STUDIES OF INJECTION INTO NATURALLY FRACTURED RESERVOIRS

Gudmundur S. Bödvarsson and Cheng Hsien Lai

Earth Sciences Divisison
Lawrence Berkeley Laboratory
University of California
Berkeley, California 94720

ABSTRACT

A semi-analytical model for studies of cold water injection into naturally fractured reservoirs has been developed. The model can be used to design the flow rates and location of injection wells in such systems. The results obtained using the model show that initially the cold water will move very rapidly through the fracture system away from the well. Later on, conductive heat transfer from the rock matrix blocks will retard the advancement of the cold water front, and eventually uniform energy sweep conditions will prevail. Where uniform energy sweep conditions are reached the cold water movement away from the injection well will be identical to that in a porous medium; consequently maximum energy recovery from the rock matrix will be attained. The time of uniform energy sweep and the radial distance from the injection well where it occurs are greatly dependent upon the fracture spacing, but independent of the fracture aperture.

INTRODUCTION

Various theoretical studies have shown that injection of water into geothermal reservoirs during exploitation can greatly enhance the energy recovery from the resource. Injection will help maintain reservoir pressure and provide water that will extract energy from the reservoir rocks. However, experience gained through commercial scale reinjection has shown that the injection operation must be carefully designed. Horne (1981) reports enthalpy decline of produced fluids at several Japanese fields due to injection. This interference is attributed to rapid flow of the injected "cold" water through fractures, as evidenced by high tracer velocities. On the other hand commercial scale injection has been successful at other geothermal fields such as the Geysers, U.S. and Ahuachapán, El Salvador. This indicates that fundamental studies of cold water movement in fractured geothermal reservoirs are needed, before confidence in the design of commercial reinjection operations can be established.

In this study the problem of cold water injection into naturally fractured reservoirs is considered. The basis model used is that of Warren and Root (1963), where three orthogonal fracture sets of equal spacing are used. Similar work on non-isothermal flow in horizontal fractures are reported by Lauwerier (1955), Bodvarsson (1969), and Bodvarsson and Tsang (1982). The objective of the present work is to extend their work to include the effects of vertical fractures and to develop a methodology for the design of injection schemes for naturally fractured geothermal reservoirs.

BASIC MODEL

The model used in this study is shown in Figure 1. It consists of rectangular matrix blocks bounded by three sets of orthogonal fractures. Steady state fluid flow is assumed in the fractures, but fully transient conductive heat transfer between the impermeable rock matrix and the fractures is considered. Thus, the cold water will flow from the injection well into the fracture network, and as it moves away from the well, it will gradually get heated up due to the heat transfer from adjacent matrix blocks.

The equation for conductive heat transfer between the matrix blocks and the fractures is derived based on the basic element shown in Figure 2. The basic element represents 1/6 of a single matrix block (cube), i.e. only one face of the cube is considered (1-Dimensional approach). In this approach we assume that the thermal gradients are much smaller within the fracture network, than in the rock matrix. Thus, if the temperature in the fractures bounding a matrix block is rather

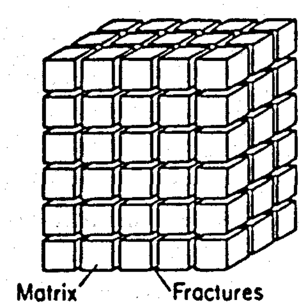

Figure 1. Idealized model of naturally fractured reservoirs (after Warren and Root (1963).

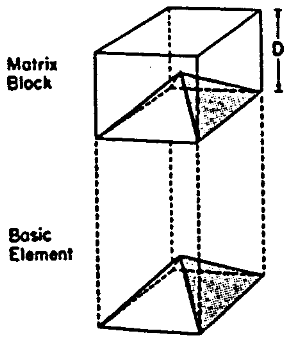

Figure 2. 1-Dimensional approximation of heat conduction in rock matrix blocks.

uniform, a heat conduction equation based on the basic element (Fig. 2) is a reasonable approximation. We have verified this approach by comparing our model to a 3-dimensional solution (Lai and Bodvarsson, 1982). The approach described above is quite similar to the one employed in the "Multiple Interacting Continuum" Method (MINC) for numerical modeling of heat and fluid flow in fractured porous media (Pruess and Narasimhan, 1982).

