PROCEEDINGS, Thirteenth Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 19-21, 1988
SGP-TR-113

The Hydraulic Fracturing of Geothermal Formations

K. Ben Naceur and M.J. Economides

Dowell Schlumberger

Abstract

Hydraulic fracturing has been attempted in geothermal formations as a means to stimulate both production and injection wells. Since most geothermal formations contain fissures and on occasion massive natural fissures, the production behavior of the man-made fractures results in certain characteristic trends.

A model is offered that allows the presence of a finite or infinite conductivity fracture intercepting a fissured medium. The method is based on a numerical discretization of the formation allowing transient interporosity flow.

Type curves for pressure drawdown and cumulative production are given for infinite acting and closed reservoirs. Since most of the fissured formations exhibit a degree of anisotropy, the effects of the orientation of the hydraulic fracture with respect to the fissure planes, and of the ratio between the directional permeabilities are then discussed.

Guidelines are offered as to the size of appropriate stimulation treatments based on the observed fissured behavior of the reservoir.

Introduction

Almost all producing geothermal reservoirs are naturally fissured. In certain cases, these reservoirs contain massive natural fractures, and in fact a well may not produce if a fracture is not met. Matrix permeability is usually extremely small (fractions of μ-darcies). As a result, hydraulic fracturing has been attempted to either create artificial injectivity for spent fluids in an injection well or, in the hope of connecting with natural fractures, to improve the production of flowing wells.

The latter may not be successful. Irrespective of the origin and geological history of the fissures and natural fractures, the current state of stresses influences their distribution and orientation. Since stresses are compressive in nature, the maximum stress would preferentially close fissures that are normal to its direction (see Fig. 1). This would result in a permeability anisotropy with a maximum value in the direction of maximum stress. However, an artificially induced fracture will also be in the direction of the maximum stress (Hubbert and Willis [1]). This configuration is the least favorable for the expected production increase from the hydraulic fracture (Ben-Naceur and Economides [2]). Furthermore, the hope of connecting natural fractures, which would also follow the general trend of the manmade fracture, may not be realized.

It is important to define here the deliberate distinction between fissured and naturally fractured systems. Although many authors have used the term interchangeably, we use the term "naturally fractured" only for those wells (usually geothermal steam wells - see Economides and Fehlberg [3]) where a log-log graph of pressure difference against time forms a slope equal to 0.5, indicative of linear flow (Gringarten *et al.* [4]). All other reservoirs are termed "fissured".

Considerations for the Treatment of Fissured Formations

The permeability distribution near a well is the key factor for deciding whether to stimulate it or not. If a massive natural fracture already intersects the plane of the well, then hydraulic fracturing would generally not contribute to a significant productivity or injectivity increase. If damage occurs near the well, within a reservoir having a relative large permeability ($\geq$ 1-5 md), acidizing or creating multiple short fractures will generally restore the production. Hence, the best candidates for stimulation are those wells that have a low matrix permeability.

Stimulating geothermal fissured formations creates unique problems during the treatment, due to the presence of discontinuities that may affect the propagation path of the induced fracture, and high leakoff due to the presence of *thief* fissures. Warpinski and Teufel [5] considered the effect of geological discontinuities on the propagation of a hydraulic fracture, giving criteria for the fracture to alter its direction. If treating pressures are large enough, shear slippage may be induced along joint or fissure sets. Jeffrey *et al.* [6] analyzed the condition for effective proppant transport in those situations. When there is proppant bridging, the resulting increase in treating pressures may lead to "dendritic" fracturing. Kiel [7] discussed the advantages of the created connected pattern which results in a volume drainage versus a classical areal drainage created by a planar fracture. Murphy and Fehler [8] discussed the conditions for such a dendritic fracture growth to occur as a function of the dilatation behavior of joints, as well as fluid rheological properties. The injection of a high viscosity fluid and high injection rates will favor the creation of a single main hydraulic fracture. Campbell *et al.* [9] described a technique to create dendritic fractures using a staged injection of low viscosity fluids, and discussed a series of treatments performed in Idaho, some of them showing evidence of large increases in productivity subsequent to hydralic fracturing. Several papers have been published on the characterization of fracture extension using acoustic techniques in an attempt to identify shear stimulation when low viscosity fluids are injected: Pine and Batchelor [10] compared the results of an actual treatment with the prediction of a numerical code, while House *et al.* [11] conducted seismic studies using a surface array of seismometers, indicating the creation of such shear features. The propagation of shear fractures is however not desirable, when the hydraulic fracture is to be propped, because of the high probability of screening out due to the accumulation of proppant at the tip of the fracture. Hence, the use of high viscosity fluids is generally recommended for an improved control of proppant transport.

