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HEAT TRANSFER IN FRACTURED GEOTHERMAL RESERVOIRS WITH BOILING

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Introduction Most high-temperature geothermal reservoirs are highly fractured systems. The fractures provide conduits through which fluid (and heat) can flow at sufficiently large rates to attract commercial interest. The rock matrix has a low flow capacity, but it stores most of the heat and fluid reserves. The fractures represent a very small fraction of the void volume, and probably contain less than 1% of total fluid and heat reserves in realistic cases. Sustained production from a fractured reservoir is only possible if the depletion of the fractures can be replenished by leakage from the matrix. The rate at which heat and fluid can be transferred from the matrix to the fractures is therefore of crucial importance for an assessment of reservoir longevity and energy recovery. Yet most work in the area of geothermal reservoir evaluation and analysis has employed a "porous medium"-approximation, which amounts to assuming instantaneous (thermal and hydrologic) equilibration between fractures and matrix. Effects of matrix/fracture interaction have been investigated by Bodvarsson and Tsang (1981) for single-phase reservoirs, and by Moench and coworkers (1978, 1980) for boiling reservoirs. Moench's work addresses the question of pressure transients during drawdown and build-up tests in fractured reservoirs. The present paper focuses on a complementary aspect, namely, enthalpy transients. We use simple analytical expressions to analyze fluid and heat transfer between rock matrix and fractures. It is shown that heat conduction in a matrix with low permeability can substantially increase flowing enthalpy in the fractures. This affects fluid mobility, and has important consequences for energy recovery and reservoir longevity. We present results of numerical simulations which illustrate these effects and show their dependence upon matrix permeability and fracture spacing.

Conductive Enhancement of Flowing Enthalpy
Production from the fractures causes pressures to decline, and initiates fluid flow from the matrix into the fractures. Assuming Darcy's law to hold in the matrix, and neglecting gravity effects for the moment, the mass flux being discharged into the fracture system can be written:

$$\underset{\sim}{F} = \sum_{\beta=\text{liquid, vapor}} \underset{\sim}{F}_\beta = -k_m \sum_\beta \frac{k_\beta \rho_\beta}{\mu_\beta} (\nabla p)_n \tag{1}$$

Here $(\nabla p)_n$ is the normal component of pressure gradient at the matrix/fracture interface. In a boiling reservoir, pressure gradients are accompanied by temperature gradients. Idealizing the reservoir fluid as pure water substance, the temperature gradient is given by the Clapeyron equation:

$$\nabla T = \frac{(v_v - v_\ell)(T + 273.15)}{h_v - h_\ell} \nabla p \tag{2}$$

Therefore, there is a one-to-one correspondence between mass flux and the conductive heat flux which is given by

$$\underset{\sim}{q} = -K\nabla T \tag{3}$$

The total heat flux discharged into the fracture system is

$$\underset{\sim}{G} = \sum_\beta h_\beta \underset{\sim}{F}_\beta - K(\nabla T)_n \tag{4}$$

In the matrix, heat is stored in rocks and fluids. In the fractures, heat resides solely in the fluid filling the void space. The heat flux given by (4) has to be carried, therefore, by the mass flux given by (2). Upon entering the fracture system, the fluid heat content is enhanced by the absorption of the conductive heat flux. From $\underset{\sim}{G} = h\underset{\sim}{F}$ we obtain the effective flowing enthalpy of the fluid entering the fractures:

$$h = \frac{\frac{k_\ell}{\mu_\ell}\rho_\ell \left[h_\ell + \frac{k_{\ell im}}{k_m k_\ell}(h_v - h_\ell)\right] + \frac{k_v}{\mu_v}\rho_v h_v}{\frac{k_\ell}{\mu_\ell}\rho_\ell + \frac{k_v}{\mu_v}\rho_v} \tag{5}$$

Here we have defined a limiting effective permeability, dependent upon heat conductivity and temperature, as:

$$k_{lim}(K,T) = \nu_g K \frac{\mu_\ell \nu_\ell (\nu_v - \nu_\ell)(T + 273.15)}{(h_v - h_\ell)^2} \tag{6}$$

In the absence of gravity effects, we have $\nu_g = 1$. The enhancement of flowing enthalpy occurs because the conductive heat flux vaporizes part (or all) of the liquid which is discharged into the fractures. The effect depends upon the ratio of heat conductivity K to effective permeability for the liquid phase, $k_m k_\ell$. The smaller the permeability of the matrix, the smaller is the mass flux which has to absorb the conductive heat flux, resulting in a stronger enhancement of flowing enthalpy. From (5) it can be seen that for $k_m k_\ell = k_{lim}$ all liquid is vaporized, giving rise to discharge of saturated steam from the matrix ($h = h_v$). Larger permeability ($k_m k_\ell > k_{lim}$) results in discharge of two-phase fluid, while for $k_m k_\ell < k_{lim}$ superheated steam is produced even if a mobile liquid phase is present in the matrix.

