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**Thermal Drawdown and Recovery of
Singly and Multiply Fractured
Hot Dry Rock Reservoirs**

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NOMENCLATURE

A fracture heat transfer surface area (one side)
b half of fracture aperture
C specific heat
erf error function
F heat flux per unit time and area
 $\dot{q}$ water flow rate
t time
 t_{ex} duration of heat extraction time
T temperature
u water flow velocity
x,y,z coordinates
 ϵ void fraction
 λ thermal conductivity
 κ thermal diffusivity, $\lambda/(\rho C)$
 ρ density

SUBSCRIPTS

i,j numerical subscripts for the z- and x-direction
in water inlet
out water outlet
r rock
ro rock at initial conditions
w water

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THERMAL DRAWDOWN AND RECOVERY OF SINGLY AND MULTIPLY FRACTURED HOT DRY ROCK RESERVOIRS

by

Rainer Wunder
Hugh Murphy

ABSTRACT

To calculate heat extraction and thermal recovery in hot dry rock geothermal reservoirs, a computer code was written to solve the differential equations for rock-water heat conduction and convection by finite differences. Temperature versus time functions for multiple fractures separated by various spacings are presented in dimensional and in nondimensional plots. The results were specialized for the limiting case of a single fracture in unbounded rock and for the other limiting case where the rock is so extensively fractured that thermal breakthrough phenomena can occur. Fracture temperatures were calculated during the thermal recovery following various extraction periods. For the single-fracture case these temperature recoveries could, with slight approximation, be represented as a single curve depending only upon the ratio of the total elapsed time and the extraction time.

I. INTRODUCTION

Thermal drawdown and recovery behavior of a hot dry rock geothermal system provide important information about the fractured reservoir size. To analyze the outlet temperature curve as a function of time, the dependence of this function upon the reservoir parameters must be well known. These parameters include the density, heat capacity, and thermal conductivity of the rock, normally given by experimental tests with drill cores, the length of the fracture in the flow direction, the total fracture surface area, and the number and spacing of fractures. Drawdown and recovery are the result of the complicated heat transport process

within fracture systems. Typically, these require at least the solution to the coupled equations of heat conduction and convection in the water and heat conduction in the surrounding rock. In some cases heating of the water introduces a buoyant effect, promoting natural convection; or some other effect, such as the type and position of the inlet and outlet, leads to two-dimensional fluid motion. In these cases separate equations, coupled to the heat transport equations, are additionally required to describe the fluid dynamics in a fracture.

Harlow and Pracht¹ have described a three-dimensional single-fracture model in which rather complete equations which embody a nonlinear buoyancy term are utilized to describe both the fluid dynamics and the resultant heat transfer during heat extraction. McFarland and Murphy² found that when the fluid inlet and outlet points were not located at the bottom and top of the fracture, complex two-dimensional streamline patterns would develop. When the ratio of viscous to buoyancy forces was large, the fluid would proceed along the line of least resistance, that is, directly from inlet to outlet; and in so doing, only a portion of the entire fracture area was useful for heat extraction. On the other hand, when the ratio of viscous to buoyancy forces was small, as for example, when the fracture was pressurized open to its maximum aperture or when thermal contraction of the contiguous rock eventually resulted in large apertures, the situation was quite the opposite. The cold, dense, incoming fluid would at first sink toward the bottom. As it gradually heated, it would begin to move horizontally outward, away from the inlet, and eventually would turn upward, heading for the fluid outlet located near the top. In this fashion a much greater fraction of the fracture area was made available for heat extraction.

In the evolution of concepts for extracting energy from hot, initially dry rock, it was quickly reasoned³ that if a slanting well could be drilled, a series of parallel vertical fractures could be created from this well, and that these fractures could be connected to a second well drilled parallel to the first, resulting in a system with much greater overall area. The theory of heat extraction from such a system was first presented by Gringarten, Witherspoon, and Ohnishi.⁴ Their model was based upon an infinite series of parallel, rectangular, equidistant vertical fractures of uniform thickness. To simplify the analysis the inlet fluid was uniformly distributed at the fracture bottoms and flowed uniformly and one dimensionally to the tops, where it was uniformly

extracted. In this manner the fluid dynamics equations could be dispensed with altogether.

In this report we consider not only heat extraction but the thermal recovery that follows the termination of the heat extraction phase. Theoretical results for thermal recovery, when combined with wellbore temperature surveys, can result in the determination of the heat-transfer-effective fracture area, as well as the thermal properties of the rock. In addition these results are of interest in connection with potential modes of operation in which heat extraction and recovery are repetitively alternated, as for example, for peak-power shaving applications.

