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Pulse Testing Analysis for Fractured Geothermal Reservoir

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ABSTRACT

Pulse testing is one of the standard methods to evaluate complicated reservoir features. It appears to be possible to predict whether a reservoir medium between two wells is porous or fractured, when hydraulic diffusivity of several different pulse flow-rate periods can be estimated from a time lag of the pressure interference at an observation well. It may be also possible to provide additional information for average fracture spacing. Examples of pressure interference data observed at the Sumikawa geothermal field in Japan is presented to discuss the pulse testing analysis.

Introduction

Pressure interference testing using multiple wells is a useful and direct method to collect reservoir information, and has a possibility to investigate characteristics of naturally fractured reservoir (e.g., Chen et al., 1984). However, it is sometimes difficult to determine whether the medium is treated as porous or fractured-type or to estimate fracture parameters uniquely in geothermal application because of inherent nature of diffusion process and background noises. To make diffusive process as discriminative as possible, pressure controlled well tests using periodically changing flow rates are also used for pressure interference tests. There are two types of periodically changing flow-rate method; one is the pulse testing method and the other is the sinusoidal method.

The pulse testing method developed in petroleum reservoir engineering employs a series of constant flow-rate production/injection and following shut-in (Johnson et al., 1966). To the authors' knowledge, there is no published application of pulse testing analysis in geothermal fields. Observable quantities, amplitude attenuation and time lag of the pressure interference at an observation well can be used to estimate the reservoir properties; transmissivity and storativity. Especially, this time lag defined independently of pressure response amplitude allows estimation of the degree of heterogeneity between the active well and the observation well. Previous studies of the pulse testing have been developed on condition that all flow times (pulse periods) must be the same and all shut-in times must be the same (Earlougher, 1977). However, it is sometimes difficult to conduct such an ideal data acquisition for geothermal application. Therefore, we will consider series of different flow-rate (pulse) periods as an individual "single pulse" and investigate characteristics of fractures such as average fracture spacing by evaluating flow-rate period dependence of hydraulic diffusivity calculated from time lags.

In this paper, we will briefly describe pressure response to a single pulse, and proceed to show an example of inverse modeling results of pressure interference data acquired at the Sumikawa geothermal field in Japan. Then the preliminary result of flow-rate period dependence of hydraulic diffusivity will be discussed by analyzing pressure interference data as a pulse testing method.

Pressure Response to a Single Pulse

We consider an ideal reservoir, which is defined as a uniformly permeable and elastic formation that extends without lateral boundary, confined above and below by parallel impermeable boundaries, and is fully saturated with a slightly compressible fluid of unchanged properties. Figure 1, overleaf, illustrates a pressure interference response in an observation well due to typical pulse flow rate of production/injection. If a single pulse rate is used, the corresponding pressure response becomes (Streltsova, 1988):

$$\Delta P(r,t) = \frac{q}{4\pi T}\left\{\left[-Ei\left(-\frac{r^2}{4\eta t}\right)\right] - \left\{-Ei\left[-\frac{r^2}{4\eta(t-\Delta t)}\right]\right\}\right\} \tag{1}$$

The time t^* ($\Delta t + t_L$) when the pressure response has a maximum value (Figure 1) is obtained by setting the first derivative of pressure with time to zero, resulting in:

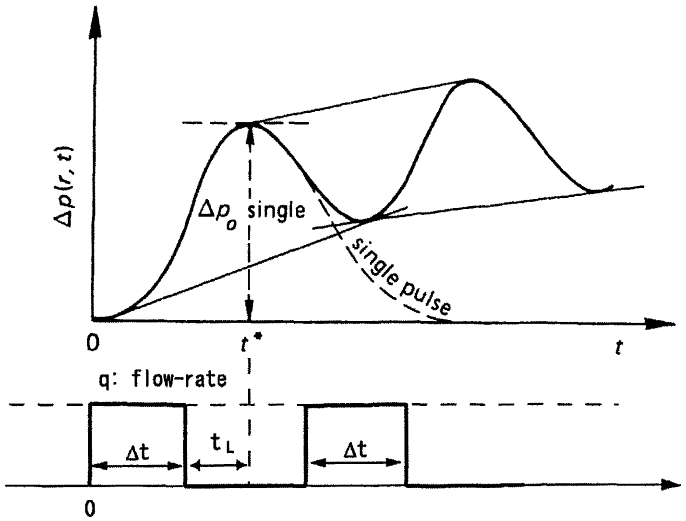

Figure 1. Pressure response to pulse flow-rates in an observation well.

$$\frac{r^2}{4\eta\Delta t} = -\frac{t^*}{\Delta t}\left(\frac{t^*}{\Delta t}-1\right)ln\left(1-\frac{\Delta t}{t^*}\right) \tag{2}$$

In Equations 1 and 2, q is the pulse flow-rate shown in Figure 1; T is the transmissivity (kh/μ); r is the distance from an active well; Δt is the pulse flow-rate period; t_L is the time lag; η is the hydraulic diffusivity (T/S); S is the storativity ($\phi C_t h$).

