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PRESSURE-TRANSIENT BEHAVIOR DURING COLD WATER INJECTION

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ABSTRACT

During injection testing, pressures in geothermal wells sometimes decline after an initial period of increase despite continued injection. The injection tests carried out at the Yutsubo geothermal field in Kyushu, Japan exhibit this peculiar behavior. During injection testing of Yatsubo well YT-2, observed downhole pressures eventually began to decline despite sustained injection rates. We have carried out numerical simulation studies using a radial flow model to examine this behavior. Double porosity ("MINC") models are adopted, in which the fracture porosity increases due both to cooling and to pressure buildup, and the permeability is very sensitive to porosity changes. This extreme sensitivity of fracture permeability to porosity appears to be necessary to reproduce the late-time pressure decline, and suggests that fractures were opened by injection-induced cooling near the well.

INTRODUCTION

Kitao et al.(1995) recently reported that injectivities and productivities of geothermal wells were improved by cold water injection at the Sumikawa geothermal field. In addition to pressure build-up and washout of cuttings (and/or drilling mud) near the wells, reversible re-opening of fractures and/or porosity increase due to local cooling are believed to be responsible.

Injection of cold water sometimes results in gradual declines in downhole pressure even during constant (but relatively low) flow-rate injection. This sort of behavior has been observed during injection testing of well YT-2, which was drilled by the New Energy and Industrial Technology Development Organization (NEDO) at the Yutsubo geothermal field in Kyushu, Japan (e.g. Nakagome et al., 1994). The observed gradual late-time pressure decline cannot be ascribed to hydraulic fracturing - during hydrofracturing tests, the pressure decrease caused by fracture propagation is very rapid (e.g. Koning and Niko, 1985; Larsen and Blatvold, 1994), as contrasted to the gradual pressure drift observed in well YT-2.

Contreas(1990), studying sandstone-water systems, suggested the existence of a reversible mechanism that causes a decrease in the absolute permeability of a rock mass as temperature increases. Gradual cooling of the reservoir rock in the neighborhood of the well is therefore a candidate mechanism for the observed gradual late-time pressure decline observed in well YT-2.

In order to examine the pressure transient behavior of well YT-2, we have carried out a series of numerical calculations using a radial-flow model. In these calculations, porosity and permeability were assumed to depend upon both local instantaneous pressure and temperature. After describing the field data collected from well YT-2, the model and the results which were obtained from it will be presented.

WELL YT-2 TEST DATA

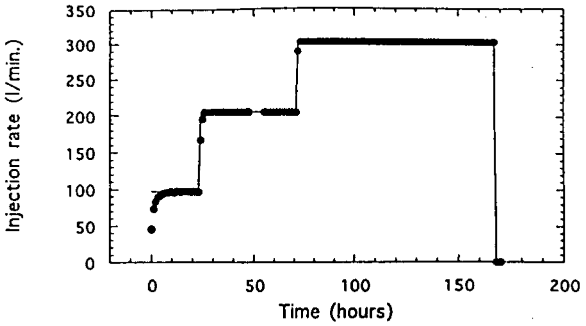
Well YT-2 was drilled vertically to a total depth of 1705 meters. The bottom of the 9 5/8-inch casing was set at 1501 meters and a 7-inch (inside diameter 6.37-inch) slotted liner was installed in the 8 1/2-inch diameter hole from 1487 meters to 1705 meters. The only mud circulation losses recorded during drilling in the uncemented part of the hole were all in the bottom 59 meters (1646 m - 1705 m). The geological column consists of a complex series of volcanic rocks, with Pre-Kusu altered tuff breccias and lavas extending from 1375 meters to bottomhole.

A temperature profile measured in January 1992 (just after drilling to total depth) shows a temperature depression centered at about 1660 meters; this depth corresponds to the major circulation loss zone. A subsequent temperature survey recorded in October 1992 displays a jump in temperature at about 1625 meters; apparently hot fluid enters the well at this depth, flows down the borehole and re-enters the formation at about 1660 meters. The temperature data available so far suggest that the major feed zone for YT-2 is at about 1650 meters. A maximum temperature of 194 C was recorded in December 1992 at about 1690 meters.