II. MATHEMATICAL MODELING

Following Gringarten et al.,⁴ we also assume that the fractures are rectangular and vertical and that fluid is uniformly provided at the bottom and extracted at the top. The rock is assumed impenetrable and has constant thermal properties. For single fractures we assume that the rock extends horizontally to infinity. In the case of multiple fractures we assume them to be parallel and equally spaced. The idealized situation is depicted in Fig. 1.

While the assumption of uniform fluid injections and extractions at the lower and upper fracture boundaries can lead to serious errors, particularly if the actual inlets and outlets are located far from the boundaries, the simplified model that results from this assumption is extremely useful for elucidating the main features of heat transfer.

The equations describing temperatures in the water and in the rock are well known. In the rock, any temperature change is induced by thermal conduction.

Neglecting the y-direction, the total temperature field in the rock is given by the differential equation:

$$\lambda_r \left(\frac{\partial^2 T_r}{\partial x^2} + \frac{\partial^2 T_r}{\partial z^2} \right) = \rho_r c_r \frac{\partial T_r}{\partial t} \quad (1)$$

In the water, energy transport not only results from heat conduction but also from the convection. Nevertheless, it

Fig. 1.
Idealized heat extraction system.

is possible to make some simplifications. As the aperture, $2b$, of the fracture is very small compared to the fracture length, water temperature gradients in x -direction are insignificant. The temperature along the flow path is then given by water conduction and convection in the z -direction and the heat transfer between water and rock. For any practical case, the heat transfer resistance at the rock surface can be neglected, so that this energy flow is governed by thermal conduction in the rock. The differential equation is then written in the following form:

$$ub\rho_w c_w \frac{\partial T_w}{\partial z} + b\lambda_w \frac{\partial^2 T_w}{\partial z^2} + \left(\lambda_r \frac{\partial T_r}{\partial x} \right)_{x=0} = \rho_w c_w b \frac{\partial T_w}{\partial t} . \quad (2)$$

It is possible to solve these two equations, connected by the heat transfer at the rock surface, analytically for some special cases. One analytical solution of these coupled equations is given by Arpaci⁵ for the special case of a single fracture in an infinite rock volume (infinite fracture spacing in Fig. 1). The temperature field during the drawdown is given by

$$\frac{T - T_{in}}{T_{ro} - T_{in}} = \operatorname{erf} \left[\frac{\frac{x}{2} + \frac{\lambda_r z}{\rho_w c_w u 2b}}{\sqrt{\frac{\lambda_r}{\rho_R c_r} t}} \right] , \quad (3)$$

where x represents the distance into the rock from the fracture face. Another case with an exact solution is the heat extraction from "rubblized" rock, that is, rock which is split into very small pieces of the size of a few cms or less. It is also the solution for rock with high matrix permeability which is not fractured. The drawdown of these systems is characterized by a very sharp breakthrough of the temperature wave. "Rubblization" or high matrix permeability allows the assumption that the rock and water temperatures are equal at any position. The temperature profile in the flow direction is then given as

$$\left. \begin{aligned} T &= T_{in} ; z < \frac{ut}{\frac{\rho_r C_r}{\rho_w C_w} \frac{1-\epsilon}{\epsilon} + 1} \\ T &= T_{ro} ; z > \frac{ut}{\frac{\rho_r C_r}{\rho_w C_w} \frac{1-\epsilon}{\epsilon} + 1} \end{aligned} \right\} \quad (4)$$

III. NUMERICAL SOLUTION OF THE HEAT EXCHANGE PROCESS

Because the differential equations [Eqs. (1) and (2)] result from heat balances during differential time steps around volumes of differential size, these equations may be approximated and solved numerically using a computer code which balances the heat during finite time steps around finite volumes.

For a differential rock volume with heat exchange only in x- and z-directions, the heat balance is given by

$$\begin{aligned} \lambda_r dz dy \frac{\partial T_r}{\partial x} + \lambda_r dx dy \frac{\partial T_r}{\partial z} - \lambda_r dz dy \frac{\partial}{\partial x} \left(T_r + \frac{\partial T_r}{\partial x} dx \right) - \lambda_r dx dy \frac{\partial}{\partial z} \left(T_r + \frac{\partial T_r}{\partial z} dz \right) \\ + \rho_r C_r dx dy dz \frac{\partial T_r}{\partial t} = 0 \end{aligned} \quad (5)$$

