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APPLICATION OF THE SGP 1-D LINEAR HEAT SWEEP MODEL

Paul Kruger

Civil Engineering Department
Stanford University
Stanford, CA 94305

ABSTRACT

A 1-D linear heat sweep model, developed to evaluate the experimental data from the SGP Physical Reservoir Model, is based on the equations for heat transfer from irregular-shaped rock blocks as a distribution of spheres having a single effective thermal center. A major parameter of the model is the number of heat transfer units, given by the ratio of the mean residence time of the fluid in one-dimensional flow and the rock mass time constant. The mean residence time is estimated from reservoir parameters and flowrates, and the rock mass time constant is estimated from thermal properties of the rock type. The model has been adapted to evaluate cold-water recharge behavior in geothermal reservoirs where reservoir temperature cooldown has been observed from Na-K-Ca and SiO_2 geothermometers. The first: application was a study of the western boundary of the original Cerro Prieto field, where the observed cooldown could be matched by mixing of sweep water from the west, percolating water from above, and hot water from the east, each at its respective temperature. Additional study of the Cerro Prieto field is underway to observe the cooldown history of the reservoir in relation to the observed piezometric level drawdown. A second application is underway at the Los Azufres geothermal field as a series of four heat sweep analyses in both the northern (2-phase) and southern (mostly steam) zones.

INTRODUCTION

A simple, one-dimensional linear heat sweep model (Hunsbedt, Lam, and Kruger, 1983) has been developed from a physical model of a fractured rock, hydrothermal reservoir to estimate energy extraction based on limited geologic and thermodynamic data. The model was developed in three phases. The first phase involved lumped-parameter analysis (Hunsbedt, Kruger, and London, 1978) using three non-isothermal production methods: (1) pressure reduction with in-place boiling; (2) reservoir sweep with injection of colder water; and (3) steam drive with pressurized fluid production. The results indicated that reservoir sweep with cold water. injection could effectively enhance reservoir rock energy extraction.

The second phase involved development of a heat transfer model for fractured rock of irregular shape and arbitrary size distribution. Heat extraction from an irregular-shaped rock to cooler surrounding water was described by Kuo, Kruger, and Hrigham (1976) in terms of heat transfer Erom a sphere of equivalent thermal radius. They showed that for rock shapes over a wide range of length to width aspect ratios, the equivalent radius for heat transfer can be expressed as the product of the radius of a sphere of equal volume and a sphericity factor given by the surface to volume ratio. The model of heat extraction from a single rock was extended to a distribution of rock block sizes by Iregui, et al. (1979). The distribution can be approximated as a spherical rock with effective thermal radius for heat transfer by the ratio of the distribution of rock block surface areas and volumes.

The third phase was an experimental verification of the model to predict energy extraction from a rock loading of regular geometric shaped rock blocks of known thermal properties in the SGP Physical Reservoir Model. A description of the experiments was given by Hunsbedt et al. (1979). An analysis of the data with the 1-D Linear Heat Sweep Model is given by Hunsbedt, Lam, and Kruger (1983), and comparison to analysis by the MULKOM geothermal reservoir simulator of Pruess (1983) is given by Lam, Hunsbedt, and Kruger (1985).

TYE 1-D LINEAR HEAT SWEEP MODEL

The 1-D Linear Heat Sweep Hodel evaluates the difference in temperature between a distribution of rock blocks described as a spherical rock of equivalent radius at a lumped mean temperature, T_r, and the surrounding pore fluid at a temperature, T_f, for a linearly decreasing reservoir fluid temperature as

$$T_r - T_f = \mu\tau\,(1 - e^{-t/\tau}) \qquad (1)$$

where μ = cooldown rate (C/h)
τ = time constant for the rock (h)

Hunsbedt, Kruger, and London (1978) showed that the time constant for spherical rock blocks can be expressed as

$$\tau = \frac{R_e^2}{3\alpha}\,(0.2 + \frac{1}{N_{Bi}}) \qquad (2)$$

where R_e = equivalent rock radius (m)
α = thermal diffusivity of the rock (m^2/h)
N_{Bi} = Biot number of the rock.

