Enhanced Geothermal Systems Creation and Production

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5 EGS CREATION AND PRODUCTION

5.1 Heat Transfer Features of EGS

Two primary determinants of the possible success of a geothermal system, from conventional hydrothermal to hot dry rock (HDR), are the recovery factors for thermal energy and the possible lifetime of a given producing region. Both features require understanding the coupling of heat transfer to the water and the change of the thermal energy in the rock. These require knowledge of, or models of, the distribution of cracks and associated fluid flow at depth; the latter are poorly constrained, and all models make assumptions about the crack network or the average permeability of the reservoir.

An important characteristic of geothermal energy extraction is that where energy is extracted from a hot rock by contacting the rock with flowing (colder) water, the temperature of the rock is gradually reduced to approach the temperature of the injected water. In the absence of significant permeability of the rock, the thermal recovery of the rock can occur only by heat conduction, which is relatively slow. Hence, heat transfer considerations mean that within t = 5 years of contact with cool water the rock has been locally cooled over a distance of $\approx (4\kappa_r t)^{1/2} = (4 \times 5 \text{ yr} \times 30 \text{ m}^2/\text{yr})^{1/2} \approx 25$ m (where κ_r is the thermal diffusivity of the rock). One implication is that if an EGS system is to produce significant useable energy for more than a year or two, it must employ flow strategies that are tailored to the fracture network. In a network of closely spaced fractures, the “cooling waves” from neighboring fractures will quickly meet in the center of the rock that separates them and this rock will no longer push much energy into the water. However, if the flow is sufficiently slow, this will happen first at the injection end of the channels and propagate slowly toward the exit. In a network of widely spaced fractures higher flow speed may be useful, at least until the cooling wave becomes significant at the channel exit. We discuss these considerations, and illustrate them with example calculations, in this section.

There appear to be practical limits to how much energy can be usefully extracted from heat mining efforts once a thermal front has propagated from the injection point to the exit of the heat-transfer region. For example, if a thermal cycle is used to produce electricity, the temperature of the water is just as important as the rate at which energy is extracted from the rock. Below, we describe one strategy for reducing the rate of decay of the produced energy by reducing the water flow rate, which keeps the thermal efficiency reasonably high.

Thermal bypass: In terms of the order of magnitude characterization discussed above (based on thinking about a model set of uniform cracks), we can remark that the temperature of water within cracks wider than b_0 does not approach the far-field rock temperature T_{r0} because it flows too fast for sufficient heat to be conducted through the rock to the flowing water. (The water itself is taken to be isothermal across a narrow crack). Such wide cracks are a source of thermal bypass, mixing their cooler water with hot water from narrower cracks at the production well. Because the typical crack opening b_0 depends on both the pressure gradient and on the time t_r over which geothermal energy has been pumped, this kind of thermal bypass will develop gradually, and may (at the price of reducing the fluid and heat flow rate) be controlled by reducing the pressure gradient (see below). A second class of thermal bypass, resulting from heterogeneous depletion of rock thermal energy (i.e. cooling of the rock), can occur even for cracks narrower than b_0.

5.1.1 Description of the heat transfer problem

To assess and illustrate the fundamental heat transfer characteristics of an EGS system in HDR, we consider coupled one-dimensional models for temperature evolution in such a system. These models have a long history in geothermal engineering (e.g [82, 83, 84]), and JASON performed similar calculations to make independent assessments of the thermal evolution in the subsurface and to explore tradeoffs available to maximize useful energy

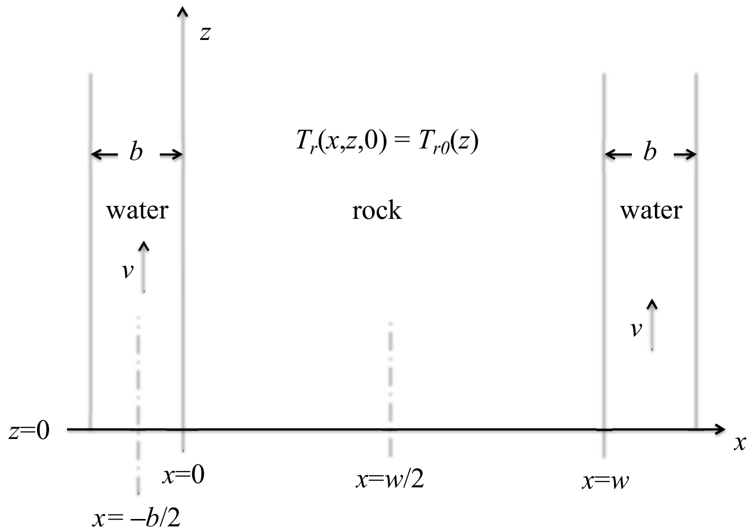

Figure 5-1: A vertical channel of width b and length $\pounds$ (in z) in underground rock, with water injected at temperature T_{w0} flowing upward with speed v. In this section z is vertically upward, consistent with the direction of flow and standard use in heat transfer calculations, but opposite the standard geophysical notation where z is downwards from the Earth's surface.

production. We study first the simple case in which the rock temperature far from the channel remains constant, and we provide quantitative estimates of the time scale on which this is a good approximation. Then we consider later times, for which the rock temperature between flow channels decreases.

