GEOTHERMAL ENERGY EXTRACTION MODELING

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INTRODUCTION

Progress in energy extraction modeling of hydrothermal reservoirs has been achieved in two major directions. One was the development of an analytic model of heat transfer in a fractured geothermal system. The other was an experimental study of the effects of thermal stressing on rock strength and porosity.

The analytic model of linear sweep heat transfer was developed by Iregui et al (1978) and described by Hunsbedt et al (1979). This one-dimensional model calculates the water temperature as a function of time and position in the idealized geothermal system depicted in Fig. 1. Cold water enters the reservoir through a series of injection wells at one end and flows horizontally to a series of production wells at the other end. The injection and production flow rates are steady and the permeability of the formation is such that the flow is considered uniform. Reservoir pressure prevents boiling at any point in the formation. Results from the analytic model are compared with experimental data obtained from the Stanford Geothermal Program (SGP) large reservoir model, shown schematically in Fig. 2.

In fractured hydrothermal reservoirs, circulation of colder water induces tensile thermal stress at and below the rock surface. Murphy (1978) has shown analytically that such stresses have the potential to create self-driven cracks of sufficient depth and aperture to enhance energy extraction and prolong useful production life. Aside from the potential of producing self-driven cracks, thermal stressing may also influence both the mechanical and thermal properties of the rock. Changes in these properties may alter the heat transfer characteristics of the rock over the production period of a reservoir. To gain some insight into the potential significance of the effects of thermal stressing on heat transfer characteristics, an exploratory study was conducted to observe the effects of thermal stressing on rock strength and porosity.

ENERGY EXTRACTION MODELING

The linear sweep model estimates reservoir rock-to-water heat transfer by treating a collection of rock fragments as an equivalent sphere. Water temperature-time behavior is computed from the following partial differential equations and initial and boundary conditions:

$$\frac{\partial T_f^*}{\partial x^*} + \frac{\partial T_f^*}{\partial t^*} + \frac{1}{\gamma}\frac{\partial T_r^*}{\partial t^*} = q^* \qquad (1)$$

$$\frac{\partial T_r^*}{\partial t^*} = N_{tu}\,(T_f^* - T_r^*) \qquad (2)$$

$$T_f^*(x^*,o) = T_r^*(x^*,o) = 1, \quad o \leq x^* \leq 1$$

$$T_f^*(o,t^*) = o \qquad t^* > o$$

where:
- x = distance from the inlet wells
- L = distance between inlet and production wells
- x^* = x/L
- t = time
- t^* = t/t_{re}
- t_{re} = water residence time = $L\phi/u_f$
- ϕ = rock matrix porosity, u_f = water velocity
- T_f^* = normalized water temp. = $\dfrac{T_f(x,t) - T_{injection}}{T_{initial} - T_{injection}}$
- T_r^* = normalized rock temp. = $\dfrac{T_r(x,t) - T_{injection}}{T_{initial} - T_{injection}}$
- γ = storage ratio = $\dfrac{\rho_f c_f}{\rho_r c_r}\,\dfrac{\phi}{1 - \phi}$
- ρ_f, ρ_r = water and rock density, respectively
- c_f, c_r = water and rock specific heat, respectively
- q^* = normalized external heat transfer into rock matrix = $\dfrac{qL}{\dot{m}\, c_f(T_{initial} - T_{injection})}$
- $\dot{m}$ = mass flow rate

N_{tu} = number of transfer units = t_{re}/τ_e

$$\tau_e = \frac{R_e^2}{3\alpha}(0.2 + 1/N_{Bi})$$

R_e = effective rock radius, α = thermal diffusivity

N_{Bi} = rock Biot number

These equations were solved using a LaPlace transform technique combined with a numerical inversion algorithm developed by Stehfest (1970).