In fractured reservoirs, the time needed for pressure equilibrium between the fracture zones and rock matrix is expressed for spherical rock matrix blocks:

$$\tau_p = \frac{\phi_m C_t \mu \lambda^2}{10 k_m} \tag{3}$$

where λ is average fracture spacing; Ct is a total compressibility; ϕm and km represent the porosity and permeability of rock matrix, respectively. Before t = τp only small storativity of fracture zones, and after τp both of fracture zones and rock matrix storativities contribute to the pressure interference response. On the other hand storativity remains constant for the porous-medium (single porosity) reservoirs, resulting in the constant hydraulic diffusivity regardless the pulse flow-rate periods. Thus it is possible to evaluate the pulse period dependence of the hydraulic diffusivity, if the time lags are successfully observed for several different pulse flow-rate periods.

Field Test Data

The Sumikawa geothermal field is located in the Hachimantai volcanic zone in northern Honshu, Japan, where the Sumikawa geothermal power station has been producing electrical power in a 43-50 MWe range since 1995 (Ariki et al., 2000). Downhole pressure interference data at well KY-1 was obtained during extensive series of short-term water injection into seven wells in 1989. From these data, two sets of injection data were focused for the analysis: injection into well SB-1 and S-4, because clear pressure interference was observed. Figure 2 shows flow-rate histories of water injection into wells SB-1 and S-4, and corresponding pressure interference observed at well KY-1. The distance between well KY-1 and SB-1 is 680 m and that between KY-1 and S-4 is 1220 m. In the following, we discuss results of inversion analysis of these data and preliminary results of a pulse testing analysis.

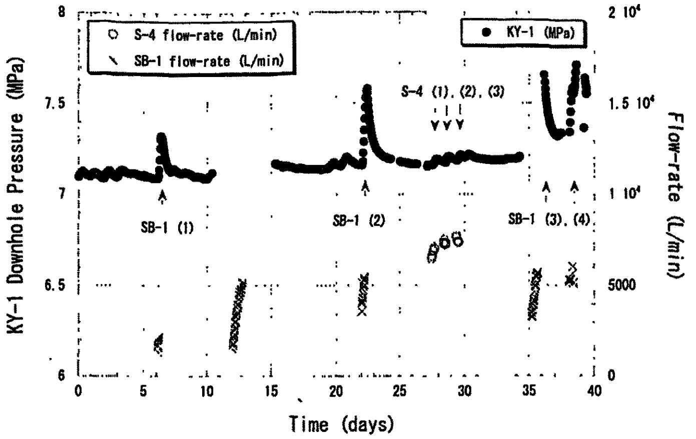

Figure 2. Histories of well KY-1 downhole pressure and injection flow-rates of well SB-1 and S-4.

For inversion analysis, we used the inversion program DIAGNS (Garg et al, 2002), which employs an iterative least-squares approach. The pressure response of well KY-1 to injection into well SB-1 (the second injection as shown in Figure 2) was fit using both a line-source single-porosity (porous) model and a Warren-Root double-porosity model.

Table 1. Estimated parameters by inversion analysis of well KY-1 pressure interference to injection into well SB-1.

	Porous model	Double-porosity model
Initial Pressure (MPa)	7.111	7.111
Pressure Drift (Pa/hour)	0	0
kh (darcy-m)	1.91	1.91
$C_t h$ (/m)	1.05E-09	1.05E-09
Fracture S / Total S {ω}		1.19E-05
Permeability Ratio		1.58E-05
Standard error / Range	3.79E-02	3.80E-02

Figure 3 shows the pressure transient match between observed data and calculated data of the best fit for the line-source single-porosity model and the double-porosity model. Estimated parameters are listed in Table1. The kh and storativity values are approximately the same for both cases. The value of fracture parameters ω (fracture-to-total storage ratio) is questionable because the 95% confidence interval is larger than the estimated value for this double-porosity case. Since there is little difference in the matching errors, it is difficult to evaluate whether the medium is treated as porous or fractured type from this inversion analysis.

