FRACTURE FLOW IN GEOTHERMAL RESERVOIRS

Gunnar Bodvarsson
School of Oceanography
Oregon State University
Corvallis, OR 97331

The following is a very brief summary of research in sane topics of geothermal reservoir engineering and related matters which has been carried out by the writer during the past few years. A number of field data from geothermal reservoirs in Iceland will also be reported on.

Type of Reservoir Flow

Geological formations exhibit mainly two types of fluid conductivity or permeability, viz., (1) micropermeability due to very small intergranular openings and (2) macropermeability due to individual fractures and other major openings. The first type of permeability is associated with the Darcy type of flow which prevails in unfractured porous clastic sediments. It is characterized by laminar flow in the small openings and hence a linear relation (Darcy's law) between the pressure gradient and the specific mass flow. Fracture flow due to macropermeability prevails in igneous rocks, limestones and fractured sediments and is well known to be the most important type of flow in the majority of known geothermal reservoirs. A considerable literature exists on the theory of Darcy type of flow whereas much less attention has been devoted to fracture flow.

Borehole Productivity and Pressure Drawdown in Fracture Flow

Consider the case of a vertical borehole producing liquid phase flow from a horizontal fracture of constant width which is assumed to be small compared to the diameter of the hole. The solution of the differential equation for the pressure field in the fracture around the borehole is a simple task and gives the following result

$$p(r) = p_o - \frac{q^2}{8\pi^2 h^2 \rho} \left[\frac{1}{r^2} + \frac{f}{hr}\right] \qquad r > d/2 \qquad (1)$$

where

$p(r)$ = pressure in the fracture at the distance r from the borehole axis
p_o = undisturbed formation pressure
q = mass flow of the borehole
d = diameter of the borehole
h = width of the fracture
ρ = density of the liquid produced
f = friction coefficient (dimensionless) of the fracture

At a given borehole pressure p_b, equation (1) gives for the mass flow

$$q = \pi hd \sqrt{\frac{2\rho(p_o-p_b)}{1+fd/2h}} \tag{2}$$

Equations (1) and (2) reveal two important facts. First, the pressure drawdown is very local. In most cases, the full formation pressure p_o prevails at a distance less than 2 meters from the borehole axis. Second, fractures of very small widths give a high productivity. For example, a borehole of $d = 0.25$ meters cutting a fracture of $h = 10$ millimeters can at a pressure differential of $p_o-p_b = 1$ atm produce about 100 kg/sec of water. These data are based on the assumption of turbulent flow. The above results can easily be extended to gas phase flows. Two-phase flows can be discussed on the basis of similar methods, but there is greater uncertainty as to the friction coefficient f.

Overall Permeability of Fracture Flow Formations

Flow in fractures is laminar at sufficiently small Reynold numbers. Slow large scale flow within fractured reservoirs with a sufficiently high fracture density can therefore quite often be treated on the basis of Darcy flow concepts and methods. Although the flow will generally be turbulent in the production zones around boreholes, these deviations are usually unimportant due to the small radius of the pressure drawdown.

There are some difficulties encountered in measuring or estimating the overall Darcy type permeability of fracture flow reservoirs. Nevertheless, useful estimates can often be obtained in the cases where borehole production is sufficiently variable to cause measurable fluctuations in the drawdown of the ground water surface. To illustrate the methodology involved, we will consider the following much simplified case.

Given a half-space of homogeneous and isotropic Darcy type permeability k and porosity ϕ, containing a stationary fluid with a horizontal surface and constant kinematic viscosity ν. A vertical well is drilled into the solid and pumping of the fluid is initiated at time t=0 from the depth H. Let the total volume of fluid produced during a given time interval be V, the resulting drawdown of the fluid surface at the well be d and the total drawdown volume be D. Assuming that d is very small compared with H, simple potential theoretical methods give the following estimate for the porosity of the solid

$$\phi = V/D = V/2\pi dH^2 \tag{3}$$

The permeability can be estimated by discontinuing pumping and observing the rate of recovery or velocity of upward movement of the fluid surface. Let the recovery process start with a drawdown d and an initial upward velocity u both measured at the well. Similar methods as used to obtain equation (3) give the following estimates for the permeability

$$k = uH\nu\phi/2gd \tag{4}$$

A variant of the method indicated has been used to estimate the permeability of the reservoir formations of the Reykjavik geothermal system in Iceland. The reservoir there is embedded in flood-basalts and has a base temperature of around 140°C. Since pumping is carried out in a group of fairly widely spaced wells, the right hand side of equation (3) cannot be used to estimate the porosity. Unfortunately, there are insufficient well data to estimate the total drawdown volume D directly. However, the average porosity of the flood-basalts can be estimated by other means and values of less than one % have been obtained. Using a value of 1/2% and the ground water surface recovery data from a single well, an estimate of the permeability of $3 \cdot 10^{-12}$ m^2 (MKS unit) or three Darcy is obtained. This is an apparent permeability which gives only an order of magnitude of the formation permeability.