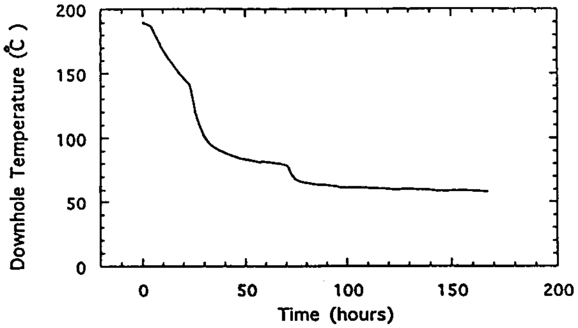
Cold water has been injected into well YT-2 on several occasions. Downhole pressures (near the feedzone depth) were recorded during two of these experiments; a short-term test performed just after drilling in February 1992 and a seven-day test carried out in September/October 1993. During the latter test, the pressure/temperature sensor was located at 1610 meters (40 meters above the primary feed zone). Fig.1 shows the histories of injection rate, observed downhole temperature and pressure during the seven-day test. Injection rates increased from 96 l/min after 24 hours to 205 l/min, and then to 303 l/min after 72 hours. Although the pressure record also indicates "jumps" at these same times, the magnitude of the pressure increases are not in proportion to the flow rate increases - the final increase of 50% in flow rate at 72 hours causes a relative pressure rise of less than 10%. Furthermore, the pressure starts to slowly decline shortly after the increase in flow rate from 205 l/min to 303 l/min at 72 hours. The rise and subsequent fall in pressure which accompany increases in injection rate are abnormal and will be discussed in the next section.

After injection ceased, the pressure fell rapidly without any further abnormal behavior. We used the DIAGNS well test analysis program (Alexander et al., 1993) to analyze these falloff data and obtained estimates of "kh" and other formation parameters (Table 1). The kh value around well YT-2 is about 0.1 darcy-meter based on the fall-off data. However, kh values between 1 and 2 darcy-meters were obtained from the analysis of the interference response measured in shut-in observation well YT-1 (located 270 meters distant from YT-2) to the injection into well YT-2 (Nakao et al., 1994).

(a) Injection Rate



(b) Downhole Temperature



(c) Downhole Pressure

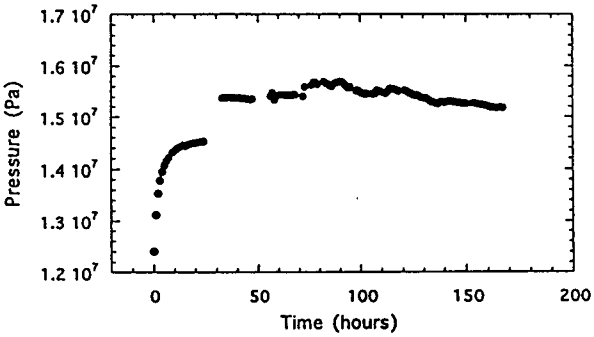


Fig.1. Histories of (a) injection rate, (b) downhole temperature and (c) pressure at depth of 1,610 meters in well YT-2.

Table 1. Estimated parameters kh, ϕch, skin, wellbore storage C, initial pressure Pi; and standard error (SE) between calculated pressure and observed data. 1.0e-8 = 10^{-8}.

well name date data used	YT-2 Sept.1993 falloff	YT-1 Sept.1993 interference from YT-2 injection	
		whole data	the later half
kh(darcy-m)	0.17	2.3	1.2
ϕch(m/Pa)	1.9e-8	7.1e-8	8.1e-8
skin	-4.2	-	-
C(m^3/Pa)	5.5e-5	-	-
Pi(MPa)	12.40	13.12	13.12
SE(Pa)	1.1e+4	3.2e+3	9.4e+2

MODEL DESCRIPTION

For our numerical simulation study, we used the STAR general-purpose geothermal reservoir simulator (Pritchett, 1995). In the STAR code, the rock's porosity as a function of time is determined from the histories of pressure (P) and temperature (T) using the following formulation (Garg, 1984),

$$\dot{\phi} = \left(\frac{1-\phi}{K+\frac{4}{3}G}\right) \times \left[\dot{P} + 3\dot{T}\left(\alpha_p \cdot K - \alpha_g\left(K+\frac{4}{3}G\right)\right)\right] \quad (1)$$

where ϕ is local instantaneous porosity; K and G are the bulk modulus and shear modulus respectively; α_p and α_g are the linear thermal expansion coefficients for dry porous rock and for the rock grain material, respectively.

The absolute permeability of the rock is assumed depend on porosity according to the following relation,

$$k = k_0\left(\frac{\phi}{\phi_0}\right)^3 \times \left(\frac{1-\phi_0}{1-\phi}\right)^2 \times \exp\left[A(\phi-\phi_0)\right] \quad (2)$$

where k_0 and ϕ_0 are the initial permeability and porosity respectively, and A is a user-specified constant. The exact Kozeny-Carman relation is recovered if A=0.