For any finite volume, which is subscripted in the z-direction by i and in the x-direction by j, this heat balance for the i, j element in the rock is given analogous to Fig. 2 as:

$$\begin{aligned} \lambda_r \Delta y \left(\Delta z \frac{T_{r,i,j-1} - T_{r,i,j}}{\Delta x} + \Delta x \frac{T_{r,i-1,j} - T_{r,i,j}}{\Delta z} - \Delta z \frac{T_{r,i,j} - T_{r,i,j+1}}{\Delta x} \right. \\ \left. - \Delta x \frac{T_{r,i,j} - T_{r,i+1,j}}{\Delta z} \right) = \rho_r C_r \Delta x \Delta y \Delta z \frac{\Delta T_{r,i,j}}{\Delta t} \end{aligned} \quad (6)$$

Assuming an infinite heat transfer coefficient between the water and rock surface so that the water and rock surface are at the same temperature, the heat balance for any water volume is given as:

$$u b \Delta y \rho_w C_w (T_{w,i-1} - T_{w,i}) + b \Delta y \lambda_w \left(\frac{T_{w,i-1} - T_{w,i}}{\Delta z} - \frac{T_{w,i} - T_{w,i+1}}{\Delta z} \right) + \lambda_r \Delta y \Delta z \frac{T_{r,i,1} - T_{w,i}}{\Delta x/2} = \rho_w C_w b \Delta y \Delta z \frac{\Delta T_{w,i}}{\Delta t} \quad (7)$$

This type of balance would require an adjustable steplength in the z-direction as a function of the flow rate in order to ensure numerical stability. So the heat balance was rewritten to incorporate the water volume and the first rock volume as shown in Fig. 2. Eliminating Δy from both sides, the equation is rewritten as

$$u b \rho_w C_w (T_{w,i-1} - T_{w,i}) + b \lambda_w \left(\frac{T_{w,i-1} - T_{w,i}}{\Delta z} - \frac{T_{w,i} - T_{w,i+1}}{\Delta z} \right) + \lambda_r \left(\Delta z \frac{T_{r,i,2} - T_{r,i,1}}{\Delta x} + \Delta x \frac{T_{r,i-1,1} - T_{r,i,1}}{\Delta z} - \Delta x \frac{T_{r,i,1} - T_{r,i+1,1}}{\Delta z} \right) = (\rho_r C_r \Delta x \Delta z + \rho_w C_w b \Delta z) \frac{\Delta T_{w,i}}{\Delta t} \quad (8)$$

Thus, we have assumed that the water flow and the first rock node are at the same temperature. While this formulation introduces some inaccuracies, we hold these to an acceptable limit by making the size, Δx , of the first rock node small.

For programming convenience these finite difference equations have been formulated in explicit form. All the temperatures on the left-hand sides are known since they are taken as the values most recently calculated. The unknown new temperatures to be calculated at the next time step appear only on the right-hand sides, which express the differences between the old and new temperatures. These equations were written into a computer code, which is described in the Appendix. To obtain a better estimate of the large temperature gradients near the water-rock surface, we used a varying step length in x-direction beginning with very small steps at $x = 0$.

Results of this computer program, calculating the temperature profile in the z-direction for $x = 0$ and in the x-direction for one value of z, for a single fracture in infinite rock, are shown in Figs. 3 and 4. A comparison with Eq. (3) shows that after a short initial period there is a good agreement between the analytical and the numerical solutions.

IV. RESULTS OF DRAWDOWN AND RECOVERY CALCULATIONS

A. Single Fractures

Figure 5 shows the cooling and recovery of the outlets of single fractures in infinite rock. The curves are calculated for a flow rate of 7.9 liters/s (125 gpm) into the whole fracture and three values of the area, A, on one side of the fracture. These values are typical of those appropriate for the Phase I test of the hot dry rock reservoir at Fenton Hill, New Mexico.

Following the form of Eq. (3) it is possible to plot the dimensionless temperature $T - T_{in} / T_{ro} - T_{in}$ versus a dimensionless time as shown in Fig. 6. Any case of heat extraction from a single fracture in infinite rock will thus be reproduced by one general function.

Thermal recovery curves for several dimensionless extraction times are also presented as dashed curves in Fig. 6. It is emphasized that so long as the appropriate value of A is used in the definition of the dimensionless time, both the drawdown and recovery curves are applicable for any position in the fracture, not just the outlet. Thus, the thermal recovery at any arbitrary location in the fracture, after any arbitrary drawdown period, is found by computing the dimensionless extraction time using the actual period of extraction and the fracture area between the inlet and the location of interest. One then finds the dimensionless thermal recovery curve starting closest to the desired dimensionless extraction period and then estimates the subsequent recovery from this curve.

