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PRESSURE TRANSIENT TEST ANALYSIS FOR TWO WELLS IN THE HELLISHEIDI GEOTHERMAL SYSTEM, SW-ICELAND

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ABSTRACT

Assessment of the properties and capacity of geothermal resources involves various kinds of tests, data interpretation, monitoring and modelling. This ranges from the analysis of data collected during testing of single wells to the simulation of the response of geothermal reservoirs to utilization for years or even decades. The purpose of well test analysis is to identify the type of reservoir involved and to determine the parameters of the reservoir quantitatively. Data from two Hellisheidi wells, HE-06 and HE-20, have been analyzed by application of modern well-test analysis techniques, such as derivative analysis and computer software simulation, in addition to the conventional log-log and semi-log methods. There is good agreement between the conventional and modern methods resulting in more reliable parameters values. The permeability-thickness (kh) estimates for wells HE-06 and HE-20 are 11 and 2.6 Dm, respectively, with a positive skin factor for both of them.

1. INTRODUCTION

Well testing is a technique which allows the petroleum/geothermal engineer, to determine reservoir properties and well conditions. These include permeability, porosity, the drainage volume of the reservoir, static pressure and, in general, characterization or description of the reservoir-well system in order to evaluate well damage or stimulation, fracturing or not of the well, the existence of faults or flow barriers, the approximate shape of the drainage area of the reservoir or the change of the reservoir lithological properties (Earlougher, 1977; Horne, 1995). During a well test, the response of a reservoir to changing production (or injection) conditions is monitored. Well test interpretation is therefore an inverse problem in that model parameters are inferred by analyzing model response to a given input (Earlougher, 1977; Horne, 1995).

Hengill is one of the highest mountains in the region east of Reykjavík, Iceland's capital. It is the central volcano of the homonymic Hengill volcanic zone, composed of crater rows and a large fissure swarm. It is located on the eastern part of the Reykjanes Peninsula, SW-Iceland. The Hellisheidi geothermal field is located in the south part of Mt Hengill, and some 20 km south of the Nesjavellir high-temperature field (Bjornsson et al., 1986).

Intense drilling activity has been ongoing in the Hengill geothermal region during the last few years. In April 2008, when this is written, 44 wells had been drilled in the Hellisheidi field with up to 3 large drill rigs being active there at once. This study focuses on the analysis of end-of-drilling injection tests for two wells HE-06 and HE-20 in Hellisheidi geothermal system. Well test modelling software developed at ISOR is used in the study to compare the hydrological parameters estimated. In the following sections, the results from the conventional and modern well test analysis methods will be compared (Daher, 2008).

2. FIELD DATA INTERPRETATION

This chapter describes the results of the analysis of the injection data from each of the two wells. The analysis was conducted using different methods such as log-log, semi-log, match point, multi-rate step, derivative plot and nonlinear regression methods. The basic equation of well testing theory is the pressure diffusion equation. It is used to calculate the pressure (P) in the reservoir at a certain distance (r) from a production well producing at given rate (q) as a function of time (t). The most commonly used solution of the pressure diffusion equation is the so-called Theis solution or the line source solution (Earlougher, 1977; Horne, 1995).

In 1935, Theis (Earlougher, 1977; Horne, 1995) proposed an integral solution for this equation with:

- Initial condition:
  $P(r, t) = P_i$ for $t = 0$ $r > 0$
- Boundary conditions :
  i) $P(r, t) = P_i$ for $r \rightarrow \infty$ $t > 0$
  ii) $q = 2\pi r h \dfrac{k}{\mu}\dfrac{\partial P}{\partial r}$ for $r \rightarrow 0$ $t > 0$

The solution to the radial diffusion equation with these boundary and initial conditions is given by:

$$P(r,t) = P_i + \frac{q\mu}{4\pi kh} Ei\left(\frac{-\mu C_t r^2}{4kt}\right)$$

where $Ei(-x) = -\int_x^\infty \frac{e^{-u}}{u} du$ is the exponential integral function

If $t > 100 \dfrac{\mu C_t r^2}{4k}$ the exponential integral function can be expanded by a convergent series and thus, the Theis solution, for a pumping well with skin gives the total pressure change as:

$$\Delta P_t = -\frac{2.303 q\mu}{4\pi hk}\left[\log\left(\frac{\mu C_t r_w^{\ 2}}{4kt}\right) + \frac{0.5772 - 2s}{2.303}\right]$$

where s = Skin factor

Skin is an additional pressure change to the normal pressure change in the near vicinity of the well due to production. A negative factor indicates that the well is in good communication with the reservoir.