The second important effect of fissures is to induce a significant increase in the volume of fluid lost during the injection. Classically, three mechanisms have been considered to model the fracturing fluid leak-off and the factors controlling it (Settari [12]):

- The first type of control is due to the creation of a *cake* deposited by the fracturing fluid on the fracture walls: the leak-off coefficient for fissured formations has been shown to be two to three times larger than for tight reservoirs (Hall and Houk [13]).
- A second mechanism is due to the viscosity of the filtrate: the corresponding permeability is the fissure permeability, hence the mechanism would not generally be effective to reduce leak-off.
- The third mechanism is due to compressibility effects in the reservoir. For fissured systems, the derivation of the corresponding leak-off coefficient is not straightforward, since the solution is based on the transient solution for a plane source in a double porosity representation. For practical purposes, however, the corresponding resistance may be neglected.

The *combined* leak-off coefficient, which lumps the previous three mechanisms, will hence generally be equal to the wall builiding coefficient. The addition of silica flower or 100-mesh proppant allows a reduction in the amount of leak-off.

Modeling the Production of Stimulated Fissured Systems

If the formation behaves as a homogeneous system, classical models simulating the effect of a vertical fracture can be used (see Cinco [14] for a review of the different models), and such an approach has been used by Glowka [15] to estimate the qualitative effects of the different types of treatments. Geothermal wells, however, generally exhibit a fissured behavior, with distinct properties for the matrix (generally extremely tight), and distributed fissures. The work of Barenblatt [16] provides a framework for modeling the effects of flow in a system characterized by two sets of porosities corresponding to the high permeability fissures, and to the tight matrix. Analytical derivations have been given by Warren and Root [17] to describe the flow of a single fluid in the non-stimulated case. Numerical models have been developed since, some of them based on the analogy between fissured media and multi-layer reservoirs (Kazemi [18], Boulton *et al.* [19], see also Van Golf Racht [20] for a detailed discussion).

The parameters describing the response of the fissured system can be lumped into the following:

- *Ratio of storativities:* $\omega = \frac{\phi_f}{\phi_f + \phi_m}$
- Interporosity Flow Factor $\lambda_0 = \alpha \frac{k_{ma}}{k_f} r_w^2$

where α is the interporosity flow shape factor [16].

The model used in this study is based on finite-difference discretization of the reservoir, allowing a spatial variation of the permeabilities (see also Ben Naceur and Economides [2] for a detailed presentation). The implicit scheme used, permits accurate modeling of the high contrasts in permeability between the formation and the vertical fracture. Symmetry conditions lead to a discretization of a quarter of the reservoir only.

The new permeability and porosity distribution in the reservoir induced by the vertical fracture is described by (see Fig. 1):

$$k(x,y) = k_F \ , \ r_w \le x \le x_F \, , \ 0 \le y \le w/2 \quad (1)$$
$$\phi(x,y) = \phi_F \ , \ r_w \le x \le x_F \, , \ 0 \le y \le w/2 \quad (2)$$

where x_F and w are the fracture half-length and width, and k_F and ϕ_F are respectively the packed proppant permeability and porosity.

