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Thermal Problems in the Siting of Reinjection Wells

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ABSTRACT

This paper presents a theoretical discussion of the thermal problems involved in the disposal of flash water from geothermal power plants by reinjection. The basic equations for the subsurface temperature field in the reinjection zone are derived both for rocks with intergranular and fracture flow. The extent of the thermal contamination by the reinjected water is discussed. In the case of a continuous mass flow of flash water of 1000 kg/sec for a period of 25 years, the contamination may reach out to as much as 5 kilometers or more from the point of re-entry, depending on the type of rock involved.

Introduction

The generation of power from fluid phase geothermal reservoirs is associated with a considerable flow of flash water which has to be disposed of in some way. For single or double flash power cycles and base temperatures in the range 200 °C to 300 °C, the mass flow of flash water is 5 to 20 kg/sec per MW of power. A 100 MW power plant would thus have to dispose of 500 to 2000 kg/sec of water at 100 °C to 200 °C depending on the flash temperatures and type of power cycle employed. In many regions, the disposal of flows of such magnitudes poses a rather serious problem. It has therefore been proposed to solve the problem by reinjecting the flash water into the ground. This appears to be a logical solution, which may even have the advantage of facilitating the maintenance of reservoir pressure.

The reinjection of waste fluids into permeable formations is gradually becoming an important method of disposal. There are now a considerable number of reinjection wells in operation (EST 1968). However, most of these projects involve relatively small mass flows of chemical wastes and there are no major problems encountered in pumping the fluids into the ground. On the other hand, the very much different magnitude of flow in the case of geothermal flash water poses a number of problems. First, in order to prevent re-emerging at the surface, the flash water has to be injected into relatively deep formations. In many cases involving low-permeability formations, the pumping pressure and power requirements for reinjection become quite substantial. Second, many types of geothermal flash waters are supersaturated with silica and other minerals. Deposits may occur at the points of re-entry and further aggravate the power problem. Finally, because of the very substantial flows into the ground, there is danger of a thermal contamination of the active producing reservoir. If the reinjection wells are not properly sited, the flash water, which has a temperature considerably below reservoir conditions, may flow into the production zones and have a detrimental effect on the steam production. This danger is especially acute in the case of geothermal reservoirs producing from a relatively deep ground water table. A small decrease in production temperature may have a considerable influence on the rate of production and on the stability of the producing wells. The siting of reinjection wells is, therefore, of particular importance in these cases.

The purpose of this paper is to present a brief discussion of the thermal problems involved in the siting of reinjection wells in geothermal reservoirs. The subsurface temperature field around the wells will be discussed in some detail with the aim of arriving at conclusions of practical interest. The present subject matter is closely related to the theory of petroleum production by thermal methods as discussed by, for example, Bailey and Larkin (1960).

The subsurface temperature field around reinjection wells

Because of complexities in the natural environment, the exchange of heat between geological formations and percolating water is a rather involved process. For the present purpose, it is, nevertheless, possible to employ simple idealized models and obtain semi-quantitative results which are quite helpful in the design of reinjection systems. Of particular importance in this respect is to recognize that geological formations exhibit mainly two different types of permeability, that is, (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 generally encountered in porous clastic sediments, whereas most igneous rocks and limestones exhibit only macropermeability due to fractures, tubes and solution openings. In the following, we will refer to the two types of flows involved as intergranular and fracture flow respectively. It is well known that fracture flow is the more important type of flow in geothermal areas, since all major geothermal production wells produce from fractures or other similar openings. The theory of

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the temperature field associated with these two flow types has to be treated along somewhat different lines, as will be discussed below.