2.1 Well HE-06

Well HE-06 was completed in October 2002. It was drilled to a depth of 2001 m and the production casing is at 770 m. It is located 420 m above sea level in the north-west part of Hellisheidi geothermal field (Jonsson et al., 2002).

A three-rate step injection test was conducted on 2002-08-07 lasting about 8 hours. The pressure gauge used to monitor the pressure changes in the well was installed at 1400 m depth. The three step injection rates were 35, 50 and 21 l/s, respectively.

Semilog analysis

The pressure response curves of the three injection steps are presented on a semi-log graph in Figure 1. A log-log plot shows that the effect of the capacity of the borehole is not significant over after a very short period, less than five minutes (cf. for more detailed master thesis Daher, 2008). A straight line pressure response with neither slope ¼ nor ½ at an early time on log $(\Delta P/\Delta Q)$ vs. log (Δt)) indicates there are no fracture effects. A short wellbore storage period indicates good hydrodynamic characteristics of the reservoir near the wellbore. A log-log plot for the second step shows a constant pressure boundary effect.

Assuming a reservoir temperature of 260°C the following values for the dynamic viscosity and fluid density were selected for the data interpretation:

$$\mu = 1.02\ 10^{-4}\ \text{Pa s} \qquad \rho = 785\ \text{kg/m}^3$$

In addition a value of $C_w = 1.7\ 10^{-9}\ \text{Pa}^{-1}$ for the compressibility of water at 260°C was used and a typical value for the compressibility of basaltic rock, $C_r = 2\ 10^{-11}\ \text{Pa}^{-1}$. A porosity $\phi = 0.14$ (Franzson et al., 2001) was used to calculate the skin effect and the total compressibility C_t.

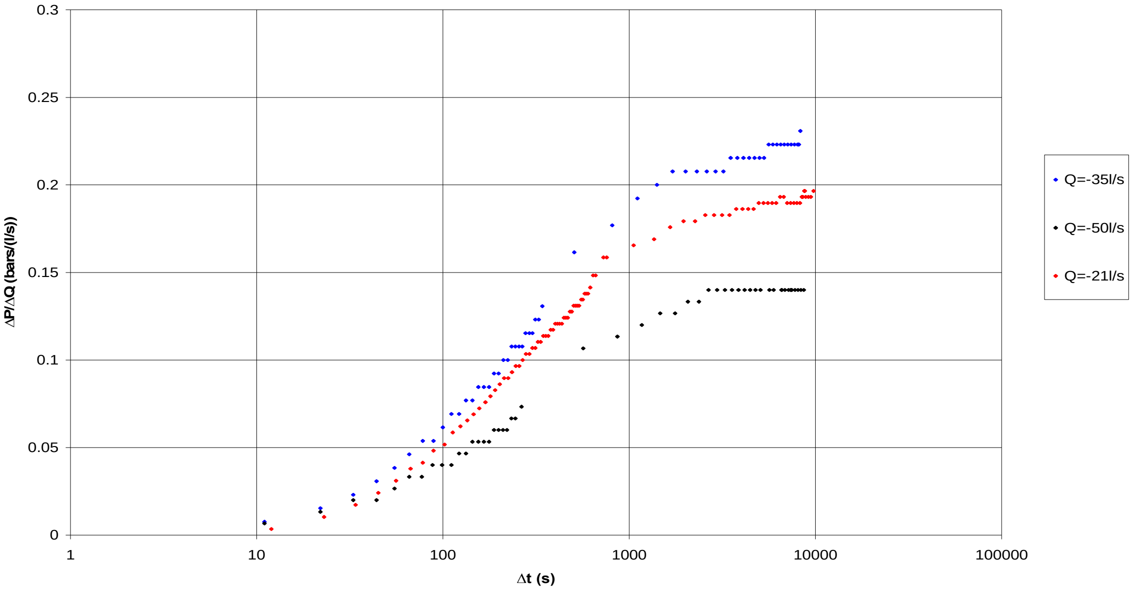

FIGURE 1: Semilog figure shows the ratio between the pressure changes in each step, ΔP, versus the flow-rate change in the step, ΔQ

The results of interpretation of the HE-6 injection test data (shown in Figure 1) with the semi-log method are presented in Table 1.

