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Analysis of Pulse Tests in a Fractured Geothermal Reservoir - A Case Study at the Sumikawa Field in Japan

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ABSTRACT

Pulse testing is one of the standard well test methods to evaluate complicated reservoir features. In this paper, a simplified analysis method of pulse testing is presented. 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 time lags of 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 a simplified analysis method of pulse tests.

1. 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. 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. One type of a periodically changing flow-rate method is a pulse testing procedure.

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). 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, the time lag defined independently of pressure response amplitude allows estimation of the degree of heterogeneity between the flowing well and the observation well. Time lags are also useful because they can be measured if only start and end times of pulse periods (flow rates) are recorded even when an accurate flow-rate history at the active well is not known.

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. To the authors’ knowledge, there is no published application of pulse testing analysis in geothermal fields.

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

2. 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: the reservoir contains a single fully-penetrating well which may be regarded as a line-source. Figure 1 illustrates a pressure interference response in an observation well due to typical pulse flow rate of production or injection. If a single pulse rate is used, the corresponding pressure response becomes (Streltsova, 1988):

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

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

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

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:

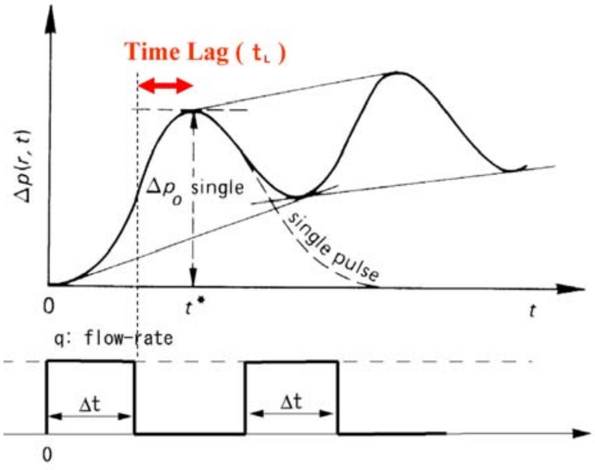

Figure 1: Pressure response to pulse flow-rates in an observation well.

$$\tau_p = \frac{\phi_m C_t \mu x_m^2}{10 \; k_m} \quad (3)$$

where x_m is average fracture spacing; C_t is a total compressibility; ϕ_m and k_m represent the porosity and permeability of rock matrix, respectively. Before $t = \tau_p$ only small storativity of fracture zones, and after τ_p 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.

The effects of wellbore storage at the observation well on pulse testing were investigated by Prats and Scott (1975). They showed that wellbore storage causes a delay in the time lag. In geothermal applications, however, a typical interwell distance is moderately away, so that the wellbore storage effect is usually negligible. The presence of an impermeable linear boundary near a pair of pulse-test wells also causes a delay in the time lag (Vela, 1977). Boundary effects should be carefully checked before estimating time lags. The effect of boundary is discussed later.

3. FIELD TEST DATA

The Sumikawa geothermal field is located in the Hachimantai volcanic zone in northern Honshu, Japan (Fig.2) where Sumikawa geothermal power station has been producing electrical power in a 43-50 MWe range since 1995 (Ariki et al., 2000). Mitsubishi Material Corporation has conducted several multiple-well pressure interference tests in this field. Analyses of the pressure transient data have been presented by Pritchett et al. (1989), Garg et al. (1991), Ishido et al. (1992) ,and Garg and Owusu (1996). Present conceptual model is that a 500-m thickness "altered andesite" formation and underlying "granodiorite" formation constitute a high permeability reservoir (kh > 10 darcy-m). The distance to the nearest impermeable boundary is interpreted to be of order of 1 km north of well KY-1 (Garg and Owusu, 1996). However, they concluded that the distances to the various boundaries or even the presence of boundaries are much less certain while the formation permeability thickness and storage are well constrained from the available data.