The thermal diffusivity is given by

$$\alpha = \frac{k}{\rho C} \qquad (3)$$

where k = thermal conductivity (J/hmC)
ρ = density (kg/m3)
C = specific heat (J/kgC)

The Biot number is given by

$$N_{Bi} = \frac{h\,R_e}{k} \qquad (4)$$

where h = heat transfer coefficient (J/hm^{2}C)

From Equation 1, the fluid temperature profile in dimensionless space and time over the linear sweep geometry shown in Figure 1 is defined as

$$T_f^* = \frac{T_f(x,t) - T_e}{T_i - T_e} \qquad (5)$$

where $T_f(x,t)$ = water temperature at a distance x from injection line at time t with reference to initial reservoir temperature T_i and recharge water temperature T_e.

In Figure 1, $x^* = X/L$, the relative distance from recharge wells to production wells, and $t^* = t/t_{res}$, relative time referenced to the mean fluid residence time.

The differential equation which describes heat transfer from the equivalent spherical rock to the recharge fluid under Linear sweep wag summarized by Kruger (1983) as

$$\frac{\partial T_f^*}{\partial x^*} + \frac{\partial T_f^*}{\partial t^*} + \frac{1}{\gamma} N_{tu}(T_f^* - T_r^*) = q^* \qquad (6)$$

where the major parameters determining the fluid temperature profile are

N_{tu} = t_{res}/τ, the "number of heat transfer units" parameter
γ = storage ratio of energy in the fluid relative to the energy in the rock
q^* = external heat transfer parameter.

The initial condition for Equation *6* is

$$T_f^*(x^*,0) = T_r^*(x^*,0) = 1 \qquad 0 \le x^* \le 1 \qquad (7)$$

and the boundary condition is

$$T_f^*(0,t^*) = 0 \qquad t^* > 0 \qquad (8)$$

The number of heat transfer units is a key parameter of the model. For small values, e.g., $N_{tu} \lesssim 10$, the reservoir is heat transfer limited, in which the heat transfer rate from the block is not sufficient to heat the recharge fluid before production, resulting in early decline in wellhead fluid temperature and a relatively small fractional energy extraction.

The solution to Equation *6* is initiated by conversion to a Laplace transform equation of the form

$$T_f^*(x^*,t^*) = \mathcal{L}^{-1}\hat{T}_f(x^*,s) \qquad (9)$$

where $\hat{T}_f(x^*,s) = [\frac{1}{s} + \frac{q^*}{Ks^2}][1-e^{-Kx^*s}]$

and $K = 1 + \frac{1}{\gamma}[\frac{1}{s/N_{tu}+1}]$

The inversion *is* accomplished numerically with the algorithm reported by Stehfest (1970):

$$T_f^*(s,t^*) = \frac{\ln 2}{t^*}\sum_{i=1}^{n} a_i \hat{T}[x^*, \frac{\ln 2}{t^*} i] \qquad (10)$$

Explanation of the model in analysis of the SGP Physical Model data, input data requirements, and output formats is given in Hunsbedt, Lam, and Kruger (1983).

APPLICATIONS

Since application of the model *to* assist in the analysis of the experimental data from the SGP Physical Reservoir Model and the hypothetical reservoir study to illustrate its use in the Manual, the 1-D Linear Heat Sweep Model has been applied at two Mexican geothermal fields.