Houze *et al.* [21] have presented solutions for the infinite conductivity fracture in a fissured medium. Ben-Naceur and Economides [2] have extended this work to finite conductivity fractures and quantified the effects of anisotropy. Further they correlated the "intensity" of the natural fissures with the conductivity of the created fracture for constant well cumulative production within a period of time.

Figure 2 is a pressure and pressure derivative type curve from Ben Naceur and Economides [2] for finite conductivity fractures in a fissured medium of known ω and λ. Data from a well test are shown matched on the type curve. To use the type curve it is essential that the values of ω and λ_0 are known from a pretreatment test. The variable λ has been defined for the posttreatment state of the well by Houze *et al.* and is given by:

$$\lambda = \lambda_0 \frac{x_F^2}{r_w^2} \tag{3}$$

A type curve such as the one shown in Fig. 2 is generated for a range of λ. Since the fissure permeability is also known from a pretreatment test, then the dimensionless pressure may be calculated in the usual manner for either oil or gas wells. This allows only one degree of movement (horizontally) for the match. Type curve matching of both pressure and pressure derivative allows the calculation of the fracture half-length, the value of λ as well as the dimensionless fracture conductivity. The procedure is demonstrated in detail in Ben-Naceur and Economides [2].

Figure 3 is a cumulative production type curve for various fracture conductivities (F_{CD}) for a fissured reservoir with typical values of λ and ω (1 and 0.1 respectively). The relationship between the interporosity flow coefficient λ and the fracture conductivity is shown on Fig. 4. For equal cumulative productions, a horizontal line allows the estimation of the desired fracture conductivity for a given value of λ. If λ_0 is known from a pretreatment test, then Fig. 4 is valuable in the design stage of a hydraulic fracture.

Figure 5 is a graph of the dimensionless pressure response for a closed fissured reservoir for various lateral penetration ratios of the fracture. The time to pseudosteady state is given by $t_{DxF} = 0.25\ (x_F/x_e)^2$ where x_e is the drainage radius of the reservoir.

The Effects of Anisotropy

Ben-Naceur and Economides [2] have defined a new equivalent dimensionless pressure:

$$\bar{p}_D = \frac{2\pi \bar{k} h \Delta p}{qB\mu} \tag{4}$$

and fracture time

$$\bar{t}_{DxF} = \frac{\bar{k}t}{\phi\mu c_t \bar{x}_F^2} \tag{5}$$

where:

$$\bar{k} = \sqrt{k_x k_y} \tag{6}$$

and

$$\bar{x}_F = x_F \left(\frac{k_y}{k_x}\right)^{\frac{1}{4}} \tag{7}$$

These definitions allow the normalization of all pressure responses for an infinite conductivity fracture into one as shown as shown in Fig. 6. This graph is identical to the Gringarten *et al.* [4] type curve for an infinite conductivity fracture.

The permeability k_x in Eq. 7 is parallel to the fracture and as explained earlier it should be larger than the normal permeability k_y. Since pressure transient analysis would extract the "apparent" value of fracture length $\bar{x}_F$, then it can be seen from Eq. 7 that the actual fracture length x_F would be larger. If both k_y and k_x have been determined from an interference test, then the actual fracture length may be calculated.

For finite conductivity fractures, the normalization mentionned on Fig. 6 (which is for an infinite conductivity fracture) cannot be done using the variables in Eqs 4 to 7. In the case of geothermal formations, however, the very low matrix permeability would almost always lead to quasi-infinite conductivity fractures.

Conclusions

The following general conclusions can be derived from this study:

1. The effect of a vertical fracture on the productivity of a geothermal (fissured) well can be assessed by using the type curves presented here.
2. Optimization of the treatment requires the determination from a pretreatment test of the flow parameters of the formation. The desired characteristics of the fracture can then be estimated using the new cumulative production type curve.
3. Posttreatment tests allow a determination of the effectiveness of a fracture and its dimensions, with the use of pressures and pressure derivatives.
4. The identification of permeability anisotropy is necessary for an accurate estimation of the potential of hydraulic stimulation. Type curves for isotropic systems can be used to predict the productivity increase, if the introduced normalizing variables are used.