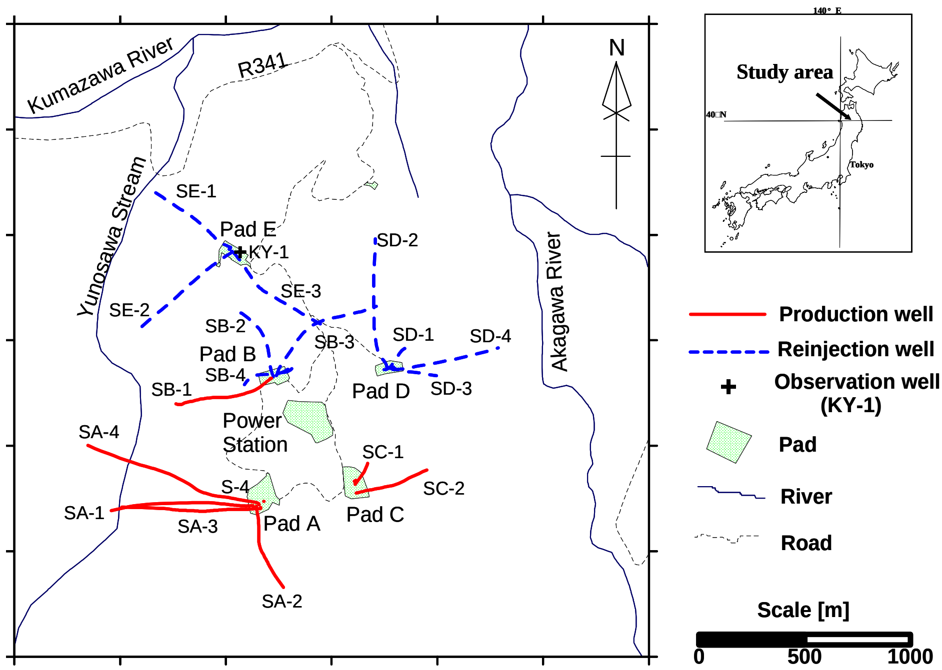

Figure 2: Sumikawa geothermal field and well locations.

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 3 shows flow-rate histories of water injection into wells SB-1 and S-4, and corresponding pressure interference observed at well KY-1. The major feedpoints for wells KY-1, SB-1 and S-4 are located at -571 m ASL, -551 m ASL and -413 m ASL, respectively in the altered andesite layer. The horizontal distance between well KY-1 and SB-1 is 690 m and that between KY-1 and S-4 is 1180 m.

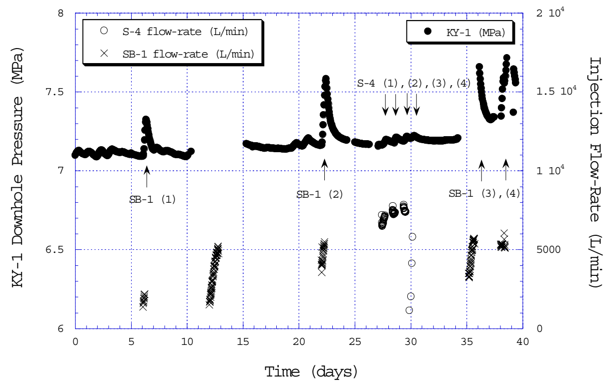

Figure 3: Histories of well KY-1 downhole pressure and injection flow-rates of wells SB-1 and S-4.

Inversion analyses of the whole pressure interference data are conducted by using 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 wells SB-1 (the second injection as shown in Fig.3) and S-4 was fit using both a line-source single-porosity (porous) model and a Warren-Root double-porosity model (Warren and Root, 1963) with and without an impermeable boundary. The cases considered are the following:

Case 1: a line-source single-porosity (porous) model.

Case 2: a line-source porous model with an impermeable boundary.

Case 3: a line-source double-porosity (DP) model.

Case 4: a line-source DP model with an impermeable boundary.

Dynamic viscosity for liquid water at a temperature of 230 ^{o}C, 1.18 x 10^{-4} Pa-s, is used in the inversions.

Figure 4 shows the inversion results of well KY-1 due to the second injection into well SB-1. Pressure transient match between observed data and calculated data is obtained for the line-source single-porosity model and the double-porosity model with an impermeable boundary (Cases 2 and 4). The formation parameters inferred are given in Table1. The distance to an impermeable boundary is detected as 680 m, which is approximately the same as the well spacing. 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. Moreover, 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 these double-porosity cases. This suggests that the quality of formation parameters obtained using double porosity models may not be reliable between wells SB-1 and KY-1.