Gravity effects diminish the limiting effective permeability, hence the conductive enhancement of flowing enthalpy. This is easily understood by noting that gravity-driven flow does not require non-zero pressure gradients, and therefore need not be accompanied by conductive heat transfer. Pruoss and Narasimhan (1981) have shown that inclusion of gravity reduces the limiting effective permeability by a factor

$$\nu_g = \frac{\left(\frac{\partial p}{\partial r}\right)^2 + \frac{k_z}{k_r}\left[\frac{\partial p}{\partial z} + \rho_\ell g\right]\frac{\partial p}{\partial z}}{\left(\frac{\partial p}{\partial r}\right)^2 + \left(\frac{k_z}{k_r}\right)^2\left[\frac{\partial p}{\partial z} + \rho_\ell g\right]^2} \tag{7}$$

Gravity effects will be small if (i) vertical pressure gradients are close to hydrostatic ($\partial p/\partial z \approx -\rho_\ell g$), (ii) if vertical permeability is small ($k_z << k_r$), or (iii) if pressure gradients at the matrix/fracture interface are significantly larger than hydrostatic.

k_{lim} is plotted as a function of temperature in Figure 1 for the no-gravity case ($\nu_g = 1$). Figure 2 shows the effective flowing enthalpy of fluid discharged into the fractures as a function of matrix permeability calculated from (5). Curves are given for different values of vapor saturation; in these calculations the relative permeabilities were assumed to be given by Corey's equation with $S_{\ell r} = 0.3$, $S_{sr} = 0.05$. It is seen that conductive enhancement of flowing enthalpy becomes significant for $k < 10^{-15}$ m^2, and becomes very large for smaller permeability.

Numerical Simulations of Fractured Reservoir Behavior The above considerations are borne out by numerical simulations. We employ an idealized model of a fractured reservoir, with three perpendicular sets of infinite, plane, parallel fractures of equal aperture δ and spacing D (see Figure 3). Modeling of transient fluid and heat flow is accomplished with the "multiple interacting continua" method (MINC). This method is conceptually similar to, and is a generalization of, the well-known double-porosity approach (Barenblatt et al., 1960; Warren and Root, 1963). A detailed discussion of the MINC-method is given in Pruess and Narasimhan (1982). This method can be easily implemented with any simulator whose formulation is based on the "integral finite difference" method. The calculations presented below were made with LBL's geothermal simulators SHAFT79 and MULKOM, with parameters given in Table 1.

(i) Radial Flow The radial flow problem uses parameters applicable to a typical well at The Geysers, and assumes a mobile liquid phase ($k_\ell = .143$ at $S_\ell = .70$). The calculations show that for $k_m k_\ell < k_{lim}$, the produced enthalpy rises to above 2.8 MJ/kg (superheated steam) within minutes, whereas for $k_m k_\ell > k_{lim}$, a two-phase steam/water mixture is produced (Pruess and Narasimhan, 1981).

(ii) Areal Depletion Problem We have studied the depletion of an areal 7 km x 3 km reservoir, with parameters similar to those used by Bodvarsson et al. (1980) in their assessment of the geothermal reservoir at Baca, New Mexico. Results for enthalpies and pressures are given in Figures 4 and 5. Two basic depletion patterns are observed, depending upon whether matrix permeability is (relatively) "high" or "low". For low $k_m = 10^{-17}$ m^2, the boiling process is localized in the vicinity of the fractures, with vapor saturations in the matrix decreasing as a function of distance from the fractures. The opposite pattern is observed for "high" $k_m = 9 \times 10^{-17}$ m^2, 10^{-15} m^2, where the depletion process causes a boiling front to rapidly move into the matrix, giving rise to largest vapor saturations in the interior of the matrix, away from the fractures.