Intergranular flow

Consider a homogeneous and isotropic porous and permeable formation saturated with an incompressible fluid which percolates through the rock. We assume that the rock grains are so small that there is a perfect temperature contact between the fluid and the grains. In other words, the grains and the fluid have at any given point the same temperature. The combined convective and conductive heat transport through the formation is then given by

$$\mathbf{h} = -k\nabla T + s\,T \qquad (1)$$

where

k = thermal conductivity of the wet rock
T = temperature
s = heat capacity of the fluid
$\mathbf{h}$ = heat transport per unit area and unit time
$\mathbf{q}$ = mass flow vector of the fluid

By observing that $\nabla \mathbf{h} = -c\rho\, \partial T/\partial t + S$, we obtain the basic heat transport equation

$$\rho c\,(\partial T/\partial t) + s\mathbf{q} \cdot \nabla T = k\nabla^2 T + S \qquad (2)$$

where

ρ = density of the wet rock
c = heat capacity of the wet rock
S = heat production per unit volume

The first term on the right of (2) represents the effect of heat conduction on the macroscopic scale. Since most practical cases involve relatively small temperature gradients ∇T, this term can be neglected compared with the convective term, which is the second term on the left of (2). Assuming no heat sources, equation (2) can thus be simplified to

$$(\partial T/\partial t) + \mathbf{w} \cdot \nabla T = 0 \qquad (3)$$

where $\mathbf{w} = s\mathbf{q}/\rho c$, which we shall call the transport vector. In the case of a homogeneous one-dimensional flow in the direction of the x-axis, this equation has the very simple solution

$$T = f(x - wt) \qquad (4)$$

where f is an arbitrary piecewise differentiable function and w is the scalar $sq/\rho c$. Equation (4) is an important result showing that the temperature field is simply translated with the velocity w. In other words, consider the case when $f(x)$ is the unit step function, that is, zero for $x < 0$ and unity for $x > 0$. As indicated in Figure 1, this temperature front is then translated through the rock with the velocity w. As a matter of course, this velocity is different from the fluid velocity in the pores.

This result can be interpreted in a slightly different way. Suppose we wish to heat a given mass M of fluid from zero temperature to a temperature T by thrusting it through a volume of porous rock having the temperature T. The formation volume V required for this heating follows from the above results,

$$V = sM/\rho c \qquad (5)$$

The volume V will be called the contact volume required for the heating of the fluid mass M. Since the total mass flow during the time t through a cross section A is $M = Aqt$, and the corresponding contact volume is $V = Ax$, equation (4) can be written

$$T = f(V - sM/\rho c) \qquad (6)$$

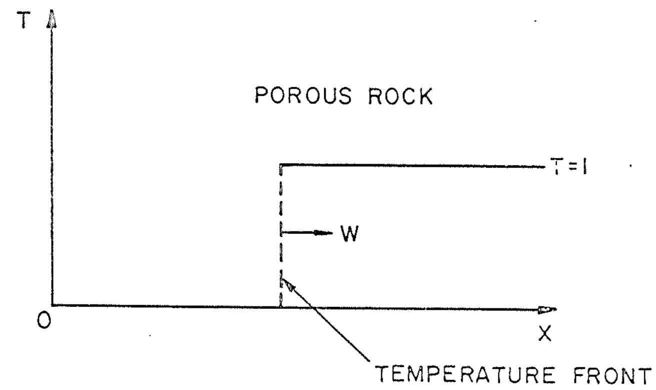

Fig. 1. — *The one-dimensional unit temperature front in porous rock.*

The advantage of this form results from the fact that by reinterpreting V, M, and q, it is also applicable to certain cylindrically and spherically symmetric flows. Two such cases are of particular interest.