Well Stimulation

Equation (2) above shows that borehole production from fractured rock can be stimulated by mainly two methods. First, by the lowering of the well pressure p_b which can be achieved by pumping. Second, by increasing the production opening or fracture width h at the well with the help of various types of fracturing techniques. Equation (2) indicated that the latter method is likely to be effective.

Both stimulation methods have been used with considerable success by the Reykjavik District Heating System in Iceland. Practically all producing wells of the system are now pumped. In many cases, hydraulic fracturing increases the well production by a factor of three to four.

Reservoir Stirnulation

The productivity of geothermal reservoirs can be stimulated to a varying degree by the injection of water into the hot formations. Declining formation pressure and productivity of artesian reservoirs can be partially restored by a simple relatively low-pressure reinjection of effluent thermal waters. Partial stimulation of this type has the advantage of providing an efficient method of effluent water disposal. Moreover, geoheat production can be initiated from formations of low or negligible permeability by the injection of water at suitable locations, Of particular interest is the injection into local permeabilities provided by natural fractures, formation contacts, fault zones and dikes. The water is subsequently recovered by wells after having been in contact with a sufficiently large surface area of hot formations. Totally forced geoheat production of this type will in general require a more advanced technology. The economic feasibility has yet to be established and no such systems are now in operation.

From the theoretical point of view, reservoir stimulation, whether partial or total, involves a number of processes which have not been given much attention. Elastic, thermoelastic and convective effects are quite important but rather complex.

The geoheat productivity of fractures in formations of a given temperature can be estimated by fairly elementary means. Assuming operation times of 10 to 20 years and production temperatures within 10% to 20% of the formation temperature, a total of 10 to 20 metric tons of thermal water can be produced per square meter fracture area.

Pattern of Subsurface Flow

A very comprehensive survey of the isotope chemistry of natural waters in Iceland has provided interesting and important results on the overall pattern of ground water flow in the flood-basalt plateau of Iceland. The results indicate the location of the recharge areas of many geothermal systems in the country and show that isotope chemistry can be a very important tool in geothermal reservoir mechanics.

REFERENCES

Reservoir mechanics and related topics:

Bodvarsson, G., 1970, An estimate of the natural heat resources in a thermal area in Iceland. United Nations Symposium on the Development and Utilization of Geothermal Resources, Pisa, Italy.

_____ 1970, Report on an investigation concerning the subsurface disposal of effluent thermal waters from a 30 MW geothermal power plant at Ahuanchapan, El Salvador. UN Development Programme Survey of Geothermal Resources in El Salvador. Tech Report.

_____ 1972, Thermal problems in the siting of reinjection wells. Geothermics 1(2):63-66.

_____ 1974, Geothermal resource energetics. Geothermics 3(3).

_____ 1974, Dikes as fluid conductors in the extraction of terrestrial heat. Geothermal Energy 2(9):42-50.

Bodvarsson, G. and G. Reistand, 1975, Econometric analysis of forced geoheat recovery for low-temperature uses in the Pacific Northwest, Second U.N. Symposium on the Development & Use of Geothermal Resources, San Francisco, CA.

Bodvarsson, G., 1975, Estimates of the geothermal resources of Iceland, Second U.N. Symposium on the Development & Use of Geothermal Resources, San Francisco, CA.

_____ 1975, Thermoelastic phenomena in geothermal systems, Second U.N. Symposium on the Development & Use of Geothermal Resources, San Francisco, CA.

Bodvarsson, G. and Axel Bjornsson, 1975, Hydroelastic cavity resonators, Jokull, 25.

Reykjavik geothermal system:

Bodvarsson, G., 1961, Physical characteristics of natural heat resources in Iceland. UN Conf. on New Sources of Energy, Rome, Jokull 11:29-38.

Thorsteinsson, Thorsteinn, 1975, Development and exploitation of the Reykir Hydrothermal System, Second UN Symposium on the Development and Use of Geothermal Resources, San Francisco, CA.

Tomasson, Jens and T. Thorsteinsson, 1975, Use of injection packer for hydrothermal well stimulation in Iceland, Second UN Symposium on the Development & Use of Geothermal Resources, San Francisco, CA.

Isotope chemistry:

Arnason, B., 1975, Ground water systems in Iceland traced by deuterium, Science Institute, University of Iceland.

Bodvarsson, G., 1962, The use of isotopes of hydrogen and oxygen for hydrological purposes in Iceland, Jokull, 12:49-54.