It is apparent from Figure 4 that produced enthalpy depends much more strongly upon matrix permeability than upon fracture spacing. Enthalpy increases with decreasing matrix permeability, in agreement with the discussion given above. From Figure 5 it can be noted that pressure decline is more rapid in case of higher enthalpy, due to the fact that the mobility of two-phase fluid generally decreases with increasing enthalpy. The crucial importance of matrix permeability is particularly evident in the case of $k_m = 10^{-17}$ m^2, where fracture spacings of 5 m and 50 m, respectively, result in virtually identical enthalpy and pressure response, even though the matrix/fracture contact areas differ by a factor of 10. It might appear from Figures 4 and 5 that porous-medium type reservoirs will have greater longevity than equivalent fractured reservoirs. This is not generally true, however, and is caused by discretization effects in this case. Below we present calculations with better spatial resolution, which show that fractured reservoirs may in some cases have greater longevity than equivalent porous medium reservoirs.

It should be pointed out that the reservoir longevities predicted from this study are probably too pessimistic, due to the use of Corey-type relative permeability functions. The well test analysis from which the (permeability) x (thickness) product is derived uses Grant's relative permeabilities, which, for the sake of consistency, should also be employed in the analysis of reservoir depletion (Grant, 1977). Substantially greater .reservoir longevities would then be expected (Garg, 1981).

(iii) Five Spot For a more realistic assessment of the depletion of a naturally fractured boiling reservoir, we investigated a five-spot production/injection strategy for the reservoir discussed in the previous example. The basic mesh as given in Figure 6 takes advantage of flow symmetry. The production/injection rate was fixed at 30 kg/s, which corresponds to the more productive wells in the Baca reservoir.

Our results show that without injection, pressures will decline rapidly in all cases. The times after which production-well pressure declines below 0.5 MPa are: 1.49 yrs for a porous medium, 2.70 yrs for a fractured reservoir with D = 150 m, $k_m = 9\times10^{-17}$ m^2, and 0.44 yrs for D = 50 m, $k_m = 1\times10^{-17}$ m^2. Note that the fractured reservoir with large k_m (9×10^{-17} m^2) has a greater longevity than a porous reservoir. The reason for this is that the large matrix permeability provides good fluid supply to the fractures, while conductive heat supply is limited. Therefore, vapor saturation in the fractures remains relatively low, giving good mobility and a more rapid expansion of the drained volume.

The results obtained with 100% injection demonstrate the great importance of injection for pressure maintenance in fractured reservoirs with low permeability. Simulation of 90 years for the porous medium case, and 42 and 103 years, respectively, for fractured reservoirs with D = 50 m and D = 250 m (k_m = 10^{-17} m^2), showed no catastrophic thermal depletion or pressure decline in either case. These times are significantly in excess of the 30.5 years needed to inject one pore volume of fluid. Figure 7 shows temperature and pressure profiles along the line connecting production and injection wells for the three cases studied after 36.5 years of simulated time. The temperatures of the porous-medium case and the fractured reservoir with D = 50 m agree remarkably well, indicating an excellent thermal sweep for the latter (see also Bodvarsson and Tsang, 1981). The temperature differences AT = $T_m - T_f$ between matrix and fractures are very small: after 36.5 years, we have AT = .2 °C near the production well, .001 °C near the injection well, and less than 5 °C in between. In the D = 50 m case, produced enthalpy remains essentially constant at h ≈ 1.345 MJ/kg. It is interesting to note that this value is equal to the enthalpy of single-phase water at original reservoir temperature T = 300 °C. Thus, there is an approximately quasi-steady heat flow between the hydrodynamic front at T ≈ 300 °C and the production well, with most of the produced heat being supplied by the thermally depleting zone around the injector.

At the larger fracture spacing of D = 250 m, the contact area between matrix and fractures is reduced, and portions of the matrix are at larger distance from the fractures. This slows thermal and hydrologic communication between matrix and fractures, causing the reservoir to respond quite differently to injection. After 36.5 years, thermal sweep is much less complete, with temperature differences between matrix and fractures amounting to 16 °C, 118 °C, and 60 °C, respectively, near producer, near injector, and in between. For the particular production and injection rates employed in this study, thermal depletion is slow enough that even at a large fracture spacing of D = 250 m, most of the heat reserves in the matrix can be produced. We are presently investigating energy recovery in the presence of a prominent short-circuiting fault or fracture between production and injection wells, under which conditions less favorable thermal sweeps are expected.