The heat transfer from the subsurface is characterized in a straightforward manner *assuming* a crack or simple crack network is present in the rock, e.g. Figure 5-1. Since cracks open up vertically due to the background lithostatic stress we assume for the summary presented here that the fluid flows vertically from an injection well to a production well. The crack opening is expected to be the smallest dimension so a one-dimensional model for the temperature of the water T_w has the form

$$\frac{\partial T_w}{\partial t} + v\frac{\partial T_w}{\partial z} = \kappa_w \frac{\partial^2 T_w}{\partial z^2} + \frac{2j_r}{C_w b}, \tag{5-1}$$

where j_r denotes the heat flux (energy/area/time) transferred from the rock to the water and the factor of 2 accounts for the two surfaces of the crack

(κ_w and C_w are the thermal diffusivity and volumetric specific heat of water, respectively). Typically we expect convective effects to dominate the heat transfer so the conductive term in equation (5-1) is neglected. The thermal evolution in the rock is determined by solving pure heat conduction in the rock:

$$\frac{\partial T_r}{\partial t} = \kappa_r \nabla^2 T_r \quad \Rightarrow \quad \frac{\partial T_r}{\partial t} = \kappa_r \frac{\partial^2 T_r}{\partial x^2}, \tag{5-2}$$

where x is directed into the rock and transverse to the flow direction (see Figure 5-1), with the latter approximation valid since transverse heat conduction occurs on a length scale $(4\kappa_r t)^{1/2} \ll £$. The heat flux $j = k_r \frac{\partial T_r}{\partial x}|_{x=0}$ from the rock to the water couples the water and the rock at their common interface, at which it is a good approximation that $T_w = T_r$. This boundary-value problem is well studied in the literature using analytical and numerical methods, e.g. [82], which is the model on which USGS estimates are based [1].

The analysis (see Appendix B) shows that after a time $t_{c1} \propto b^2/\kappa_r$, where b is the channel width, the water temperature in the channel equilibrates with the local rock-surface temperature. This takes only a few minutes for $b \approx 1$ cm. After this brief initial phase and once the first injected water has made its way to the exit of the heat-transfer zone , the equation for the water temperature becomes quasi-steady, i.e. $v\frac{\partial T_w}{\partial z} = \frac{2j_r}{C_w b}$. A "diffusion" front grows into the rock as the water progressively cools the rock, and a "cooling front" propagates from the injection point towards the channel exit. As a result, there is a distinct front between the region in which water has cooled the rock to its injection temperature, a narrow transition region, and a region in which the water has been heated to the initial rock temperature. Most of the heat transfer from rock to water occurs in this transition region.

As mentioned above and discussed in Appendix B, there is a second critical time t_{c2} when the transverse conduction front ("cooling wave") in the rock has propagated a transverse distance $£_T$ to the mid-point between two parallel cracks. This time is about $t_{c2} \approx £_T^2/(4\kappa_r)$. For example, if two parallel cracks are separated by $2£_T = 30$ m, the central rock temperature will decrease on a time scale $t_{c2} \approx 2$ years. Even before this happens, the heat flow to the water has dropped from its initial transfer rate because it is driven by the temperature gradient in the rock, which falls approximately in proportion to $1/t^{1/2}$ if the cooling water temperature at a given position remains constant. Once the cooling waves collide the gradient falls even more quickly.

Finally, there is a third characteristic time scale t_{c3}, which is when the propagating "cooling front" reaches the exit of the heat-transfer zone (on its way to the production well). A balance of terms in the governing equations shows that it should be expected that the water can no longer be heated close to the ambient rock temperature after a time t_{c3}, where

$$t_{c3} \approx \left(\frac{C_r \; \pounds}{C_w \; vb}\right)^2 \kappa_r, \qquad (5\text{-}3)$$

and where C_r and C_w are the volumetric specific heats of rock and water, respectively.

The time scale t_{c1} is short and not important for the performance of the EGS. However, the competition between t_{c2} and t_{c3} has significant implications for the useful energy that can be extracted from an EGS system and for it longevity. We illustrate this with a series of results below, following the discussion of energy production.

5.1.2 Illustrative examples

We illustrate with a series of results, which we obtained by solving our coupled 1D models as detailed in Appendix B. We consider the following geometry:

1. water injection at $z = 0$ at $T_{w0} = 320$ K;
2. heat-exchange distance, $\pounds$, of 1 km;
3. rock temperature of 550 K at $z = 0$, falling linearly to 525 K at $z = \pounds = 1$ km;