The solution for the water and rock temperatures in the LaPlace space are:

$$\hat{T}_f^* = \left[\frac{q^*}{Ks^2} + \frac{1}{s}\right]\left[1-e^{-KsX^*}\right] \quad (3)$$

$$\hat{T}_r^* = \frac{1}{s+N_{tu}} + \frac{N_{tu}}{s+N_{tu}}\left[\frac{q^*}{Ks^2} + \frac{1}{s}\right]\left[1-e^{-KsX^*}\right] \quad (4)$$

where: $K = 1 + \dfrac{N_{tu}}{\gamma(s+N_{tu})}$

The water and rock temperatures as functions of time and space were obtained by the numerical inversion technique with variables of the form

$$T_f^* = f_1(N_{tu},\gamma,q^*)$$

$$T_r^* = f_2(N_{tu},\gamma,q^*)$$

Initial comparison of analytic and experimental data obtained from the SGP reservoir model was presented by Hunsbedt et al (1979). Further comparisons were given by Nelson and Hunsbedt (1979) incorporating data from the most recent experiment.

The comparison of experimental water temperatures with sweep model results obtained by the LaPlace transform/numerical inversion solution showed considerable disagreement for some points in the SGP model. Fig. 3 shows the experimental and predicted water temperatures as functions of time at various locations along the model centerline. It is noted that the slope of the predicted temperature curves are generally greater than the experimental data suggest.

The sweep model was also evaluated using a finite difference solution to check the adequacy of the LaPlace transform solution. Comparison of finite difference results, also given in Fig. 3, with the LaPlace solution shows poor agreement. The finite difference technique was examined further by varying time step and mesh size, but no significant improvement in results was obtained.

The observation that the predicted temperature versus time curves are generally steeper than the experimental curves led to a closer examination of the actual behavior of the physical system and the modeling assumptions. One of the results was an observation that the temperature-time characteristic of the water entering the SGP model follows an exponential rather than a step change assumed in the analytic model. The effect of an exponential reduction in water inlet temperature was investigated using the LaPlace solution, and results are given in Fig. 4. It is noted that the slopes of the predicted curves are similar to those of the experimental data. However, a time lag is present in the predicted curves that might be related to axial heat conduction in the rock/water matrix and non-uniform heat transfer from the steel vessel. The latter effect is currently modeled by a constant heat transfer term, as shown previously in Eq. 1.

The effect of axial conduction was investigated with a finite difference solution, and resulted in a reduction of both the slope and time lag of the calculated temperature-time curves. Studies of the combined effects of axial conduction and exponential water inlet temperature reduction are not yet completed, but are expected to give predicted results which agree more closely with the experimental data. However, it is clear that the mathematical modeling of the laboratory model needs further improvement.

In attempting to model the long-term heat transfer behavior of large-scale fractured hydrothermal systems, several uncertainties in the present sweep model need to be resolved. One concerns the influence of heat transfer from the steel vessel, which releases an amount of energy comparable to that from the rock loading. Another is modeling heat transfer from the distribution of rock fragments comprising a particular geothermal reservoir heat source. Also, the potential change in rock heat transfer characteristics resulting from thermal stressing due to reservoir reinjection needs to be investigated and, if significant, incorporated in the model.

THERMAL STRESS EXPERIMENTS

To explore the effect of thermal stressing on rock strength and porosity, rectangular granite slabs were heated to 450°F. All sides of the slabs were insulated. After a uniform temperature had been achieved, the insulation on one end of the slab was quickly removed and the face quenched with a 70°F water spray. This produced tensile thermal stress on and below the quenched face and compressive thermal stress deeper in the slab. Details of the temperature-time and transient thermal stress behavior in the slabs were reported previously by Nelson and Hunsbedt (1979).

After quenching, the slabs were cut into smaller rectangular specimens and loaded to fracture in three-point bending. It was found that specimens taken from regions of tensile thermal stress had, on average, less than one-half the strength of unquenched specimens. On the other hand, there was no loss of strength in specimens taken from regions of compressive thermal stress. Loss of strength was not due to heating alone. It was also observed that repeated tensile thermal stressing (five cycles) reduced strength to about one-third of that in unquenched rock. The reduction in strength may be due to microcracking caused by tensile thermal stress.