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Nomenclature

- D: Fracture spacing (m)
- $\underset{\sim}{F}$: Mass flux ($kg/m^2 \cdot s$)
- g: Gravitational acceleration (9.81 m/s^2)
- $\underset{\sim}{G}$: Heat flux (W/m^2)
- h: Specific enthalpy (J/kg)
- k: Absolute permeability (m^2)
- K: Heat conductivity (W/m°C)
- k_{lim}: Limiting effective permeability (m^2)
- k_β: Relative permeability for phase β, dimensionless
- p: Pressure (Pa)
- $\underset{\sim}{q}$: Conductive heat flux (W/m^2)
- r: Radial coordinate (m)
- S: Saturation (void fraction), dimensionless
- $S_{\ell r}$: Irreducible liquid saturation, dimensionless
- S_{sr}: Irreducible vapor saturation, dimensionless
- T: Temperature (°C)
- v: Specific volume (m^3/kg)
- z: Vertical coordinate (m)
- ν_g: Gravity reduction factor for k_{lim}, dimensionless
- μ_β: Viscosity of phase β (Pa·s)
- ρ_β: Density of phase β (kg/m^3)

Subscripts

- f: Fracture
- ℓ: Liquid
- m: Matrix
- n: Normal component
- v: vapor
- β: Phase (β = liquid, vapor)

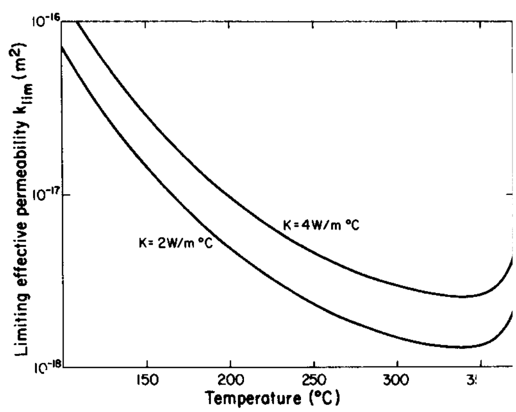

Figure 1: Limiting effective permeability.

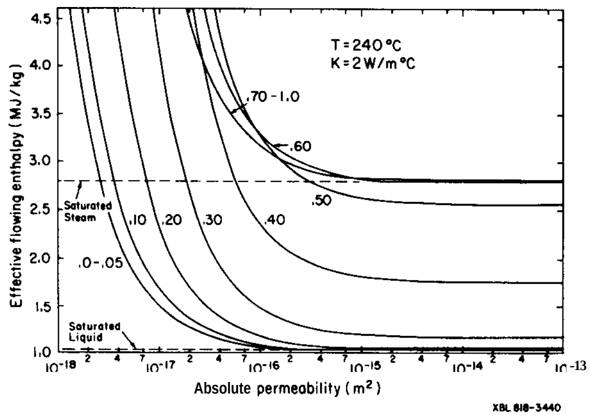

Figure 2: Effective flowing enthalpy.

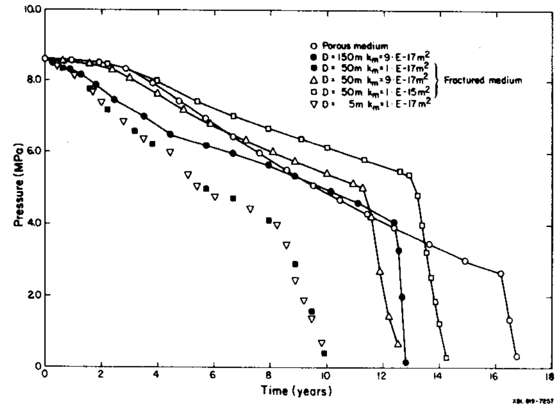

Figure 5: Pressure decline for areal depletion problem.

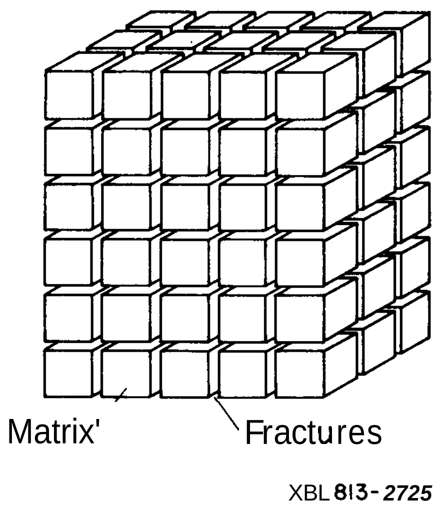

Figure 3: Idealized model of fractured reservoir.