TABLE 1: Results of semi-log analysis of 07.08.2002 injection test data from well HE-06

	q (l/s)	**Δq (l/s)**	**m (bars/(l/s)//log-cycle)**	**Kh (Dm)**	**Skin**
Step1	21 -> 35	14	0.027	7	3.5
Step2	35 -> 50	15	0.02	9.3	2
Step3	50 -> 21	29	0.02	9.3	4.8

According to these results, the permeability-thickness is estimated to be 8.5 Dm on the average. As it doesn't vary much for the different steps, this estimate is considered reliable.

The skin factor for well HE-06 is positive (average = 3.4). It describes an additional pressure change in the near vicinity of the well due to different near-well permeability, during production or injection. The positive factor obtained indicates that the well is not in good communication with the reservoir.

WellTester numerical software modelling

WellTester is computer software that was developed at Iceland GeoSurvey (ÍSOR) to handle data manipulation and analysis of well test data (mainly multi-step injection or production tests). The goal of the WellTester development was to make user friendly software that could speed up the process of analyzing and reporting the results from a given well test. To this end the process was divided into five (or in some cases six) simple stages that range from setting initial conditions to modelling and giving a final report (Juliusson et al., 2007).

Figure 2 shows the results for the first step of the HE-06 injection test, as an example. The derivative plot on the right in the figure is compared with the trend of the different boundaries cases and an appropriate model selected. Information on the model selected for step 1 is summarized in Table 2.

TABLE 2: Summary of model selected for step 1 of HE-06 injection test

Well testing model - Step 1	
Reservoir	Homogeneous
Boundary	No-Flow
Well	Constant Skin
Wellbore	Wellbore Storage

