HYDRAULIC-FRACTURE GEOTHERMAL RESERVOIR ENGINEERING

H. D. Murphy
Los Alamos Scientific Laboratory
University of California
Los Alamos, New Mexico 87544

The Dry Hot Rock Geothermal Energy Program being conducted by the Los Alamos Scientific Laboratory has been described in detail by Smith et al.[1] Basically we have proposed that man-made geothermal energy reservoirs can be created by drilling into relatively impermeable rock to a depth where the temperature is high enough to be useful; creating a large hydraulic fracture; and then completing the circulation loop by drilling a second hole to intercept the hydraulic fracture.

Thermal power is extracted from this system by injecting cold water down the first hole, forcing the water to sweep by the freshly exposed hot rock surface in the reservoir/fracture system, and then returning the hot water to the surface where the energy is removed from the water by the appropriate power producing equipment. System pressures are maintained such that only one phase, liquid water, is present in the reservoir and the drilled holes.

In the discussion to follow, the beneficial effects of thermal stress cracking, anticipated because of the cooling and thermal contraction of the rock, will be ignored. Instead, it will be assumed that the fluid flow is entirely confined to the gap between the impermeable rock surfaces and that heat is transferred to this fluid only by means of thermal conduction through the solid rock.

RESERVOIR FEATURES AND EXPECTED PERFORMANCE

Based upon the theory of elasticity and brittle material fracture mechanics[2], we idealize the fracture as being circular with a fracture gap width, w, which varies elliptically with radius. The maximum fracture width is extremely small compared to the maximum fracture radius, R; a typical value being 3 mm (1/8 in.) for a radius of 500 m (1640 ft). Furthermore, since the direction of the least principal earth stress is expected to be horizontal, we anticipate that the fracture plane will be vertically oriented, indicating that fluid buoyancy effects may be important.

The maximum thermal power that can be extracted from the rock surface occurs when the entire rock surface is suddenly and uniformly lowered in temperature from its initial value, T_r, to the cold water injection temperature, T_i. This power, E, is given as a function of time, t, by[3]

$$E = 2\pi R^2 \sqrt{\frac{\lambda \rho_s c_s}{\pi t}} (T_r - T_i) \quad ,$$

where λ, ρ_s, and c_s are the thermal conductivity, density, and specific heat capacity of the rock. Because the thermal conductivity of the rock is small, it can be shown that rather large fracture radii are required to produce significant amounts of power for reasonable periods of time. For example, if the temperature difference, $T_r - T_i$, is 200°K, a 500 m fracture is required if one wishes to be able to produce at least 25 MW(t) continuously for 10 years. To continue this same example, it can be shown[3] that even after 10 years the initial rock temperature is diminished less than 5% for distances of 40 m or more away from the fracture surface. Thus, it is seen that heat is being removed from the rock only in a relatively narrow zone immediately adjacent to the fracture, and we conclude that even for more complicated examples, where the surface temperature is not uniform, the conduction in the rock will be essentially one dimensional; perpendicular to the plane of the crack.

A simple heat balance shows that the minimum water flow rate, Q, required to produce the power is given by

$$Q = \frac{E}{\rho c (T_r - T_i)} \quad ,$$

where ρ and c are the density and specific heat capacity of water. Using typical values it can be shown that our 25 MW(t) example will require a minimum flow rate of 0.03 m^3/sec (1 ft^3/sec or 500 gpm). Since this flow is confined within the very narrow fracture, the water velocities will be of the order of 0.02 m/sec (0.07 ft/sec); quite high compared to, say, the usual flow velocities through porous media, and we conclude that heat transport due to fluid conduction is negligible compared to fluid convection.