The first external application was a study of the cooldown history at the western boundary of the

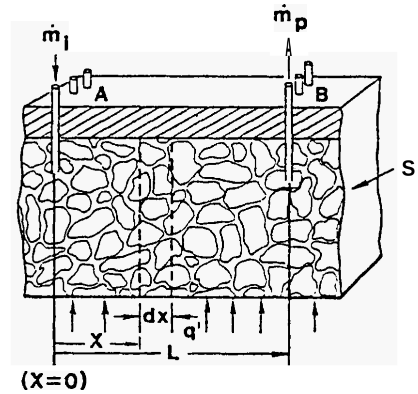

Fig. 1. Geometric schematic of the 1-D Linear Heat Sweep Model

original Cerro Prieto reservoir (CPI) reported by Kruger et al. (1985). In this study the sweep of cooler water From the outer western zone of the reservoir was modeled as a slab of hot rock based on the cross-section of Halfman et al. (1982) which shows a sandstone layer from the west approximately at the depth of the westernmost production wells and a fault near a non-productive stepout well to the west. The cross-section also shows a fault dividing the western line of wells from the next inner wells to the east closer to the central upflow source of hot water. From literature values of sweep geometry, downhole temperature measurements at the stepout well, and thermal properties of sandstone, the results of the 1-D Linear Heat Sweep Model indicated that significant thermal energy was contained in the western outer zone and that cooldown to abandonment temperature could be expected in a period of 25 to 60 years.

Over the 10-year period of continuous production at Cerro Prieto, a significant temperature decline has been observed at the western line of wells. From reported chemical and thermal changes with production, Grant and O'Sullivan (1982) considered the reservoir as a leaky aquifer and attributed one quartet to one half of the recharge to percolation of fresh water from cooler rocks above the reservoir. From the accumulated chemical and production database, Grant, Truesdell, and Mañon (1984) suggested that the western part of the upper aquifer was essentially unbounded and that the reservoir response to continued fluid extraction is dilution by mixing with colder water.

To examine the assumption of linear recharge sweep, the large database for the western line of wells was analyzed to obtain an "observed" cooldown history over the production period and compared to the "observed" cooldown history of the neighboring inner line of wells on the other side of the fault indicated by Halfman et al. (1982). For each of the two lines of wells, data were compiled as six-month averaged values of wellhead pressure, liquid and steam flowrates, wellhead fluid enthalpy, and chemical components Na, K, Ca, SiO_2, and Cl. The chloride values were used as a sample quality check for the geothermometer components. From these data mean values were calculated for reservoir temperature by the Na-K-Ca method of Fournier and Truesdell (1973) and the SiO_2 method of Fournier and Potter (1982). The resulting temperature cooldown histories of the two lines of wells are shown in Figure 2. The results of linear and exponential. regression analysis of the data are given in Table 1. The data showed a common initial reservoir temperature of about 295°C. The linear cooldown rate €or the border wells of -2.3 C/y is decidedly steeper than the value of -1.0 C/y for the inner line of wells.

Rased on these results, the 1-D Linear Heat Sweep Model was modified to include a uniformly distributed source of cold percolating water from above. Figure 3 **shows a** schematic of **a** mixing model

Table 1

TEMPERATURE COOLDOWN ANALYSIS

	Border Wells†				Inner Wells††			
	T_1 (°C)	LCDR* (°C/y)	a** (y^{-1})	r^2	T_1 (°C)	LCDR (°C/y)	λ (y^{-1})	r^2
Wellhead	176	−0.3	−0.002	0.28	186	−0.45	−0.003	0.06
Bottom hole	270	−3.0	−0.012	0.99	271	−1.57	−0.006	0.63
Reservoir	295	−2.3	−0.008	0.92	293	−1.0	−0.003	0.69

† M43, M29, M30, M35
* linear cooldown rate'

†† M11, M19A, M25, M31, M26
** exponential cooldown constant

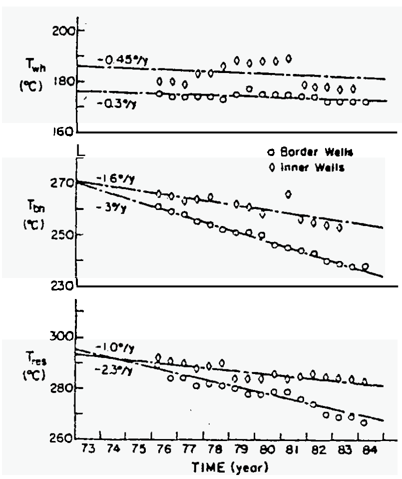

Fig. 2. CPI observed wellhead, bottomhole, and reservoir temperature histories.

for combined flows of horizontal sweep from the west, vertical percolation recharge from above, and hot-water recharge from the east, each with its source temperature. Figure 4 shows the results of the analysis based on the geological analysis of Cobo (private communication) and percolating water temperature of 52" C estimated by Castaneda et al. (1983). The Stehfest Laplace inversion algorithm was compared to those of Crump (1976) and Piessens and Branders (1971). The simulated and observed cooldown curves were adequately matched for the distribution of component flows given in Table 2.