Porosity measurements were made on the same specimens used in the bend tests. The average porosity of unquenched specimens was 1.6%, whereas the average for specimens experiencing one and five applications of tensile thermal stress was 3.8% and 4.8%, respectively. The increase in porosity may also be a result of microcracking.

The above results were obtained from tests conducted at atmospheric pressure. Ideally, such experiments should be conducted under simulated tectonic stresses. Nevertheless, the observed reduction in rock strength and increase in porosity caused by tensile thermal stress may favor formation and growth of self-driven thermal cracks in geothermal reservoirs. It also seems plausible that tensile thermal stress may alter rock heat transfer characteristics (e.g., thermal conductivity). Further tests are underway to investigate this possibility.

FUTURE EFFORTS

Additional heat extraction experiments in the SGP large reservoir model are underway. These experiments will utilize regularly shaped, large granite blocks. This rock loading will allow a more detailed analysis of the heat transfer behavior using the one-lump parameter analytic model adapted for rocks with a known size and shape distribution. The experiments will also test the influence of the number of heat transfer units parameter, N_{tu}, on model behavior. It is anticipated that N_{tu} values will be as low as 3.0, which is well into the reservoir "heat transfer limited" region, that is, where large rock-to-water temperature differences exist. Those differences should also induce significant tensile thermal stresses in the rock.

A second major effort is the improvement of the analytical means to evaluate experimental data. The first step is to develop a finite element model to account for the heat transfer from the steel vessel of the SGP reservoir model. Removal of that component from the heat extraction data will increase the understanding and usefulness of the one-lump rock heat transfer model over the range of N_{tu}. A second step will be to evaluate experimental results with the current sweep model using the LaPlace transform solution in order to further develop the model as a simple means for assessing heat transfer performance of fractured geothermal reservoirs. A third step will be to incorporate the results of thermal stressing experiments from the large block loading into the model to account for possible changes in heat transfer characteristics. The final step will be the development of the model to analyze the heat transfer performance of full-scale fractured hydrothermal systems, such as the Baca field in New Mexico and the Los Alamos fracturing experiment at the Site 2 location.

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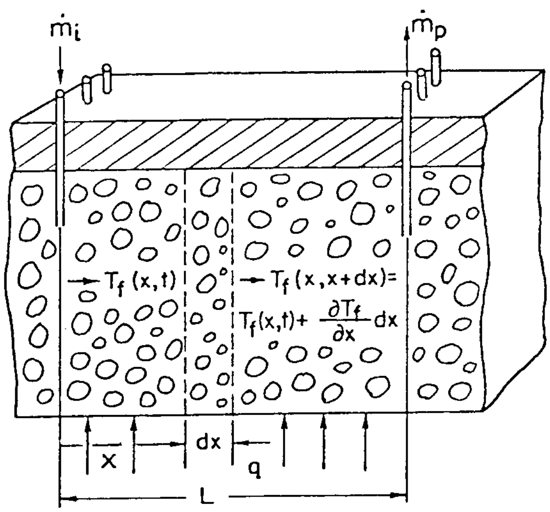