RESERVOIR SIMULATION MODELS

Fluid flow and fluid heat transport are idealized as being two dimensional, in the plane of the fracture. The horizontal coordinate is taken as x, the vertical coordinate as y. Solid rock conduction takes place along the z-coordinate, perpendicular to the x-y plane. Using Darcy's law with a permeability for an open fracture of $\frac{w^2}{12}$, the x and y direction velocities become

$$u = -\frac{w^2}{12\mu} \frac{\partial P}{\partial x} \qquad (1)$$

$$v = -\frac{w^2}{12\mu} \left[\frac{\partial P}{\partial y} - \rho g \beta (T - T_o) \right] \qquad (2)$$

where the extra term in the equation for v represents the effects of buoyancy. Making the Boussinesq approximation the equations of conservation of mass and energy in the flowing water are

$$\left(\frac{w^3}{\mu}\frac{\partial P}{\partial x}\right) + \frac{\partial}{\quad} \Bigg| \left(\frac{\partial P}{\partial y} \qquad g(T-T_o)\right) \Bigg| \tag{3}$$

$$\rho c w u \frac{\partial T}{\partial x} + \rho c w v \frac{\partial T}{\partial y} - 2e = 0 \quad . \tag{4}$$

Finally the rock conduction equation is

$$\frac{\partial \theta}{\partial t} = \frac{\lambda}{\rho_s c_s}\frac{\partial^2 \theta}{\partial z^2} \quad , \tag{5}$$

subject to the initial and boundary conditions

$$\theta(x,y,z,t=0) = T_r \tag{6}$$

$$\theta(x,y,z=0,t) = T(x,y,t) \tag{7}$$

$$\theta(x,y,z\rightarrow\infty,t) = T_r \quad . \tag{8}$$

The additional nomenclature is as follows:

- w = fracture width
- P = pressure
- μ = viscosity
- ρ = reference water density (evaluated at T_o)
- T_o = reference temperature
- T = temperature of the fluid
- g = acceleration of gravity
- β = volumetric expansion coefficient of water
- θ = temperature of the rock
- e = the flux of energy delivered to the water by one rock surface; evaluated as $e(t) = \lambda\frac{\partial\theta}{\partial z}(x,y,z=0,t)$.

Equations (3) through (8) represent a considerable simplification of the equations first proposed in the pioneering work of Harlow and Pracht[4] and continued by McFarland.[5] These writers had at their disposal very powerful numerical methodologies[6,7] which made it convenient to include advection as well as transient terms in Eq. (3), and conduction and transient terms in Eq. (4). By formal nondimensionalization and rationalization of the complete equations it can be shown[8] that these additional terms are negligible for calculations of practical interest.

At present the solution procedure consists of first solving the rock conduction Eq. (5), with Eqs. (6) through (8), via Duhamel's superposition integral,[9] and then differentiating the result to evaluate e. Thus

$$e(x,y,t) = \lambda \frac{\partial \theta}{\partial z}(x,y,0,t) = \int_0^{\tau=t} \sqrt{\frac{\lambda \rho_s c_s}{\pi (t-\tau)}} \frac{\partial [T_r - T(x,y,t)]}{\partial t} d\tau . \qquad (9)$$

This solution for e is substituted into Eq. (4). One then has a set of two coupled, nonlinear, time varying, integro-differential equations for T and P. This set of equations is then solved numerically via finite difference analogues to the real equations.[8]

REFERENCES

1. M. C. Smith, R. L. Aamodt, R. M. Potter, and D. W. Brown, "Man-Made Geothermal Reservoirs," Second United States Geothermal Energy Symposium, San Francisco, CA, May 19-29, 1975.

2. T. K. Perkins and L. R. Kern, "Widths of Hydraulic Fractures," J. Pet. Tech, 937-949 (September 1961).

3. H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids (Oxford University Press, 2nd Edition, 1959), pp. 58-62.

4. F. H. Harlow and W. E. Pracht, "A Theoretical Study of Geothermal Energy Extraction," J. Geophys. Res. 77 (1972).

5. R. D. McFarland, "Geothermal Reservoir Models--Crack Plane Model," Los Alamos Scientific Laboratory report LA-5947-MS (April 1975).

6. A. A. Amsden and F. H. Harlow, "The SMAC Method: A Numerical Technique for Calculating Incompressible Fluid Flow," Los Alamos Scientific Laboratory report LA-4370 (1970).

7. A. D. Gosman and W. M. Pun, "KASE Problems for the Teach Computer Programs," Imperial College of Science and Technology, London, U.K. report HTS/74/3 (January 1973).

8. H. D. Murphy, Los Alamos Scientific Laboratory, unpublished data, 1975.

9. H. S. Carslaw and J. C. Jaeger, Conduction of Heat in Solids (Oxford University Press, 2nd Edition, 1959), p. 30.