PROCEEDINGS, Thirty-Third Workshop on Geothermal Reservoir Engineering
Stanford University, Stanford, California, January 28-30, 2008
SGP-TR-185

ASSESSMENT OF THE HOFSSTADIR GEOTHERMAL SYSTEM IN W-ICELAND

Mahnaz Rezvani Khalilabad[1)] and Gudni Axelsson[2)]

1) Institute of Earth Sciences, University of Iceland, Sturlugata 7, IS-101 Reykjavík, Iceland
2) ÍSOR, Iceland GeoSurvey, Grensasvegur 9, IS-108, Reykjavik, Iceland
mar7@hi.is, gax@isor.is

ABSTRACT

The Hofsstadir low-temperature geothermal system is modeled with a lumped parameter model to obtain information on the properties of the system as well as to predict its pressure response to hot water production needed to sustain the Stykkisholmur district heating system. The model shows continuous water-level draw-down since production started in 1997. Proper countermeasures have to be taken by the developer to avoid overexploitation and technical problems, such as maintaining continuous injection during long-term use and lowering the pump in the production well. Connections between injection and production well are being investigated by a tracer test, which is currently ongoing. The data from the test have been analyzed by simple model, which in turn can be used to predict the effects of long-term injection.

INTRODUCTION

Geothermal energy plays a major role in the energy economy of Iceland and the principal use of geothermal energy is for space heating (Ragnarsson, 2003). One of the low-temperature fields, which have been used for district heating, is Hofsstadir in W-Iceland. The nature and properties of the system have been studied on the basis of comprehensive reservoir engineering data, mostly production testing data, some long term production and pressure response data, and recently a tracer test has been started. Since the area was devoid of surface manifestations the question has arisen whether the reservoir can supply sufficient fluid for long term use of nearby district heating system or not. The main production well was comprehensively tested and its response modeled by a lumped parameter model in the early days. Since 1997 the response of the well and geothermal reservoir has been monitored carefully through a computerized monitoring system and this paper continues previous work. Its purpose is to evaluate the reservoir on the basis of new sets of data that continue the early data, which were used by Axelsson *et al.* (2005). Lumped parameter modeling has been applied to predict the reservoir behavior for the upcoming 20 years production and simple modeling has been used for preliminary analysis of the currently available tracer test data.

HOFSSTADIR GEOTHERMAL FIELD

The Hofsstadir geothermal system was discovered during an extensive regional temperature-gradient reconnaissance on the northern part of the Snaefellsnes peninsula in W-Iceland (see Figure 8). This reconnaissance was based on direct temperature measurements in contrast to the indirect nature of resistivity surveying. In fact temperature gradient surveying has to some extent replaced resistivity surveying as the principal tool of low-temperature geothermal exploration in Iceland (Axelsson *et al.*, 2005).

More than 120 exploration wells, mostly 50 - 100 m in depth, have been drilled in the region since 1995. The region has a surface area of approximately 800 km^2. During the reconnaissance a temperature gradient anomaly was discovered at Hofsstadir about 5 km south of the town of Stykkisholmur, which has 1500 inhabitants. This was followed up by more localized geological-, magnetic- and temperature gradient surveying, which confirmed a pronounced temperature gradient anomaly of up to 400°C/km as shown in Figure 8 (Kania *et al.*, 2005).

The heat source is believed to be the abnormally hot crust of Iceland, but faults and fractures, which are kept open by the continuously ongoing tectonic activity also play an essential role by providing the channels for the water circulating through the systems and mining the heat (Arnorsson, 1995; Bodvarsson, 1982).

Well HO-01, was drilled to a depth of 855 m in the center of the main anomaly with main production aquifer located at depths of 819 m. It provides 90% of the flow and the fluid temperature is 87°C.

Injection is considered as an integral part of management strategies in most low temperature geothermal fields. At the end of April 2007, at 1200 m distance from HO-1, a second well at 413 m depth was taken into operation to dispose of the waste water. The main permeability was found at 369 m depth in that well.

LUMPED PARAMETER MODELLING

Detailed numerical modeling of geothermal reservoirs is time consuming, costly and requires large amounts of field data Lumped parameter modeling is a cost effective alternative and provides information on the global hydrological characteristics of the geothermal reservoir. The LUMPFIT software developed by Axelsson (1989) is used to model the Hofsstadir geothermal field data. LUMPFIT tackles the pressure change simulation as an inverse problem and simulates even very long data-sets very accurately provided data quality is sufficient (Axelsson, 1989). The parameter κ_i is the storage coefficient and σ_i simulates the flow resistance in the reservoir, controlled by permeability (see Figure 1).