We used a simple reservoir geometry for our numerical study, as illustrated in Figure 2; pertinent parameter values are listed in Table 2. We consider a horizontal single-layer fractured-medium reservoir containing a single fully-penetrating injection well (YT-2) which may be regarded as a line-source. The outer radius is sufficient that the system may be considered infinite in lateral extent. Beyond 97.2 meters radius the system is treated as a simple porous medium, but within that radius a "MINC"-type (Pruess and Narasimhan, 1985) fracture/matrix composite representation is employed. In this region, the only difference between the initial rock properties prescribed in the "fracture zone" (1% of the volume) and in the "matrix region" (99%) is the permeability; 10^{-18} m^2 in the relatively impermeable "matrix region" and 1.7 x 10^{-13} m^2 in the "fracture zone" (yielding 1.7 x 10^{-15} m^2 "equivalent porous medium" permeability). Both upper and lower boundaries are impermeable and insulated. The kh, storativity and skin factor estimated from the falloff data analysis were taken into account to construct the model. The imposed time-histories of injection flow rate and injected water temperature were based on measured data (Figure 1).

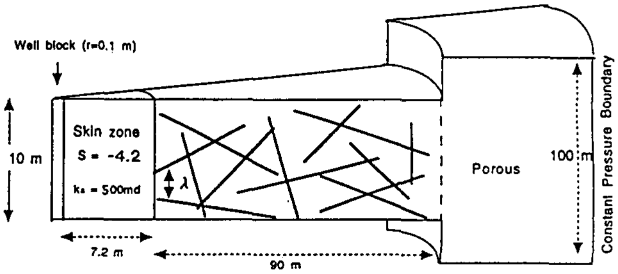


Fig.2. Model geometry used for numerical simulation of cold-water injection.

Table 2. Model parameters used for the numerical simulation of injection test of well YT-2.

Reservoir geometry
Horizontal layer: Thickness=10 m for inner reservoir (r < 97.2m)
Thickness=100 m for outer reservoir
Well block: k = 1.0x10^{-11} m^2, ϕ = 0.99
Skin zone: k_0=5.0x10^{-13} m^2, ϕ_0=0.05, A=0
Inner Reservoir: k_0=1.7x10^{-15} m^2, ϕ_0=0.05
    Fracture zone volume fraction = 0.01
    Fracture spacing: 3 to 10 m
    A: 0 to 1200
Outer Reservoir: k_0=1.7x10^{-15} m^2, ϕ_0=0.05, A=0
Common rock parameters:
    Rock grain density=2500 kg/m^3
    Rock grain heat capacity=1000 J/kg°C
    Rock grain thermal conductivity=3.0 W/m°C
    Rock bulk modulus=1.0x10^9 Pa
    Thermal expansion coefficient for dry porous rock=0
    Thermal expansion coefficient for rock grain material=10^{-5}
Initial Condition:
    Temperature=190 °C
    Pressure=12.40 MPa

RESULT AND DISCUSSION

First, consider the effect of "A" (Equation 2), which influences the sensitivity of the permeability/porosity relationship. Figure 3 shows calculated pressure histories (all assuming 10 m fracture spacing) for A = 0, 600, 900 and 1200. For large A values, computed pressures decline gradually after 70 hours of injection, and the best fit is obtained for A = 900. By contrast, if we assume A = 0 (Kozeny-Carman relationship), the calculated pressure does not decline at all and cannot be matched to the data.

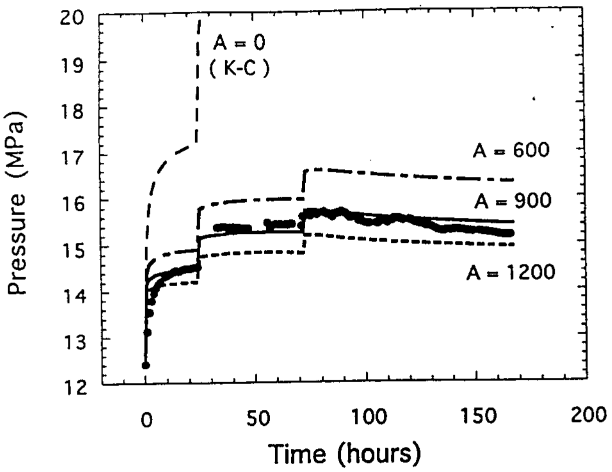


Fig.3. Calculated pressure-transients with different values of parameter A. The fracture spacing is 10 meters in all cases.

Another case in which α_g (Eqn. 1) is assumed to be zero (maintaining A = 900) is illustrated in Figure 4, and compared to the above fit. Setting α_g equal to zero eliminates the influence of temperature changes upon porosity. In this case, the observed pressure decline under continued injection does not occur, suggesting that thermal contraction of the rock plays a key role in the anomalous pressure response.