Nomenclature

Roman

- B: Formation volume factor
- b_F: Fracture width
- c_t: Formation total compressibility
- F_{CD}: Dimensionless fracture conductivity ratio
- h: Height (formation and vertical fracture)
- k_f: Fissure permeability
- k_F: Hydraulic fracture (or proppant) permeability
- k_{ma}: Matrix permeability

- k_x: Directional permeability in the x-direction
- k_y: Directional permeability in the y-direction
- $\bar{k}$: Reservoir average permeability
- Δp: Pressure drop
- p_D: Dimensionless pressure drop
- q: Production rate
- q_D: Dimensionless production rate
- Q: Cumulative production rate
- Q_D: Dimensionless cumulative production rate
- r_w: Wellbore radius
- t: Time
- t_{Dx_F}: Dimensionless time
- x_F: Hydraulic fracture length
- $\tilde{x}_F$: Equivalent anisotropic hydraulic fracture length

Greek

- α: Interporosity flow shape factor
- λ_0: Interporosity flow parameter before stimulation
- λ: Interporosity flow parameter after stimulation
- ω: Ratio of storativities
- μ: Reservoir fluid viscosity

References

[1] Hubbert,M.K. and Willis,D.G. "Mechanics of Hydraulic Fracturing". *Trans. AIME*, 210:153–166, 1957.

[2] Ben Naceur,K. and Economides,M.J. "Production from Naturally Fissured Reservoirs Intercepted by a Vertical Fracture". In *SPE California Regional Meeting*, 1988. SPE 17425.

[3] Economides,M.J. and Fehlberg,E.L. "Two Short-time Build-up Tests Analysis for Shell's Geyser Well D-6 a Year Apart". In *Proc. of the 5th Workshop on Geother. Res. Eng.*, pages 139–152, 1979.

[4] Gringarten,A.C., Ramey,H.J. and Raghavan,R. "Unsteady State Pressure Distributions Created by a Single Infinite Conductivity Vertical Fracture". *Soc. Pet. Eng. J.*, 347, 1974.

[5] Warpinski,N. and Teufel,L.W. "Influence of Geological Discontinuities on Hydraulic Fracture Propagation". In *SPE Annual Meeting - Houston*, 1984. SPE 13224.

[6] Jeffrey,R.G. and Vandamme,L. . "Mechanical Interaction in Branched or Subparallel Hydraulic Fractures". In *SPE/DOE Meeting on Low Permeability Reservoirs*, 1987. SPE 16422.

[7] Kiel,O.M. "The Kiel Process - Reservoir Stimulation by Dendritic Fracturing ". In *SPE-AIME 52nd Annual Conference, Denver*, 1977. SPE 6984.

[8] Murphy,H.D. and Fehler,M.F. "Hydraulic Fracturing of Jointed Formations". In *SPE International Meeting on Petroleum Engineering - Beijing*, 1986.

[9] Morris,C.M.
Campbell,D.A. and Verity,R.V. "Geothermal Well Stimulation Experiments and Evaluation". In *SPE Annual Fall Meeting, San Antonio*, 1981. SPE 10316.

[10] Pine,R.J. and Batchelor,A.S. "Downward Migration of Shearing in Jointed Rock during Hydraulic Injections" . *Int. J. Rock Mech. Min. Sci. Geomech. Abst.*, 21:249–263, 1984.

[11] Keppler,H. House,L. and Kaieda,H. "Seismic Studies of a Massive Hydraulic Fracturing Experiment". In *Proc. of Geother. Res. Council Annual Meeting*, August 1985.

[12] Settari,A. "A New General Model of Fluid Loss in Hydraulic Fracturing". In *SPE/DOE Symposium on Low Permeability Reservoirs, Denver*, 1983. SPE 11625.