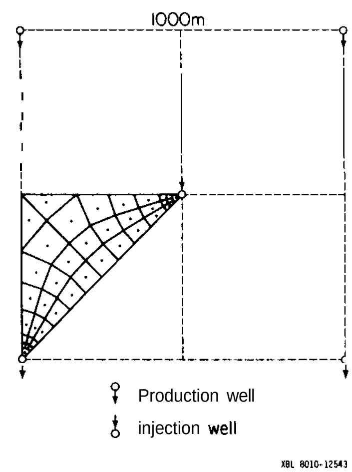

Figure 6: Five-spot computational mesh.

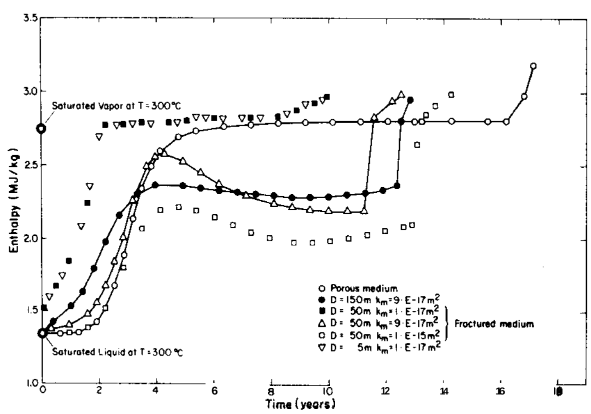

Figure 4: Produced enthalpy for areal depletion problem.

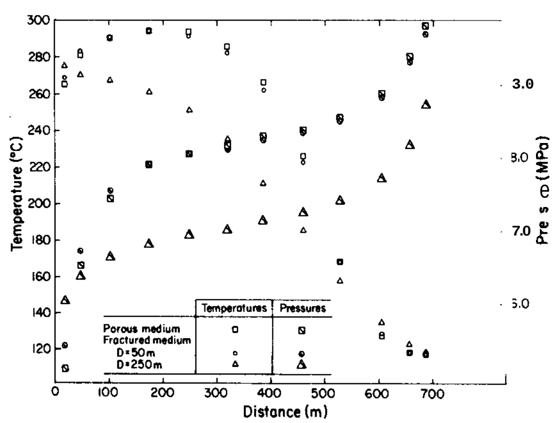

Figure 7: Temperature and pressure profiles for five-spot after 36.5 years.

TABLE I: Parameters Used in Simulations

	Radial Flow Problem	Depletion Problem
Formation		
rock grain density	ρ_R = 2400 kg/m^3	2600 kg/m^3
rock specific heat	C_R = 960 J/kg^{o}C	950 J/kg ^{o}C
rock heat conductivity	K = 4 W/m^{o}C	2.22 W/m ^{o}C
porosity	Φ = .08	.10
permeability x thickness	kh = 13.4×10^{-12} m^3	1.83×10^{-12} m^3
reservoir thickness	h = 500 m	305 m
matrix permeability	k_1 = 10^{-15} m^2, 10^{-16} m^2, 10^{-17} m^2	10^{-15} m^2, 9×10^{-17} m^2, 10^{-17} m^2
Fractures		
three orthogonal sets		
aperture	δ = 2×10^{-4} m	(a)
spacing	D = 50 m	5 m, 50 m, 150 m
permeability per fracture	k_f = 62/12 = 3.3×10^{-9} m^2	(a)
equivalent continuum . permeability	$k_2 \approx 2k_f\delta/D$ = 26.8×10^{-15} m^2	6×10^{-15} m^2
equivalent continuum porosity	$\Phi_2 \approx 3\delta/D$ = 1.2×10^{-5}	.10
Relative Permeability		
Corey-curves	$S_{\ell r}$ = .30, S_{sr} = .05	$S_{\ell r}$ = .30, S_{sr} = .05
Initial Conditions		
temperature	T = 243 ^{o}C	300 ^{o}C
liquid saturation	S_ℓ = 70%	99%
Production		
wellbore radius	r_w = .112 m	
skin	s = -5.18	
effective wellbore radius	$r'_w = r_w e^{-s}$ = 20.0 m	
wellbore storage volume	V_w = 27.24 m^3	
production rate	q = 20 kg/s	82.5 kg/s[(b)]; 30 kg/s[(c)]
Injection		
rate	---	30 kg/s[(c)]
enthalpy	---	5×10^5 J/kg

(a) fractures modeled as extended regions of high permeability, with a widty of $\approx$ .2 m
(b) rectangular reservoir
(c) five-spot