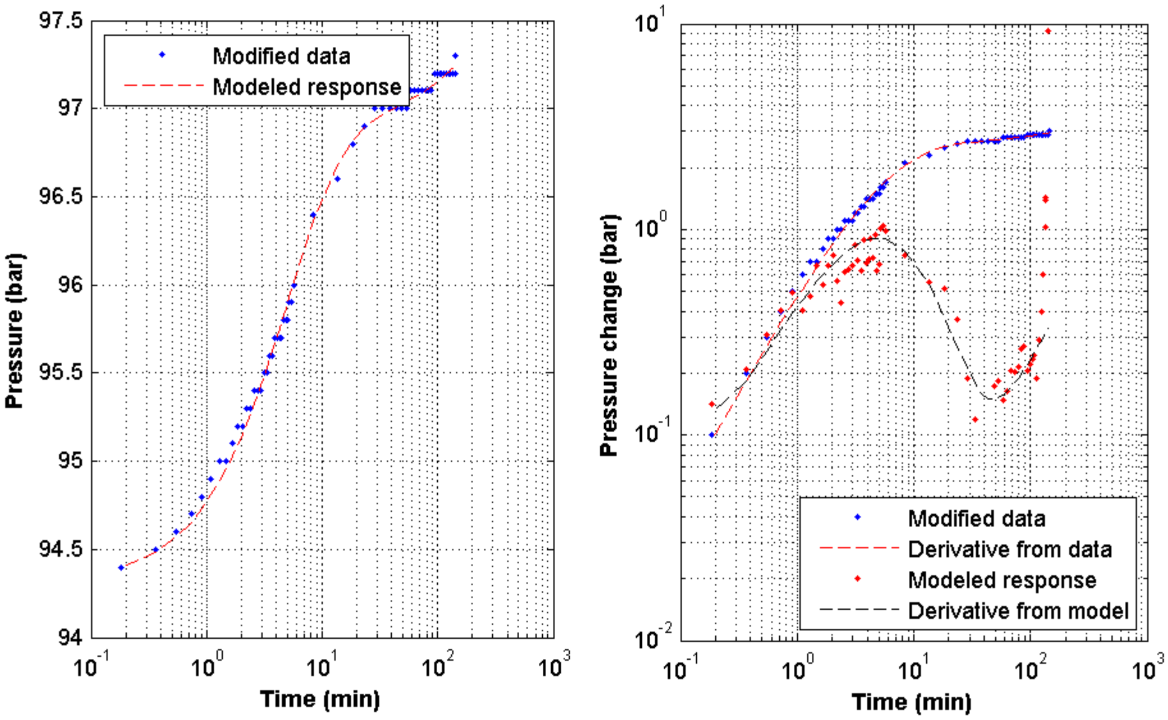

FIGURE 2: Fit between model and selected data on log-linear scale (left) and log-log scale (right) for well HE-06 with nonlinear regression method

The parameter estimates obtained on basis of different steps and models selected are finally presented in Table 3.

TABLE 3: Summary of results from nonlinear regression parameter estimate using injection test data from well HE-06 from 07-08-2002

	Transmissivity ($m^3/(Pa\cdot s)$)	**Storage coefficient ($m^3/(Pa\cdot m^2)$)**	**Kh (Dm)**	**skin**
Step 1	$1.11 \cdot 10^{-7}$	$4.73 \cdot 10^{-8}$	11.2	6.39
Step 2	$1.07 \cdot 10^{-7}$	$1.81 \cdot 10^{-8}$	10.8	2.00
Step 3	$1.06 \cdot 10^{-7}$	$6.08 \cdot 10^{-8}$	10.7	5.09
All steps	$1.06 \cdot 10^{-7}$	$2.31 \cdot 10^{-8}$	10.7	4.67

Permeability, permeability-thickness and transmissivity can vary by several orders of magnitude in geothermal systems. The permeability-thickness kh value estimate is around 11 Dm. This value is close to the results of the semi-log analysis.

The skin factor obtained by WellTester modelling is positive (4.7 for all steps combined) and the same order of magnitude of the one obtained from the semi-log analysis (3.4).

2.2 Well HE-20

Well HE-20 was completed in December 2005. It was drilled to a depth of 2002 m. The production casing is at 693 m. It is located 350 m above sea level in the north-east part of Hellisheidi geothermal field (Mortensen et al., 2006).

The two-rate step injection test was conducted on 2002-12-10 for 3½ hours. The pressure gauge was installed at 1350 m depth. The two step injection rates were respectively 40 and 50 l/s.

Semilog analysis

Considering a reservoir temperature of 260°C, the following values for the dynamic viscosity and the density of fluid were selected for the interpretation:

$\mu = 1.02\ 10^{-4}$ Pa s $\qquad \rho = 785\ \text{kg/m}^3$

Figure 3 shows a multi-rate injection test plot (Earlougher, 1977; Horne, 1995). A plot of $\frac{P_i - P_{wf}(t)}{q_N}$ vs. $\sum_{j=1}^{N}\left[\frac{(q_j - q_{j-1})}{q_N}\log(t - t_{j-1})\right]$ should show a straight line with slope m′ (Daher, 2008):

$$m' = \frac{2.303\mu}{4\pi kh} \quad (\text{Pa}/(\text{m}^3/\text{s})) \qquad \text{with}$$

P_i = Initial pressure (Pa)
$P_{wf}(t)$ = Flowing pressure well at time t (Pa)
N = Number of flow rates
q_j = Flow step between t_{j-1} and t_j (m^3/s)
t_j = Time at the flow rate q_j (s)