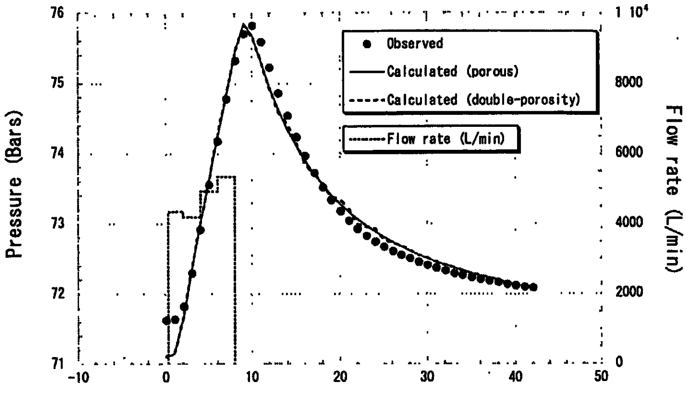

Figure 3. Pressure transient match by inversion analysis. Solid circles and lines represent the observed and calculated data of well KY-1(to injection into SB-1(2) as shown Figure 2), respectively.

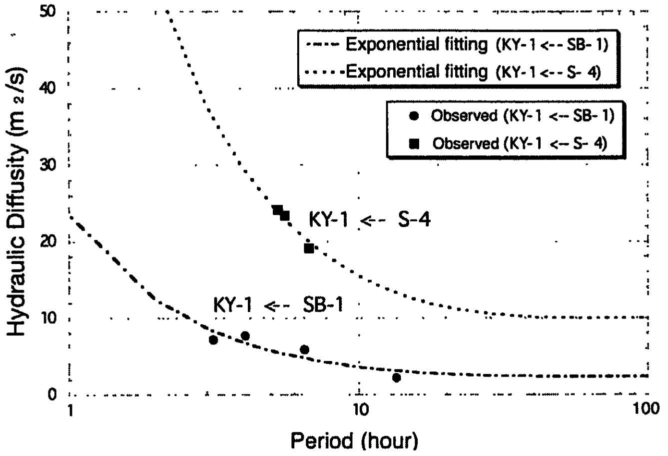

Figure 4. Dependence of hydraulic diffusivity on pulse flow-rate periods in the Sumikawa field.

Pulse Testing Analysis

The pulse flow-rate periods (Δt) of well SB-1 and well S-4 are 3.14, 4.08, 6.47 and 13.45 hours, and 5.25, 5.53 and 6.70 hours, respectively. The hydraulic diffusivity value for each pulse period is calculated from Equation 1. These hydraulic diffusivity values versus pulse flow-rate periods are plotted in Figure 4. It can be seen that the hydraulic diffusivity calculated from the observed data decreases as the pulse flow-rate period increases, suggesting the medium between the wells is fractured type.

The dashed lines in Figure 4 are the exponential fitting curves for the preliminary analysis. The fitting curve reaches its sill, which is expected to be the hydraulic diffusivity based upon the effective fracture permeability and the sum of the fracture and matrix storativities. The difference in hydraulic diffusivity curves between two well tests is caused by the difference in reservoir properties between two well pairs, namely, caused by the reservoir heterogeneity. The expected hydraulic diffusivity value for injection into well SB-1, approximately 2.4 m^2/s, is one fifth of the value estimated from the inversion analysis. The possible sources of this inconsistency should be examined further.

We will define that the time (τ_p) required for pressure equilibrium between the fracture zones and rock matrix is the point when the hydraulic diffusivity on the fitting curve approaches to within a 5% difference of the sill. τ_p, approximately 30 hours, is the same for both of well SB-1 and well S-4 injections. If we assume that the porosity and permeability of the rock matrix are 0.05 and 10^{-17} m^2, the average fracture spacing (λ) can be estimated to be 40 m for both cases, from Equation 3 where $\mu = 1.34 \times 10^{-4}$ (Pa-s) and $C_t = 1 \times 10^{-9}$ (Pa^{-1}) are used. The λ becomes 13 m for both cases, when the permeability of the rock matrix is assumed to be 10^{-18} m^2.

Concluding Remarks

We showed that estimating hydraulic diffusivity has a possibility to detect whether the reservoir medium is porous or fractured, only if we successfully observe the time lags in pressure interference for several different pulse periods. These pressure interference data can be obtained by intermittent reinjections or productions. The pressure interference data observed at the Sumikawa geothermal field was analyzed as a pulse testing method. The medium between two wells appears to be the fractured-type, because estimated hydraulic diffusivities for several pulse periods decrease as the pulse period increases. The average fracture spacing is also estimated by assuming the parameters for rock matrix.

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