Consider a homogeneous porous and permeable solid having a temperature T_o. A point source of mass flow Q kg/sec is introduced at time $t = 0$. Let the temperature of the inflowing fluid be zero. Neglecting density currents and assuming spherical symmetry of the temperature and flow fields where r is the distance from the source, it follows that

$$q = Q/4\pi r^2, \qquad \nabla T = \partial T/\partial r \qquad (7)$$

and hence equation (3) is of the form

$$(\partial T/\partial t) + (sQ/4\pi\rho c r^2)\,(\partial T/\partial r) = 0 \qquad (8)$$

which has a solution of the form (6) where

$$V = 4\pi r^3/3 = sQt/\rho c = sM/\rho c \qquad (9)$$

At time t when a total mass of $M = Qt$ has been injected into the formation, the temperature is zero inside a contact volume V which is a sphere with a radius

$$r = \sqrt[3]{3sM/4\pi\rho c} \qquad (10)$$

and T_o outside this sphere. This is shown on the sketch in Figure 2.

The same considerations apply to the cylindrically symmetric case of a line source of mass flow Q kg/sec, meter embedded in a formation of thickness h as shown in Figure 3. The contact volume per unit length of the source is then $V = \pi r^2$ where r is the distance from the source. The corresponding result for the radius of V is then with $M = Qt$

$$r = \sqrt{sM/\pi\rho c} \qquad (11)$$

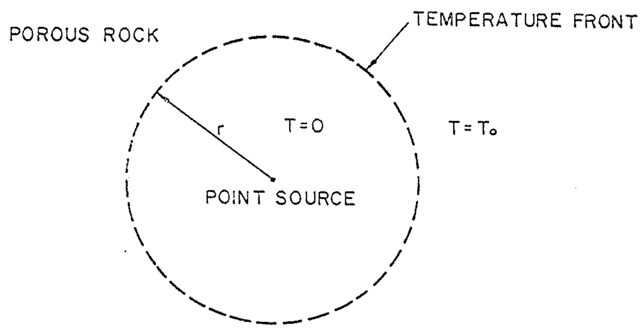

FIG. 2. — *Temperature field around a point source of temperature zero in homogeneous porous rock with initial temperature* T_o.

FRACTURE FLOW

The model of interest in the present context is the case involving the injection of a fluid from a borehole into an extensive fracture of a small uniform width. For convenience, the fracture will be assumed to be horizontal and to extend to infinity in all directions. Let the rock be impermeable and have a constant initial temperature T_o and let the injection from the

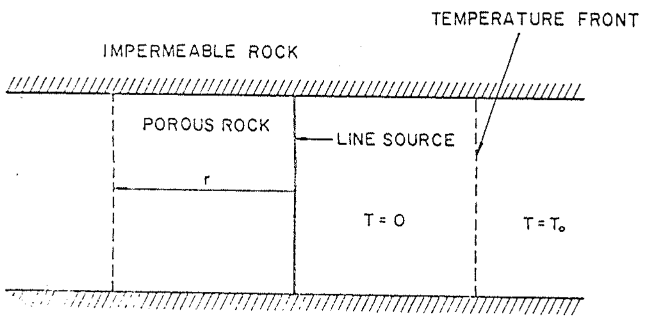

FIG. 3. — *Temperature field around a line source of temperature zero in a layer of porous rock with initial temperature* T_o.

borehole start at time $t = 0$. The temperature of the inflowing fluid is assumed to be zero and the mass flow Q kg/sec is assumed constant. The problem is to derive the resulting temperature field in the rock. This case is similar to a case treated elsewhere by the present writer (BODVARSSON 1969), and a slight modification of these results will furnish the solution in the present case.

As indicated in Figure 4, let r be the radial distance from the borehole and y be the coordinate perpendicular to the fracture which is located at $y = 0$. Moreover, let a be the thermal diffusivity of the rock, and neglecting heat conduction in the radial direction, the problem is then to solve the simple heat conduction equation

$$a\partial^2 T/\partial y^2 = \partial T/\partial t \qquad (12)$$

with the boundary condition at $y = 0$

$$sQ\ (\partial T/\partial r) = 4\pi rk\ (\partial T/\partial y) \qquad (13)$$

and the initial condition $T = T_o$ at $t = 0$. The solution is obtained by assuming that T is of the form T (u, t) where $u = \pi r^2 b + y$ and $b = 2k/sQ$. Since