[13] Hall,B.E. and Cook,S.G. "Fluid Loss Control in the Naturally Fractured Buda Formation". In *SPE Annual Fall Meeting, San Francisco*, 1983. SPE 12152.

[14] Cinco,L.H. "Evaluation of Hydraulic Fracturing by Transient Pressure Analysis Methods". In *International Meeting on Petroleum Engineering - Beijing*, 1982. SPE 10043.

[15] Glowka, D.A. "Effects of Artificial Fracture Geometry on Geothermal Well Production". In *Proc. of geother. Res. Council Annual Meeting*, pages 507–512, 1985.

[16] Barenblatt, G.I., Zheltov, Y.P. and Kochina,I.N. "Basic Concepts in the Theory of Seepage of Homogeneous Liquids in Fissured Rocks". *J. Appl. Math. Mech.*, 852–864, 1960.

[17] Warren,J.E. and Root,P.J. "The Behaviour of Naturally Fractured Reservoirs". *Soc. Pet. Eng. J.*, 245–255, 1963.

[18] Kazemi, H. Seth,M.S. Thomas,G.W. "The Interpretation of Interference Tests in Naturally Fractured Reservoirs with Uniform Fracture Description". *Soc. Pet. Eng. J.*, 463–475, 1969.

[19] Boulton,N.S. and Streltsova, T.D. "Unsteady Flow to a Pumped Well in a Fissured Water-Bearing Formation". *J. Hydrol.*, 257–269, 1977.

[20] Van Golf-Racht T.D. *Fundamentals of Fractured Reservoir Engineering.* Elsevier, Amsterdam, 1982.

[21] Houze,O.P., Horne,R. and Ramey, H.J. Jr. "Infinite Conductivity Vertical Fracture in a Reservoir with Double Porosity Behaviour". In *SPE California Regional Meeting*, 1984. SPE 12778.

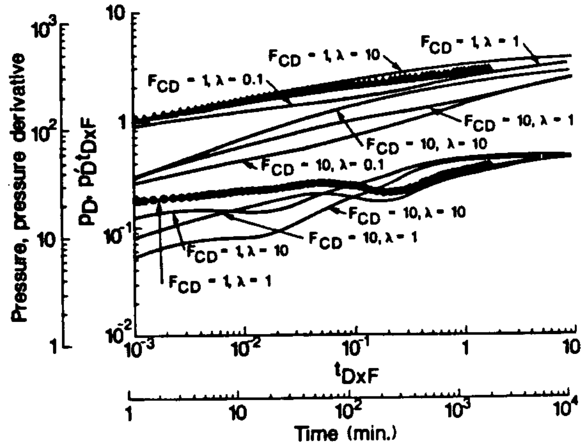

Figure 2: Interpretation of a Well Test in a Fissured Reservoir Intercepted by a Finite Conductivity Fracture

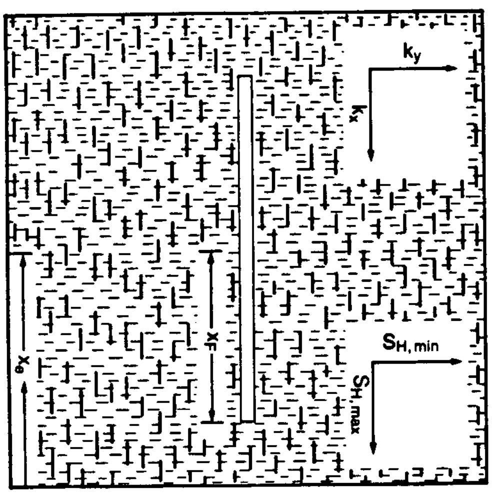

Figure 1: Conceptual Diagram of Open and Closed Fissure Distribution Leading to Permeability Anisotropy as a Result of Stress Anisotropy