An even simpler procedure results from the observation that all the curves for thermal recovery in Fig. 6 are similar in shape, suggesting the possibility that they can be collapsed to a single curve. The transformation of variables required to achieve this result is suggested by the thermal recovery of rock in which the drawdown took place such that: (1) the heat flux F, removed from the rock per unit time, was constant; (2) the drawdown temperature was constant during the drawdown. In an actual reservoir this second case sometimes occurs at the reservoir inlet.

In the first case the temperature at the end of the extraction time, t_{ex} , is (Ref. 6, p. 75):

$$(T_{ro}-T)_{max} = \frac{2F\sqrt{k_r t_{ex}}}{\lambda_r \sqrt{\pi}} \quad (9)$$

During the recovery the temperature is given by Duhamel's superposition theorem (Ref. 6, p. 30):

$$T_{ro}-T = \frac{2F}{\lambda_r} \sqrt{\frac{k_r}{\pi}} (\sqrt{t} - \sqrt{t-t_{ex}}) \quad (10)$$

The ratio is simply

$$\frac{T_{ro}-T}{(T_{ro}-T)_{max}} = \sqrt{t/t_{ex}} - \sqrt{t/t_{ex}-1} \quad (11)$$

In the second case with constant drawdown temperature, the thermal recovery is given by

$$\frac{T_{ro}-T}{(T_{ro}-T)_{max}} = 1 - \frac{2}{\pi} \tan^{-1} \sqrt{\frac{t}{t_{ex}} - 1} \quad (12)$$

Equations (11) and (12) are graphed in Fig. 7. Both results are remarkably similar despite the difference in boundary conditions during the drawdown. Also shown are representative numerical results for more realistic drawdown conditions. Within a small error band all the recovery values fall upon a single curve.

B. Multiple Fractures

In many cases, energy from hot dry rock will be extracted not from a single fracture but from multiple fractures. For our calculations, we idealized this multiple-fracture system as uniform parallel flow paths of constant spacing, equal flow rates, and equal areas. The temperature drawdown and recovery of one of these flow paths will then be influenced by the adjacent fractures. However,

Fig. 6.
Dimensionless drawdown and recovery in a single fracture.

Fig. 7.
Thermal recovery of single fractures in transformed coordinates.

neglecting effects at the boundaries of the total system, the reservoir drawdown and recovery is represented by the behavior of any one fracture of the system.

As a result of the superposition of heat flows in multiple fractures we obtain very different drawdown and recovery behavior compared to a single fracture. A comparison of the temperature versus time function between a single fracture and multiple fractures of 1-m spacing is shown in Fig. 8. Although after an extraction time of 1000 h the outlet temperatures are fortuitously coincident, (the flow rate per unit area was different for the two cases), the drawdown and recovery functions are very different. A depleted multiple-fractured reservoir with this spacing shows very little recovery in times comparable to the extraction time.

Fig. 8.
Typical drawdown and recovery results for multiple-fracture systems.

For the limiting case of infinitely fractured or rubblized rock the heat transfer area per rock volume is so large that the temperature inside the rock pieces is the same as that of the water wetting the rock surface. Calculating with differential volumes and timesteps would show a rectangular temperature wave. Finite volumes and time steps result in numerical dispersion, which smoothes and adds curvature to the temperature wave. This effect increases with increasing distance

from the inlet. Figure 8 shows one result, calculating the breakthrough in rubblized rock. The temperatures are calculated at a distance $z = 30$ m beyond the inlet for a flow velocity $u = 2.5 \times 10^{-4}$ m/s and a void fraction of 0.034. The properties of rock and water are: $\rho_r = 2700$ kg/m³; $C_r = 1050$ J/kg K, $\rho_w = 1000$ kg/m³, $C_w = 4200$ J/kg K. Taking these numbers, Eq. (4) predicts breakthrough after 670 h, which is in good agreement to our computer simulation. There is, of course, no thermal recovery in rubblized systems.

V. CONCLUSIONS

Calculation of drawdown and recovery of hot dry rock reservoirs by computer simulation is in good agreement with the exact solution of the differential equations for heat conduction, as shown for single fractures in infinite rock. It was shown that, with little approximation, thermal recovery could be represented as a single curve depending only upon the ratio of the total elapsed time and the extraction time. Furthermore, the results demonstrate that the efficiency of heat extraction from hot dry rock increases with decreasing fracture spacing. The optimum is given for rubblized rock, because all the energy is then produced with the highest temperature which is possible, the initial rock temperature.