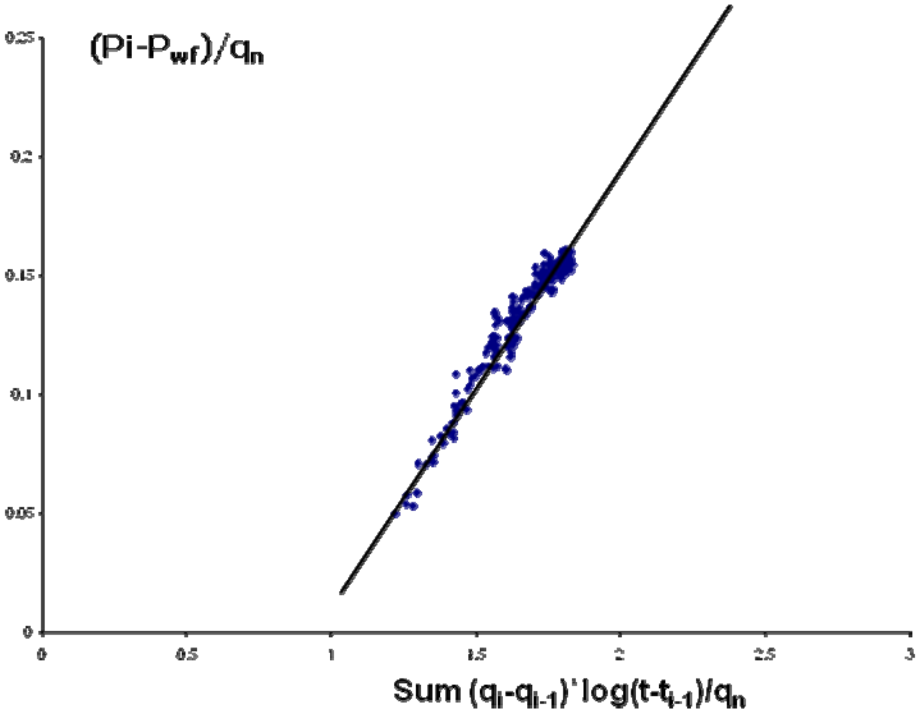

FIGURE 5: Well HE-20 multi-rate injection test plot

The results of interpretation of the drawdown tests by the semilog method, a type curve match and by multi-flow rate analysis are presented in Table 4.

TABLE 4: Results of semi-log, type curve match and multirates analysis of 12.10.2002 injection test data from well HE-20

			Semilog		**Match method**	
	***q* (l/s)**	**Δq (l/s)**	**kh (Dm)**	**skin**	$\begin{pmatrix} t_D;P_D \\ t(s);\Delta P/\Delta q \end{pmatrix}$	***kh* (Dm)**
Step 1	20 -> 40	20	1.86	2	$\begin{pmatrix} 200;1.6 \\ 100;0.1 \end{pmatrix}$	2.9
Step 2	40 -> 50	10	1.69	3	$\begin{pmatrix} 2000;1.2 \\ 1000;0.1 \end{pmatrix}$	1.93
All steps	Multiple		0.93			

The permeability-tichkness obtained from all the methods indicates a very low permeability. The skin value is low, but positive.

Nonlinear regression method
The parameters results to the selected model for the two steps are shown in Table 5.

The permeability-thickness kh value is around 2.6 Dm. This value is close to the ones obtained from the semilog plot, reflecting a very low permeability. The simulation model gives a positive skin factor. This confirms the result obtained from the semilog method.

TABLE 5: Summary of results from nonlinear regression parameter estimate using injection test data from well HE-20 from 12-10-2002

	Transmissivity ($m^3/(Pa\cdot s)$)	**Storage coefficient ($m^3/(Pa\cdot m^2)$)**	**Kh (Dm)**	**Skin**
Step 1	$3.00 \cdot 10^{-8}$	$2.75 \cdot 10^{-7}$	3	1.31
Step 2	$1.64 \cdot 10^{-8}$	$5.51 \cdot 10^{-7}$	1.7	0.92
All steps	$2.59.10^{-8}$	$1.01.10^{-7}$	2.6	1.75

3. CONCLUSION

In summary, the main results of the analysis of injection test data from wells HE-06 and HE-20 are:

- The estimated permeability-thickness for well HE-06 is high, or about 11 Dm, with a positive skin factor (around 3)
- The estimated permeability-thickness for well HE-20 is low, or about 2.6 Dm, with a positive skin factor (around 2).
- There is good agreement between all the methods used in analysing the well test data.

For the future, it will better to use directly the modern well testing method as it saves time and provides reliable parameter values.

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