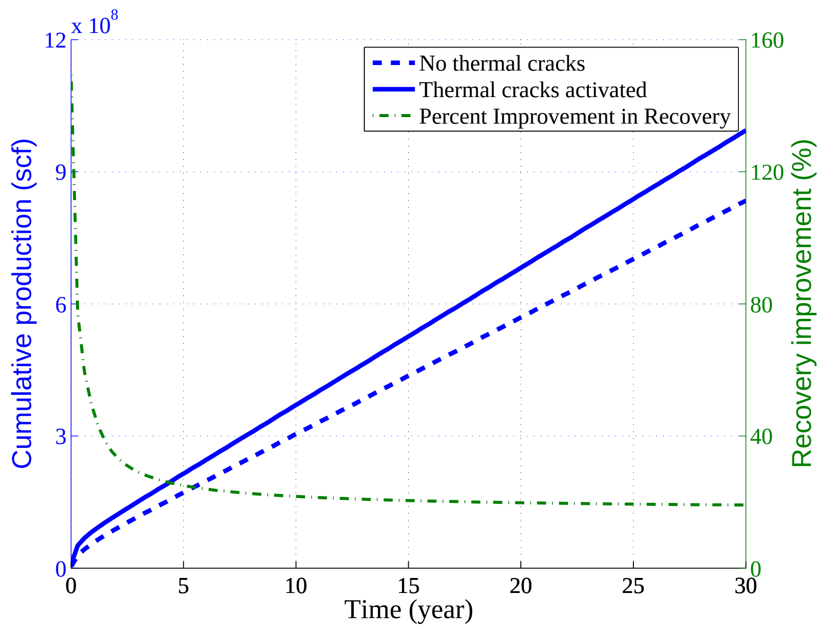
It should be noted that in the case (b), only one of the cracks has extended to intersect natural fractures. In reality, due to the presence of a network of natural fractures, more than one crack has the potential to grow and connect to existing fractures. Growth of multiple thermal cracks improves the productivity relative to that shown in Figure 9 (c).



(a) Pressure distribution for stimulation with hydraulic fractures ($t = 5$ years)



(b) Pressure distribution for stimulation with hydraulic and thermal fractures ($t = 5$ years)



(c) Recovery improvement due to thermal cracks

Figure 9: Pressure distribution and recovery improvement as a result of thermal cracks

Conclusions

- Fluid production from the low permeability formations depends on the connectivity of natural and induced fractures. We have shown that a thermal shock during hydraulic fracturing can create small cracks, which might extend further to intersect natural fractures or be extended by subsequent hydrofracturing.
- For the case of gas production presented in this work, in the first 5 years, production enhancement due to thermal cracks declines from 150% to 20% and remains at 20% thereafter.
- Stiffer rocks, i.e., rocks with larger moduli of elasticity, are easier to fracture by cooling down the rock. This can be observed from Equation (9).

Aknowledgement

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