$$\partial T/\partial r = 2\pi rb\ (\partial T/\partial u)$$

and $\quad \partial T/\partial y = \partial T/\partial u,\ \partial^2 T/\partial y^2 = \partial^2 T/\partial u^2 \qquad (14)$

the boundary condition (13) is satisfied and equation (12) takes the form

$$a\partial^2 T/\partial u^2 = \partial T/\partial t \qquad (15)$$

The transformed boundary conditions are

$$T\ (u, 0) = T_o \qquad T\ (0, t) = 0 \qquad (16)$$

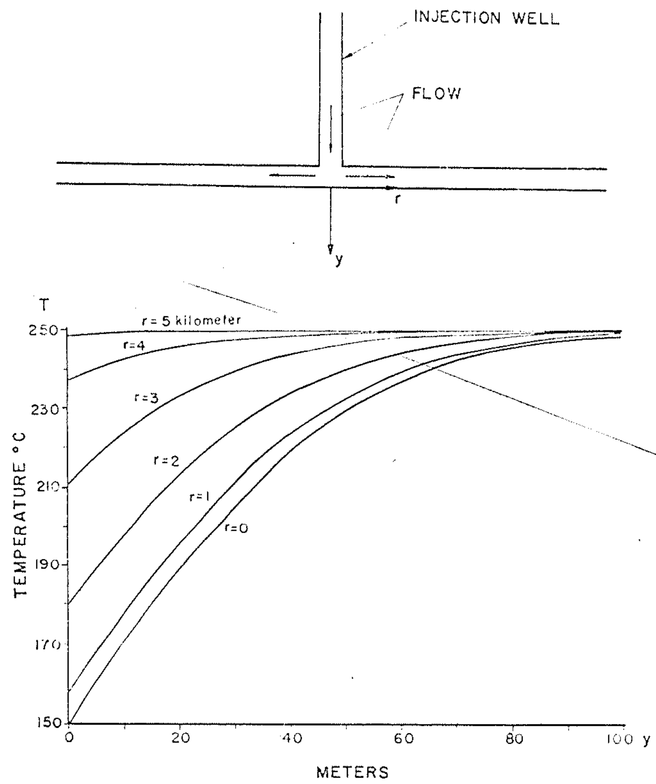

FIG. 4. — *Temperature field in the rock adjacent to a narrow horizontal fracture into which 1000 kg/sec of water of temperature 150 °C have been continuously injected during a period of 25 years. The initial temperature of the rock is 250 °C.*

The solution of the problem defined by (15) and (16) is well known (CARSLAW and JAEGER 1959, page 59).

$$T = T_o \text{ erf } (u/2\sqrt{at}) = T_o \text{ erf } [(\pi br^2 + y)/2\sqrt{at}] \qquad (17)$$

where *erf* denotes the error-function which is tabulated in the mathematical literature (CARSLAW and JAEGER 1959, page 485). Fora $(u/2\sqrt{at}) < 1/2$, equation (17) can be simplified to

$$T = T_o\ [(\pi br^2 + y)/2\sqrt{at}] \qquad (18)$$

Equations (17) and (18) can be applied to estimate the extent of the thermal contamination in the injection fracture.

Practical considerations

The main results of the above discussion are given by equations (6), (10), (11), and (17). Clearly, these simple results have been obtained with the help of highly idealized models, and their applicability in practical cases is therefore greatly restricted. Nevertheless, it is possible to apply the formulas in order to obtain useful semi-quantitative estimates of a number of quantities which are important in the designing of geothermal reinjection systems. This does, in particular, apply to the minimum distances of reinjection wells from production zones. An illustrative example will be discussed below.