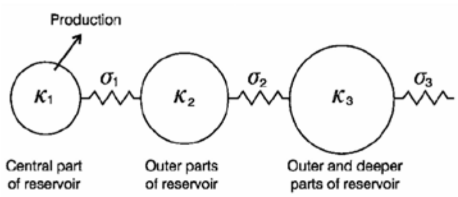

Figure 1. A general lumped parameter model used to simulate water level or pressure changes in geothermal systems

The approach, applied during lumped parameter modeling, which has evolved during the last two decades, may be summarized as follows: The modeling is usually based on the whole production history of a geothermal system and used to simulate the available pressure (or water level) decline history, preferably from a centrally located observation well. If reinjection is applied the net production is used. The aim is to end up with two models, one open and the other closed, that simulate the data accurately. The closed and open model results are the optimistic and pessimistic extremes of lumped parameter modeling. It is likely that the real behavior of a reservoir is somewhere between these two simulated responses.

LUMPFIT MODELING OF THE HOFSSTADIR GEOTHERMAL FIELD

To evaluate the potential of the Hofsstadir geothermal field to supply the required hot water for the nearby town, a production test was carried out soon after drilling. The results were modified in early 1997, indicating that the reservoir was capable of supplying 15 – 20 l/s hot water (Bjornsson *et al.*, 1996).

Utilization of well HO-1 started during late 1999. Since then the production rate, as well as the pressure response, has been monitored carefully through a computerized monitoring system. The average yearly production has been of the order of 20 L/s. The water level decline of well HO-1 has been accurately simulated by a lumped parameter model (Figure 3). As the graph shows that water level did, in fact, drop very rapidly (Axelsson *et al*, 2005).

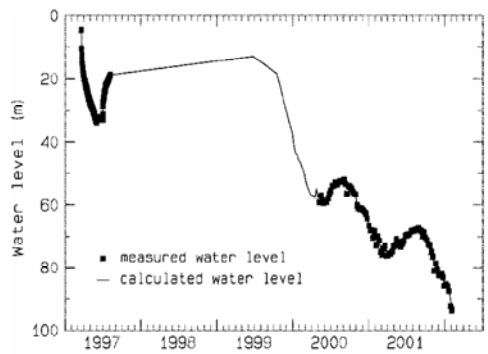

Figure 2. Water level data from well HO-01 at Hofsstadir simulated by a lumped parameter model. The data set used includes data from the production test in 1997 and the first two years of the production history of the well. (Axelsson et al., 2005)

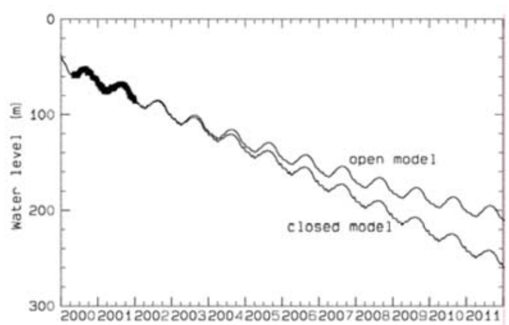

Figure 3. Predicted water level changes in well HO-1 at Hofsstadir until 2012 for a production scenario assuming the same production as in 2001, calculated by a closed and open version of a lumped parameter model (Axelsson et al., 2005).

To continue the simulation work new data from 2002 – late 2004 were arranged as an input file. Accurate data collection through time plays a major role in the reliability of the method for prediction. At Hofsstadir two different data sets were combined to have a continuous series of the eight years production and water level history. Figures 4 and 5 show the results.

Illustrated are the first three months of production testing, followed by a 5 weeks pumping stop included in the input file. As can be seen the observed data points from 2002 up to 2005, show a good match with the prediction.

Axelsson (2005) estimated a 120 m draw-down of the water level by the year 2005, which can be compared with data points illustrated in figures 5 and 6. A continues draw-down trend can be observed in the graph, from early production up to now.

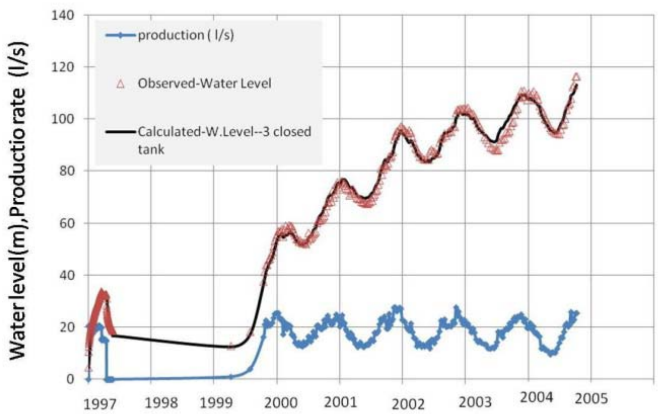

Figure 4. Water level data from well HO-01 simulated by a closed 3-tank lumped model.

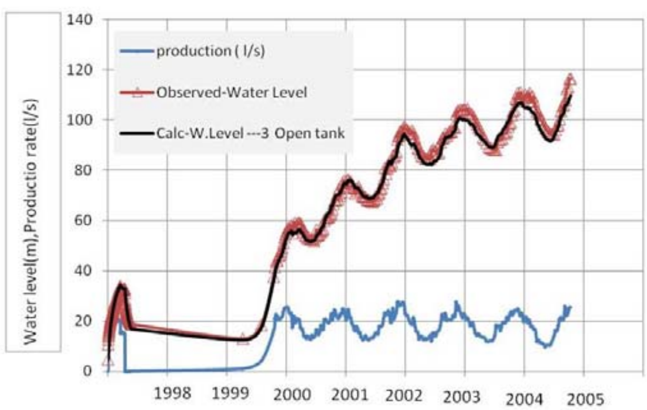

Figure 5. Water level data from well HO-01 simulated by an open 3-tank lumped model.