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APPENDIX

COMPUTER PROGRAM AND DESCRIPTION

Figure A-1 shows the model the computer code is based upon. The program operates in the flow direction starting with $I = 6$ and with the heat flow from the crack starting with $J = 1$. The first calculated temperature is $TR(I,J) = TR(6,1)$. The last calculated node is $TR(K + 15,H)$. To simulate adiabatic boundary conditions as shown in Fig. A-1, additional mirror-image temperatures are equalized to the boundary temperatures so that the heat flux is made zero.

Brief Description of Program Steps in Order of Appearance

- Data input
 - Defining start conditions for total time, loop counter, N, and print statement counting variable F
 - Defining special nodes for loop statements
 - Defining step length in flow direction, z, and a unity length in node direction x for the variable rock node
 - Start conditions for the total temperature field $T(I,J) = TINITL$
 - Defining $TSTEP; TSTEP < 1.6 \rho_r C_r / \lambda_r 16x^2$ for the chosen rock nodes and $TSTEP < \rho_r C_r z 4x / ub \rho_w C_w$
 - Statement 100: Beginning of the calculation loop
 - Definition of starting conditions (no heat flow across the adiabatic boundaries (for $I = 6$, $HROUT$ is later defined $HROUT = HRIN$))
 - Calculation of heat capacity of one water volume
 - The DO 200: Loop in flow direction
 - The enthalpy flow between two volumes has to be the same for both volumes
 - Calculation of enthalpy flows in the water
- 120: Adiabatic boundary at $J = H$
- D0700: Loop in rock direction
- Heat flow between two volumes is the same for both volumes
 - Calculation of heat flows by conduction
 - Calculation of heat capacity of the actual rock volume
- GO to 125: Jump to calculation of rock temperatures for J greater than 1
- Jump to calculation of water temperatures (equal to temperature of first rock volume)
 - Jump out of temperature calculation

- Jump back to calculation loop

```

190 UROUT(J)=URIN
200 IF(I.EQ.K+15) TR(K+16,J)=TR(K+15,J)
    TIME=TIME+TSTEP
    N=N+1
C   END OF TEMPERATURE CALCULATION
C
C   RESULTS
    IF(N.NE.1.O.U.EQ.0.) GO TO 300
    PRINT 500,PATML,Z,K,ROCKL,X,H,U,B,TINITL,TINLET,TSTEP
500  FORMAT(XFRAC LENGTH=X,F7.2,2X,STEPLENGTH=X,F6.2,2X,
    1XNODES=X,I3,/*ROCK THICKNESS=X,F6.2,2X,*UNITY LENGTH=X,
    2F6.4,2X,*NODES=X,I3,/*FLOW VELOCITY=X,F6.4,
    32X,*HALF OF GAP WIDTH=X,F6.4,/*INITIAL TEMPERATURE=X,F7.2,2X,
    4XINLET TEMPERATURE=X,F7.2,/*Timestep=X,F8.1,///)
300  CONTINUE
    NPRINT=60*F
    IF(U.EQ.0.) GO TO 870
    IF(TIME.GE.EXTIME) GO TO 849
    IF(MOD(N,NPRINT).NE.0) GO TO 850
    F=F*2
849  DAYS=TIME/86400.
    PRINT 400,DAYS
400  FORMAT(2X,*EXTRACTION TIME=X,F7.2,*DAYS*,/)
    DO 840 I=11,22
    PRINT 800,(TR(I,J),J=1,H)
840  CONTINUE
    DO 850 I=26,50,4
    PRINT 800,(TR(I,J),J=1,H)
800  FORMAT(10F6.1,/)
850  CONTINUE
C
?   IF(TIME.LT.EXTIME) GO TO 860

    F=1
    J=6.
    N=6.
    TIME=0
    TSTEP=RLYS*EP
860  CONTINUE
    IF(U.LT.0.) GO TO 100
870  IF(TIME.GE.RECTIME) GO TO 1849
    IF(MOD(N,NPRINT).NE.0) GO TO 1850
    F=F*2
1849  DAYS=TIME/86400.
    PRINT 1400,DAYS
1400  FORMAT(2X,*RECOVERY TIME=X,F7.2,*DAYS*,/)
    DO 1840 I=11,22
    PRINT 1800,(TR(I,J),J=1,H)
1840  CONTINUE
    DO 1850 I=26,50,4
    PRINT 1800,(TR(I,J),J=1,H)
1800  FORMAT(10F6.1,/)
1850  CONTINUE
    TU(10)=TU(11)
    IF(TIME.LT.RECTIME) GO TO 100
    STOP
    END

```