FIGURE 1. LINEAR SWEEP MODEL

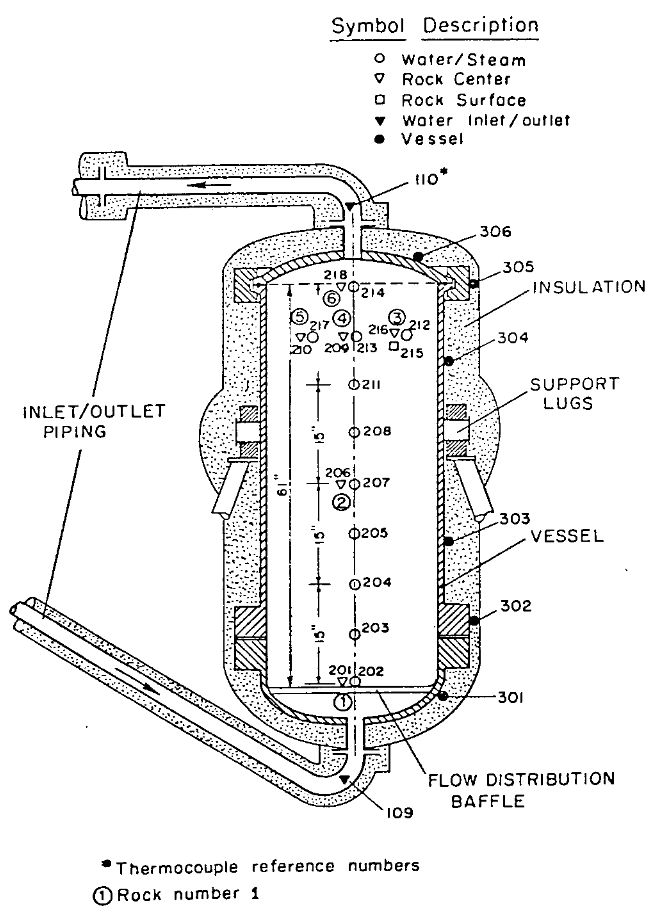

FIGURE 2. SGP RESERVOIR MODEL

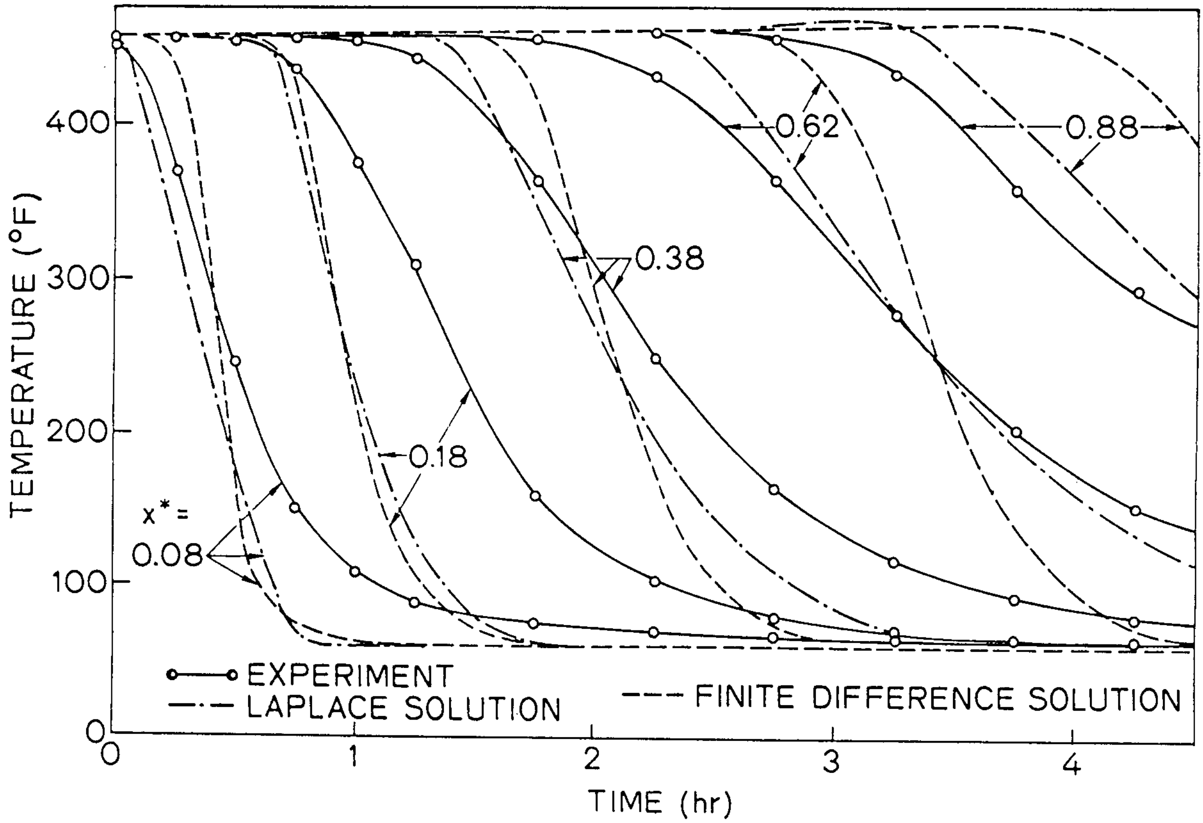

FIGURE 3. COMPARISON OF EXPERIMENTAL AND