MATHEMATICAL DEVELOPMENT

In dimensionless form the governing equations for the temperatures in the fractures (T_2) and the rock matrix (T_1) are:

Fractures ($\eta = 1$):

$$-\frac{\delta T_{D_2}}{\delta \xi} - 12 \left. \frac{\delta T_{D_1}}{\delta \eta} \right|_{\eta=1} = \theta \frac{\delta T_{D_2}}{\delta \tau} \tag{1}$$

Rock matrix ($\eta < 1$):

$$\frac{\delta^2 T_{D_1}}{\delta \eta^2} + \frac{2}{\eta} \frac{\delta T_{D_1}}{\delta \eta} = \frac{\delta T_{D_1}}{\delta \tau} \tag{2}$$

The intial and boundary conditions are

$$T_{D_1}(\xi,\eta,0) = T_{D_2}(\xi,0) = 0 \tag{3a}$$

$$T_{D_2}(0,\tau) = \begin{cases} 0 & \tau < 0 \\ 1 & \tau > 0 \end{cases} \tag{3b}$$

$$T_{D_1}(\xi,1,\tau) = T_{D_2}(\xi,\tau) \tag{3c}$$

$$T_{D_1}(\xi,0,\tau) < \infty \tag{3d}$$

The dimensionless parameters in equations (1-3) are defined as:

$$T_D = \frac{T - T_o}{T_i - T_o} \quad (4a) \qquad \tau = \frac{4\lambda t}{\rho_r c_r D^2} \quad (4b)$$

$$\eta = \frac{2z}{D} \quad (4c) \qquad \xi = \frac{\pi r^2 H \lambda}{\rho_w c_w q D^2} \quad (4d)$$

$$\theta = \frac{4\rho_f c_f b}{\rho_r c_r H} \tag{4e}$$

The real parameters in equations 4 are defined in the Nomenclature.

The solution of equations (1-3) can be obtained in the Laplace domain as (Bodvarsson and Lai, 1982):

$$u = \frac{1}{p} \exp - \left[\theta p + 12\sqrt{p} \frac{I_{3/2}(\sqrt{p})}{I_{1/2}(\sqrt{p})} \right] \xi \tag{5}$$

$$v = \frac{u}{\sqrt{\eta}} \frac{I_{1/2}(\sqrt{p}\eta)}{I_{1/2}(\sqrt{p})} \tag{6}$$

Equations (5) and (6) are inverted using a numerical method developed by Stehfest (1970).

RESULTS

It is of primary interest in this study to examine the rate with which the "cold" water front advances away from the injection well during injection. This information is useful in the design of the safe location and rates of injection wells in relation to the production wells. We will define the thermal front (cold water front) as the locus of points with temperature being the average of the initial temperature of the reservoir (T_o) and, the temperature of the injected water T_i ($T_{TF} = 1/2[T_o+T_i]$). In Figure 3 the dimensionless radial distance ξ of the thermal front from the well is plotted against dimensionless time τ for various values of θ. The parameter θ represents the ratio of the average fracture aperture (b) to the reservoir thickness (H). In most cases realistic values of θ lie in the

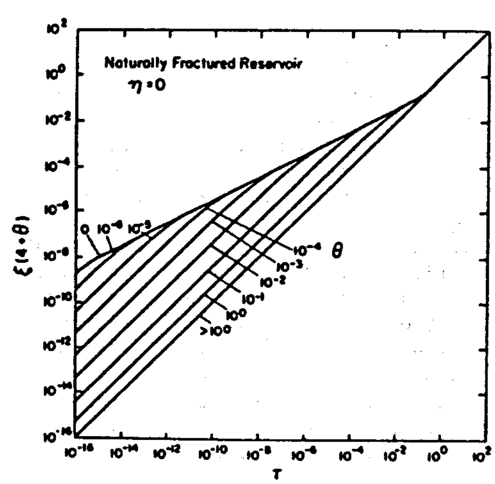

Figure 3. Type curves for thermal front movement in naturally fractured reservoirs.

range of 10^{-5} - 10^{-8}. The figure actually shows for a given value of θ, the radial location of the thermal front (cold water front in the fractures) away from the injection well, at any given time. If one follows the advancement of the thermal front for one value of θ, say $\theta = 10^{-5}$, one can see three different rates of advancement. At early times when conduction heat transfer from the rock matrix is negligible, the front moves as r^2/t away from the injection well. During this period the thermal front moves in the fractures only, in an analogous manner to a single radial system with insulated upper (caprock) and lower (bedrock) boundaries, and a thickness corresponding to the average fracture aperture. Bodvarsson (1972) has derived an expression for the movement of the thermal front in this case. At intermediate times, the slope in Figure 3 decreases by half, and consequently the advancement of the thermal front is proportional to r^4/t. During this period the conductive heat transfer between the rock matrix and the fractures dominates, resulting in a much slower movement of the thermal front away from the injection well. The large heat transfer causes a very slow movement of the thermal front in the fractures, but rapid extraction of heat from the rock matrix.