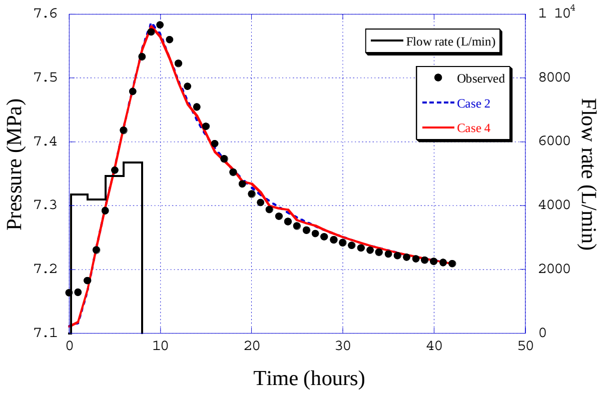

Figure 4: Pressure transient match by inversion analysis. Solid circles and lines represent the observed and calculated data of well KY-1 (to injection into SB-1(2) as shown Figure 3), respectively.

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

	Case 1	Case 2	Case 3	Case 4
Initial Pressure (MPa)	7.11	7.11	7.11	7.11
Pressure Drift (Pa/hour)	0	0	0	0
kh (darcy-m)	1.69	3.37	1.68	3.36
ϕch (m/Pa)	1.05E-09	2.11E-09	1.05E-09	2.11E-09
Fracture S / Total S { ω}	NA	NA	6.40E-06	3.36E-06
Permeability Ratio	NA	NA	1.32E-05	1.27E-05
Distance to boundary(m)	NA	680	NA	680
Standard error / Range	3.79E-02	3.79E-02	3.79E-02	3.79E-02

Figure 5 shows the inversion results of well KY-1 due to injection into well S-4. The best match of pressure transients between observation and calculation is obtained for the double-porosity model with an impermeable boundary (Case 4). The kh and $\phi C_t h$ are 20 darcy-meters and 2.11 x 10^{-8} m/Pa, respectively. The formation parameters inferred are given in Table2. For double-porosity model, the distance to the impermeable boundary is detected as 1220 m, which is approximately the same as the interwell distance. Since there is significant difference in the matching errors, the double-porosity model with the impermeable boundary provides the proper characteristics between wells S-4 and KY-1.

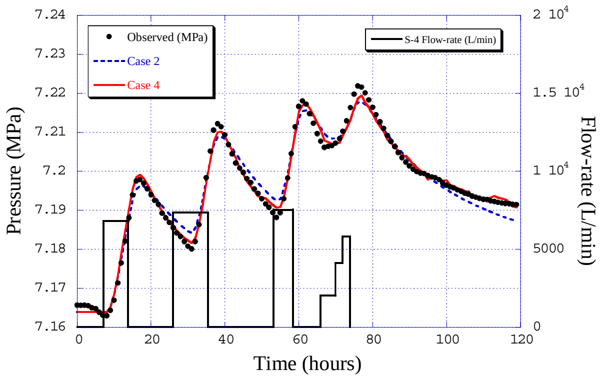

Figure 5: Pressure transient match by inversion analysis. Solid circles and lines represent the observed and calculated data of well KY-1 (to injection into S-4 as shown Figure 3), respectively.

Table 2: Estimated parameters by inversion analysis of well KY-1 pressure interference to injection into well S-4.

	Case 1	Case 2	Case 3	Case 4
Initial Pressure (MPa)	7.16	7.16	7.16	7.16
Pressure Drift (Pa/hour)	0	0	0	0
kh (darcy-m)	15.03	29.71	6.70	20.00
ϕch (m/Pa)	7.08E-09	1.08E-08	1.45E-08	2.11E-08
Fracture S / Total S { ω}	NA	NA	0.27	0.45
Permeability Ratio	NA	NA	1.63E-08	9.36E-09
Distance to boundary(m)	NA	1410	NA	1220
Standard error / Range	4.14E-02	4.08E-02	3.53E-02	2.62E-02

4. 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, 6.70 and 10.0 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 6. It is observed 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 6 are the exponential fitting curves. The fitting curve reaches its sill, which is expected to be the hydraulic diffusivity based upon the total radial permeability and the sum of the fracture and matrix storativities. The expected hydraulic diffusivity values for injection into wells SB-1 and S-4 are 2.4 m^2/s and 12.8 m^2/s, respectively. The difference in hydraulic diffusivity curves between two well tests is caused by the difference in reservoir properties between two well pairs, namely, it is caused by the reservoir heterogeneity.