PREDICTED RESERVOIR TEMPERATURES

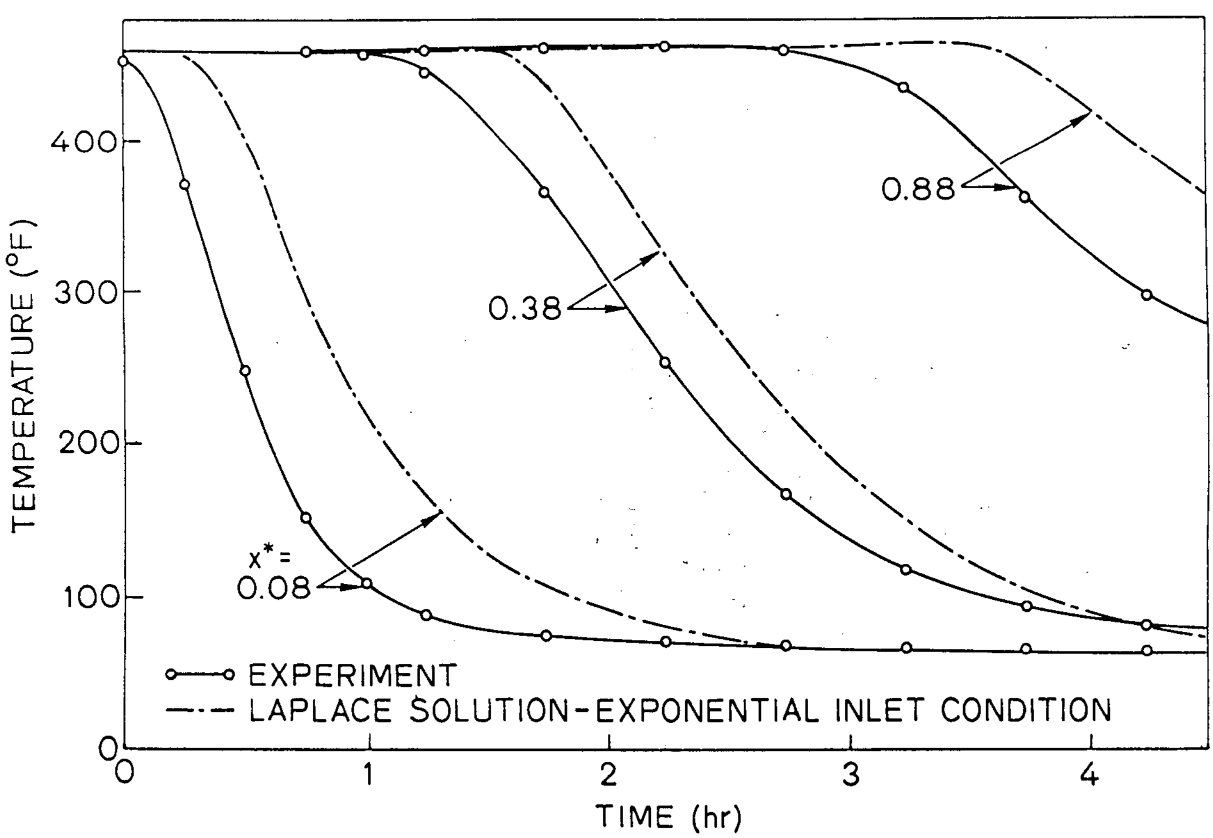

FIGURE 4. COMPARISON OF EXPERIMENTAL DATA WITH LAPLACE SOLUTION FOR AN EXPONENTIAL INLET BOUNDARY CONDITION