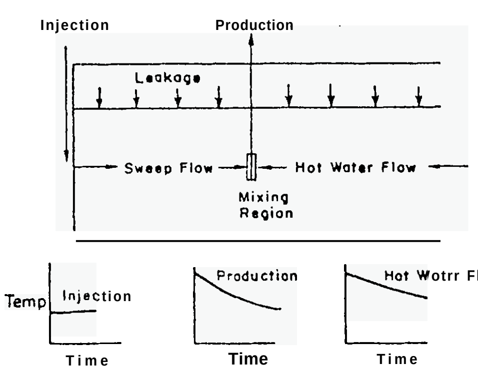

Fig. 3. Schematic of the 1-D linear heat sweep model for CPI analysis.

Further applications are underway at the Cerro Prieto and Los Azufres fields in Mexico. At the Cerro Prieto field, the 1-D Heat Sweep Model is being adjusted for radial flow in an attempt to match the temperature cooldown history of the CPI reservoir as a series of concentric rings around the center well as defined by the piezometric level drawdown reported by Sánchez and de la Peña (1981). Mean radial temperature declines are being calculated from the geochemical data for 15 wells in three radii about the central well. These temperature cooldown histories may be matched by a mixing model of horizontal sweep, vertical percolation, and upflow from the hot-water zone.

At the Los Azufres field a series of four sweep cases are underway to examine the potential for cold-water breakthrough in the undeveloped areas of the field in preparation for reinjection siting €or future wellhead and central power plants. The four reservoir study zones are

(1) Az-31 (injector) to Az-26 (producer) in the eastern part of the south zone

(2) Az-8 (injector) to Az-2 (producer) in the western part of the south zone

(3) Az-15 injection past future production wells in the north zone

(4) 55-MWe power-plant system of 15 production wells and 4 injection wells in the south zone.

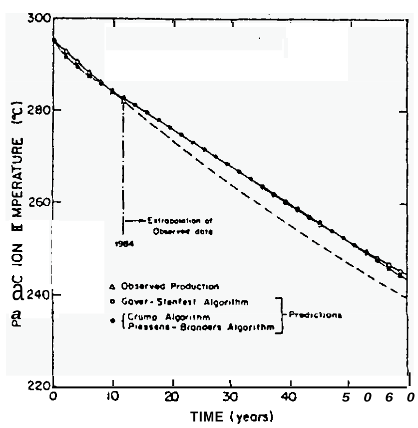

Fig. 4. Comparison of simulated and observed production temperature cooldown.

Table 2

RESULTS OF COOLDOWN HISTORY MATCH

Component	Input Temperature (°C)	Matched Flowrate (kg/s)	Estimated Contribution (%)
Percolation	52	55.2	41±2
Sweep	150	68.7	51±2
Hot Water	$T_{in}+\Delta T\ e^{-\lambda t}$ (see Table 1)	10.8	8±4

A large value already achieved in this project is the decision making for problem definition. Each of the four problems required compilation of estimates for a range of reasonable values for: (1) geologic structure of the reservoir zone; (2) flow characteristics in the zone; (3) initial reservoir temperature; (4) recharge water temperature; and (5) thermal properties of the reservoir formation. The output of these sweep simulations will be the calculated cooldown history to evaluate the sensitivity of the parameter choices for reservoir ,structure, geometry, thermal properties, and production--recharge conditions. The simulations should provide an estimate of heat extractability to an abandonment wellhead fluid temperature of 170°C.

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