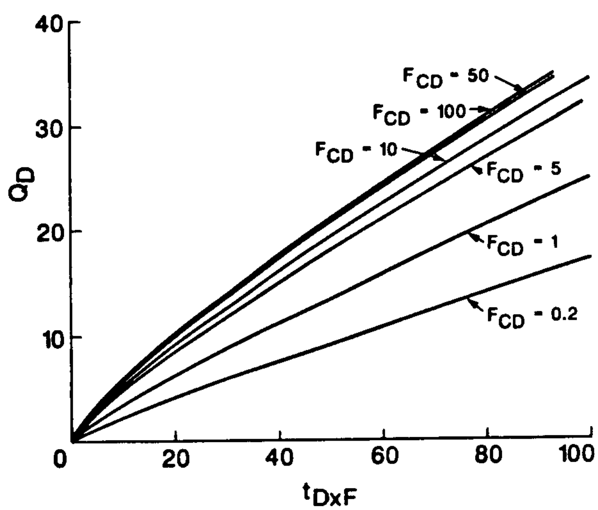

Figure 3: Cumulative Production for a Fissured Reservoir Intercepted by a Finite Conductivity Fracture. (ω =•1, $\lambda = 1$)

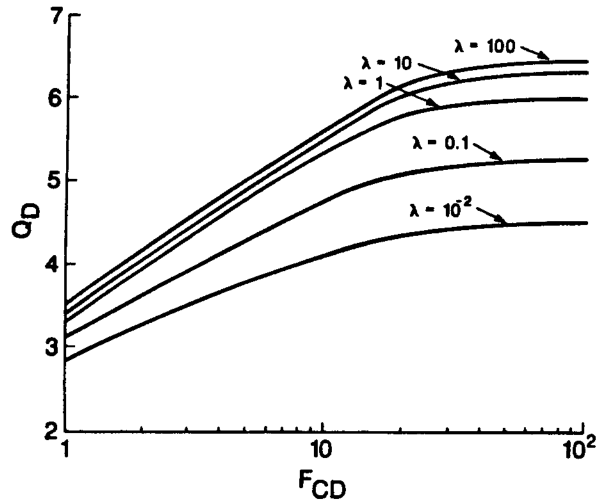

Figure 4: Correlation of Hydraulic Fracture Conductivity and Natural Fissure Intensity (λ) [$t_{DxF} = 10$, $\omega = 0.1$]

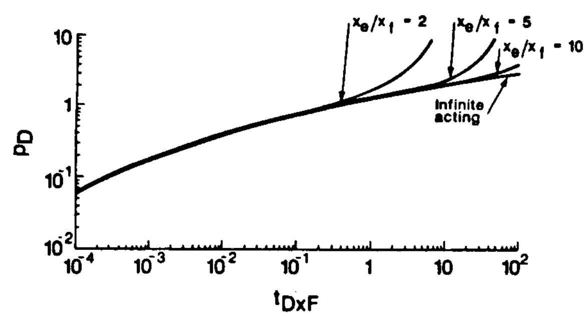

Figure 5: Closed Boundary Effects of the Behavior of an Infinite Conductivity Fracture in a Fissured Medium

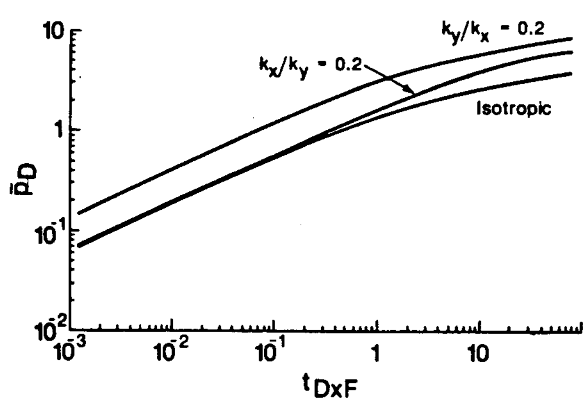

Figure 6: Dimensionless Pressure for an Infinite Conductivity Fracture in an Anisotropic Homogeneous Medium. Effect of Permeability Ratio. When using the normalized variables, all curves will collapse on the isotropic one