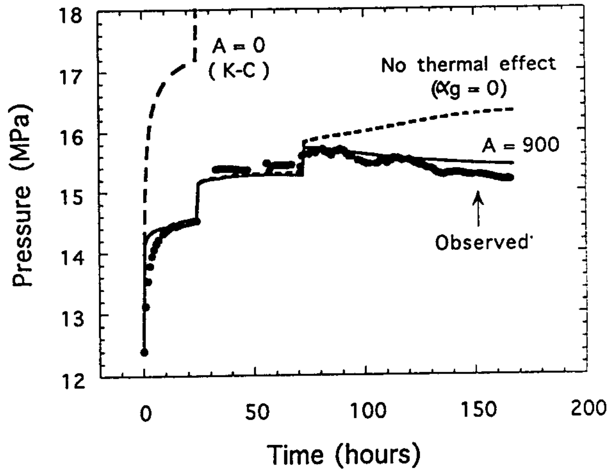


Fig.4. Calculated pressure transient assuming no thermal effect is shown for A=900 and 10 m fracture spacing case.

Sensitivity of the results to the fracture spacing is illustrated in Figure 5. As the fracture spacing increases, the degree of pressure decline likewise increases. This difference is caused by the difference in cold front propagation rate outward into the reservoir. If the inner reservoir is treated as a porous medium (fracture spacing = 0), the cold region is confined to the immediate neighborhood of the well even at the end of the 7-day injection period. For larger fracture spacings the cold zone penetrates farther into the reservoir, enlarging the zone of thermal-contraction-induced permeability enhancement and increasing the late-time pressure decline.

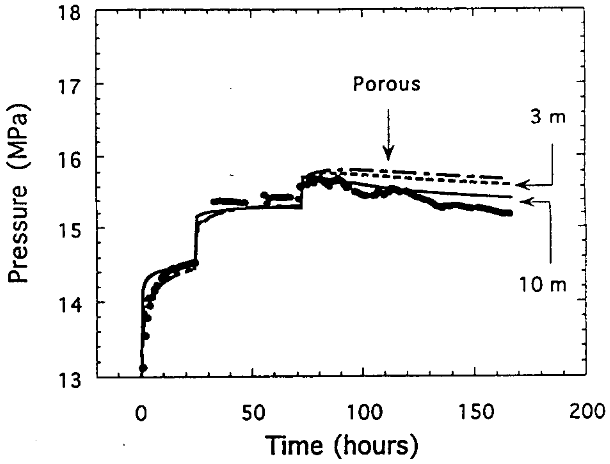


Fig.5 Calculated pressure-transients for different fracture spacing. The parameter A is 900.

Figure 6 shows the radial distribution of the calculated temperature and porosity in the fracture zone and the "equivalent porous medium" permeability (proportional to the fracture permeability) after seven days of injection for the best model (A=900; fracture spacing=10 m). Porosity increase and resulting permeability enhancement are significant in the inner reservoir between 7.2 and about 30 meters of radial distance, where the temperature decreases substantially. As seen in Figure 6, the permeability increases by more than two orders of magnitude owing to a porosity increase of about ten percent. If the present model represents the actual mechanisms taking place in the reservoir penetrated by well YT-2, this strong dependence suggests that the opening of fractures was induced by the cold water injection.

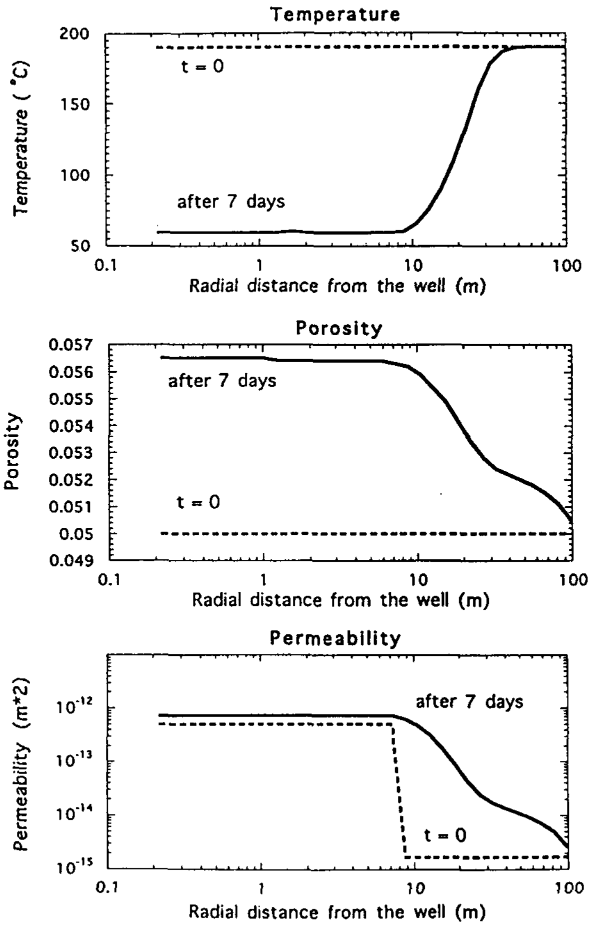


Fig.6 Radial distribution of the calculated temperature, porosity and permeability after 7-day cold water injection. (A=900 and fracture spacing = 10 meters.)

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