Finally, at very late times ($\tau \geq 1.0$), the thermal front again advances at a rate proportional to r^2/t. At this time quasi-steady state heat transfer between rock matrix and the fractures has been reached, and consequently the thermal front will move as if only a porous medium was present i.e. independent of the fracture nature of the reservoir. However, in contrast to the early time behavior, the thermal front now moves at the same rate in the fractures as in the rock matrix.

In order to explain this more fully Figures 4-5 were constructed. The figures show the time sequence of the dimensionless temperature profiles away from the injection wells in the fractures and the rock matrix for a given value of θ. The dimensionless temperature of $T_D = 1.0$ represents the temperature of the injected water, whereas the dimensionless temperature $T_D = 0.0$ corresponds to the initial reservoir temperature. Temperature profiles are given for the fractures ($\eta = 1.0$), the center of the cubes ($\eta = 0.0$) and two intermediate values ($\eta = 0.3, 0.7$). The figures show

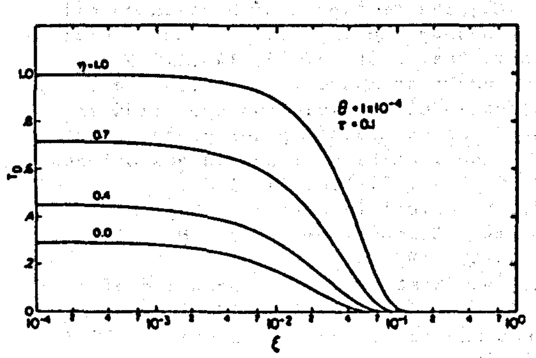

Figure 4. Temperature profiles in fractures and rock matrix; $\tau = 0.1$.

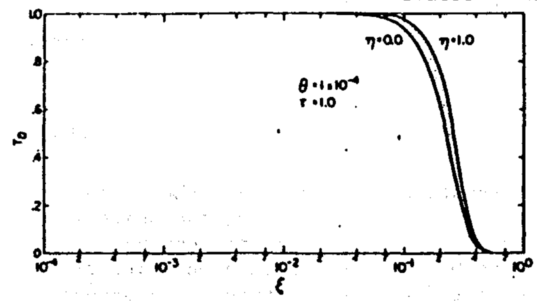

Figure 5. Temperature profiles in fractures and rock matrix; $\tau = 1.0$.

that at early times ($\tau = 0.1$) there is a considerable difference between the temperature profiles in the fractures and the rock matrix. At later times the curves start to converge, although the cold water front is constantly moving away from the well. At a dimensionless time of $\tau = 1.0$ the temperature profiles are practically identical in the fractures and the rock matrix. This can be shown analytically by considering an asymptotic solution for the late time behavior of equation (6).

The reason for this phenomenon is that at early time the cold water shoots rapidly through the fractures, increasing the surface area for conductive heat transfer between the fractures and the rock matrix. The large surface area enhances energy transfer from the rock matrix to the fracture fluids, thus retarding the advancement of the cold water front along the fractures. This in turn, tends to equilibrate the temperatures in the fractures and the rock matrix so that eventually the temperature profiles away from the well are identical for the fractures and the rock matrix.

PRACTICAL CONSIDERATIONS

The most interesting aspect of the results obtained is that even for fractured reservoirs, uniform energy sweep of the reservoir can be obtained. A uniform energy sweep will maximize the amount of recoverable energy from the resource. A necessary requirement for such conditions is that the injection wells be appropriately located with respect to the production wells. Similar conclusions were obtained by Bodvarsson and Tsang (1982) for the case of horizontal fractures only; however in that case the criteria for proper siting of the injection wells are different from what we propose here for naturally fractured reservoirs.

For the design of an injection system for naturally fractured reservoirs mathematical expressions that can be used to calculate the time and radial distance from the injection wells where uniform sweep conditions prevail are quite useful. Figure 4 shows that uniform energy sweep condition will prevail when:

$$\xi \, (4 + \theta) = \tau \approx 1.0 \tag{7}$$

In general $4 \gg \theta$ so that equation (7) can be written in terms of real parameters as:

$$r_c = \left(\frac{\rho_w c_w q D^2}{4\pi\lambda H}\right)^{1/2} \tag{8a}$$

$$t_c = \frac{\delta_r c_r D^2}{4\lambda} \tag{8b}$$

Inspection of equations (8a) and (8b) shows that both the time and radial distance of the uniform energy sweep condition depend greatly on the fracture spacing D. However, both quantities are independent of the fracture aperture b. Fractures possessing small apertures will contain very small amounts of fluids, so that even though fluid velocities are high very little energy is needed to increase the temperature.