Consider the case of a single flash power plant of 100 MW which is operated on a fluid phase geothermal reservoir with a base temperature of 250 °C. Let the mass flow of flash water be 1000 kg/sec at 150 °C. Assuming almost continuos operation, the cumulative flow during an amortization period of 25 years would be 7.5×10^8 metric tons of water. We will assume that this water has to be reinjected into the ground. Since $s = 4.2$ kJ/kg°C, and we can assume that $\rho = 2.5 \times 10^3$ kg/m³ and $c = 1$ kJ/kg°C, equation (5) gives the total contact volume of 1.3 km³. Considering the simplest case, that is, the case of a spherically symmetric contact volume in rock with intergranular flow and a single injection point, we find a radius of almost $r = 0.7$ km. Since this is the case of maximum symmetry, this figure is the minimum distance of thermal contamination from the injection point. In unsymmetric flow, the thermal effects would reach a greater distance in some preferred direction.

Reinjection into one or more fracture-like openings is, however, the case of greater practical interest. Many of the major geothermal reservoirs are found in volcanic formations composed of a series of almost horizontal lava beds. Some of the contacts between the lava beds are highly permeable due to vesicular and tubular openings. Very thin permeable horizons extending over areas of tens of square kilometers are often formed by the contacts. They represent the principal horizontal conductors of thermal water in geothermal areas of this type. Some of these horizons can be used for reinjection purposes. Assuming one injection point and a rotationally symmetric flow from this point, equations (17) and (18) can be used to estimate the extent of thermal contamination by the reinjected water. In contrast to the above case of intergranular flow, this case involves a smooth temperature field where the temperature increases gradually with increasing distance from the point of re-entry. Using the above example and prescribing a temperature decrease of 5 °C as the maximum acceptable thermal contamination within the permeable horizon, equations (17) and (18) can be applied to estimate the distance from the point of re-entry to the boundary of the acceptable contamination. For computational purposes, the temperature of the water to be reinjected is taken to be zero and all temperatures will therefore have to be reduced by 150 °C. Using equation (17) with $T_o = 250 - 150 = 100$ °C, $k = 2.5$ watt/m°C, $Q = 10^3$ kg/sec and hence $b = 1.2 \times 10^{-6}$ 1/m, we find that following an injection period of 25 years a computed temperature of $T = 95$ °C will be present at a distance of 4.5 kilometers from the point of re-entry. Hence, the actual temperature of the water in the permeable horizon at this distance is estimated at 245 °C. The unacceptable thermal contamination is thus estimated to have reached a distance of 4.5 kilometers from the point of re-entry. The temperature field in the formations adjacent to the permeable fracture according to equation (17) is shown in Figure 4.

As stated, the above results have been obtained with the help of a number of simplifications. In this respect, there are mainly three factors which have to be stressed. First, the actual subsurface flow is rarely uniform and there will be preferred directions. Second, a possible interaction between production and reinjection has been neglected. Finally, on the positive side is the fact that density currents within the reservoir may be helpful in minimizing this interaction. In the present example, the density of pure water at 250 °C is 800 kg/m³ whereas water at 150 °C has a density of 915 kg/m³. The flash water has, therefore, a density excess of 115 kg/m³. This density difference can generate density currents causing the colder water being reinjected to sink below the hotter reservoir water. Density currents may thus in many cases help to prevent a harmful intermixture of the two components. The subject of density currents is, however, quite involved and an attempt at an useful discussion will have to be based on specific field models.

The principal result of the above discussion is that the reinjection of volumes of water of the order of one cubic kilometer during periods of a few tens of years should be carried out into (1) extensive thick formations with intergranular permeability or (2) one or more extensive permeable contacts which are open over areas of the order of several tens of square kilometers. Nevertheless, even under such favorable circumstances, the thermal effects of the injected water may reach out to several kilometers from the points of injection. Reinjection wells will, therefore, have to be sited at considerable distances from the active parts of the reservoir. Moreover, in order to take maximum advantage of density currents, the depth of injection should be greater than the depth of main production zones.

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