As mentioned before, the presence of an impermeable linear boundary near a pair of pulse-test wells causes a delay in the time lag (Vela, 1977). He also showed that the effect on the time lags is able to be ignored when the distance to the boundary from either well is more than one-half the well spacing. Based on the inversion analyses of pressure interference presented in this paper, the distance to the impermeable boundary from wells detected is the same as the well spacing for both cases. We thus think that the boundary effect on time lags can be negligible.

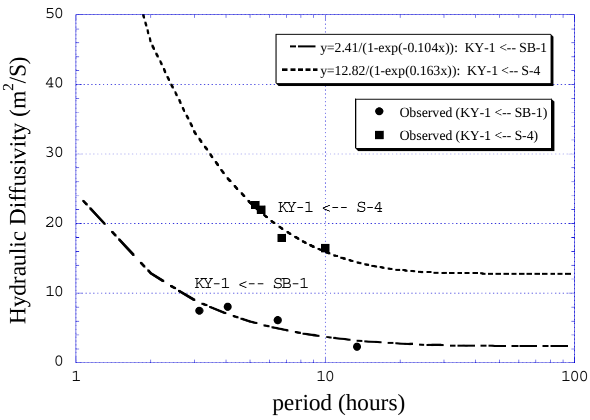

Figure 6: Dependence of hydraulic diffusivity on pulse flow-rate periods in the Sumikawa field.

Next, 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. For well SB-1 injections, τ_p becomes approximately 29 hours. If we assume that the porosity and permeability of the rock matrix are 0.05 and 10^{-17} m^2, the average fracture spacing (x_m) can be estimated to be 42 m from Equation 3, where $\mu = 1.18 \times 10^{-4}$ (Pa-s) and $C_t = 1 \times 10^{-9}$ (Pa^{-1}) are used. The x_m becomes 13 m, when the permeability of the rock matrix is assumed to be 10^{-18} m^2. Similarly, the x_m is estimated to be 11 m ~ 34 m according as the rock matrix permeability is 10^{-18} ~ 10^{-17} m^2 for well S-4 injections.

The fracture spacing (x_m) can be also calculated from the value of fracture parameters λ (transmissivity ratio), which is derived form the inversion analysis of the whole pressure interference data. If the rock matrix blocks are cubes or spheres, λ is given by:

$$\lambda = \frac{60}{x_m^{\ 2}} \frac{k_m}{k} r_w^{\ 2} \qquad (4)$$

where r_w is wellbore radius and k is total radial permeability (e.g. Kazemi, 1969). Let us consider the case of well S-4 injections. Since the λ becomes 9.36×10^{-9}, the fracture spacing is evaluated as 11 ~ 35 m when assuming that the formation thickness and the rock matrix permeability are 150 m and 10^{-18} ~ 10^{-17} m^2, respectively (wellbore radius is 0.05 m). The formation thickness of 150 m is consistent with the vertical distance between main feedpoints of wells S-4 and KY-1.

5. CONCLUSIONS

In this paper, a simplified analysis method of pulse testing is presented. We show that the estimating hydraulic diffusivity of several different pulse flow-rate periods has a possibility to detect whether the medium is porous or fractured (+ fracture spacing), 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 without disturbing power-plant operations. In case that the analysis of whole pressure interference data is possible, that is, when an accurate flow-rate history of flowing well is available, the fracture spacing can be compared with the value derived from a fracture parameter λ (transmissivity ratio) for a double porosity model.

The pressure interference data observed at the Sumikawa geothermal field is analyzed. 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. From both of the simplified pulse testing analysis and the inversion analysis of the whole pressure interference data, the average fracture spacing and the formation thickness are estimated by assuming the parameters of rock matrix.

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