Now let us consider an injection well in a naturally fractured reservoir using the parameters shown in Table 1. If the average fracture spacing is not known the following expressions can be calculated.

$$r_c = 2.6 \times D \text{ (meters)} \tag{9a}$$

$$t_c = 0.01 \times D^2 \text{ (years)} \tag{9b}$$

Thus, for an average fracture spacing of 50 meters, uniform energy sweep conditions will prevail 130 m away from the well after 25 years of injection.

Table 1: Parameters Used in Example

Injection rate, q	:	20 kg/s
Fluid density, ρ_w	:	1000 kg/m^3
Fluid heat capacity, c_w	:	4200 J/kg.°C
Thermal conductivity, λ	:	2.0 J/m.s.°C
Reservoir thickness, H	:	500 m
Rock density, ρ_r	:	2700 kg/m^3
Rock heat capacity, c_r	:	1000 J/kg.°C

In summary, we have developed a model that can be used to determine proper locations and flow rates of injection wells in naturally fractured reservoirs. The model can help in optimizing an injection operation so that maximum energy recovery from the resource is obtained.

NOMENCLATURE

- b: Fracture aperture (m)
- D: Fracture spacing (m)
- H: Reservoir thickness (m)
- $I_{1/2}$, $I_{3/2}$: modified spherical Bessel functions of the first kind
- p: Laplace parameter
- ϕ: Porosity (-)
- q: Injection rate (m^3/s)
- r: Radial coordinate (m)
- r_c: Radial distance from injection well to the location of uniform energy sweep
- t: Time (seconds)
- t_c: Time of uniform energy sweep (seconds)
- T: Temperature (°C)
- T_i: Injection temperature (°C)
- T_o: Initial reservoir temperature (°C)
- T_{TF}: The isotherm defined as the "thermal front", $T_{TF} = (T_i + T_o)/2$
- u: Temperature in fracture in Laplace domain
- v: Temperature in rock matrix in Laplace domain
- z: Rock matrix coordinate (m)
- λ: Thermal conductivity of rock matrix (J/m.s.°C)
- ρc: Volumetric heat capacity (J/m^3.°C)

Subscripts:

- f: Fracture
- r: Rock matrix
- w: Liquid water

ACKNOWLEDGEMENT

Critical review of this manuscript by S. Benson, C. Doughty, M. Lippmann and K. Pruess is most appreciated. This work was supported by the Assistant Secretary for Conservation and Renewable Energy, Office of Renewable Technology, Division of Geothermal and Hydropower Technologies of the U.S. Department of Energy under Contract No. DE-AC03-76SF00098.

REFERENCES

Bodvarsson, G., On the temperature of water flowing through fractures: J. Geophys. Res., Vol. 74, No. 8, 1969.

Bodvarsson, G., Thermal problems in the siting of reinjection wells: Geothermics, Vol. 1, No. 2, 1972.

Bodvarsson, G.S., and Tsang, C.F., Injection and thermal breakthrough in fractured geothermal reservoirs: J. Geophys. Res., Vol. 87, No. B2, pages 1031-1048, 1982.

Bodvarsson, G.S., and Lai, C.H., Injection into naturally fractured reservoirs; paper in preparation, 1982.

Horne, R., Geothermal reinjection experience in Japan: paper presented at the California Regional SPE meeting, Bakersfield, California, SPE-9925, (March 25-26) 1981.

Lai, C.H., and Bodvarsson, G.S.,: Verification of the MINC method, in preparation, 1982.

Lauwerier, H.A., The transport of heat in an oil layer caused by the injection of hot fluid: Appl. Sci. Res. Scat. A., 5, 145, 1955.

Pruess, K., and Narasimhan, T.N., A practical method for modeling fluid and heat flow in fractured porous media: paper presented at the 6th annual meeting of SPE in New Orleans, SPE-20509, (Jan. 31-Feb. 2), 1982.

Stehfest, H., Numerical inversion of Laplace transforms: Communications of ACM, Vol. 13, p. 44-49, 1970.

Warren, J.E., and Root, P.J., The behavior of naturally fractured reservoirs: Society of Petroleum Engineers Journal, September 1963, pp. 245-255.

TECHNICAL INFORMATION DEPARTMENT
LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
BERKELEY, CALIFORNIA 94720