The results of simulation with variable sized models are shown in Table 1. The coefficient of determination is best for the three-tank closed model.

The best fitting models can be used to predict water level changes for a given future production scheme. The future production of 20 years was appended to the input file. Stykkishomur is expected to require an average annual hot water flow rate between 12 and 20 l/s. Consequently predictions were calculated for constant production cases of 20 l/s using both open and closed versions of the model. The results are illustrated in Figure 6.

Model number	3	4	5	6
Number of tanks	2	2	3	3
Model type	closed	open	closed	open
A_1	3.70E-07	6.10E-07	6.20E-07	6.20E-07
L_1	1.90E-07	5.20E-07	5.40E-07	5.40E-07
A_2		5.70E-08	5.50E-08	4.40E-08
L_2		1.10E-08	1.40E-08	1.70E-08
A_3				1.70E-08
L_3				6.10E-09
B	2.30E-08	0	5.00E-09	0
K_1 (ms^2)	256.066	152.74	149.326	149.169
K_2	4122.43	1694.67	1592.71	1587.64
K_3			15837.4	13868.1
σ_1	4.60E-05	7.30E-05	7.40E-05	7.40E-05
σ_2		2.00E-05	2.30E-05	2.40E-05
σ_3				1.00E-04
coeff. of determ.%	97%	99%	99.59%	99.43%

Table 1. Results of lumped parameter simulations with models of variable complexity.

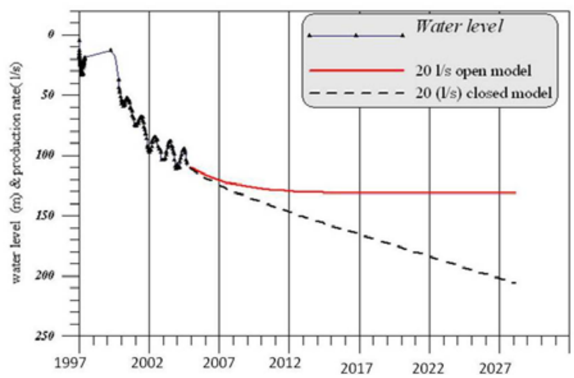

Figure 6. Predicted water level changes in well HO-01 over the next 22 years.

The difference between the closed and open model results are the optimistic and pessimistic results of the lumped parameter modeling. It is assumed that the real behavior of the reservoir will be somewhere between these two simulated responses. Comparing the simulated results with actual data points, from 2002 to 2005 simulation with observed water level reveals this more clearly.

RESERVOIR PROPERTIES

The storage in a liquid-dominated geothermal system can be the result of two types of storage mechanisms. Storage may be controlled by liquid/formation compressibility described by equation (1) or by the mobility of a free surface described by equation (2).

$$\kappa = V\rho C_t \qquad (1)$$

Here V is the volume of the part of the reservoir in question that the capacitor simulates, ρ the liquid density and C_t the compressibility of the liquid saturated formation. The compressibility is given by

$$C_t = \varphi c_w+(1-\varphi)c_r \quad (2)$$

where c_w is water compressibility, c_r is the rock matrix compressibility and φ is porosity. The water compressibility c_w is estimated to be $4.4*10^{-10}$ (Pa^{-1}) at reservoir conditions (87ºC). The compressibility of the rock matrix, composed of basalt, is $3*10^{-11}$ (Pa^{-1}). Storage due to mobility of a free surface is given by

$$\kappa=A\varphi/g \quad (3)$$

where A is the surface area of the part of the reservoir in question a capacitor simulates, φ is its porosity and *g* the acceleration due to gravity.

The storativity of the Hofsstadir reservoir is estimated using equations (1) and (2). The storativity is then used to estimate reservoir volume and area. The results of the estimation of the Hofsstadir reservoir properties are shown in Table 2. An educated guess regarding the porosity of the reservoir rock which is not fresh basalt, is made. A porosity value of φ=0.1 is used. Based on geophysical surveys a 1000 m reservoir thickness is assumed, and considered for calculations, the wells are just drilled into the uppermost part of the reservoir.

Model type	Reservoir volume (m^3)		Area (m^2)		Permeability K (m2)	
	Confined	Free surface	Confined	Free surface	Confined System (2-D radial flow)	Free Surface (2-D radial flow)
2-tank closed	7.20E+10	6.44E+08	5.86E+06	5.55E+05	4.04E-15	4.04E-15
2-tank open	3.04E+10	2.72E+08	3.81E+06	3.60E+05	4.88E-15	4.95E-15

Table 2. Reservoir properties according to lumped parameter models.

DISCUSSION OF THE LUMPED PARAMETER RESULTS

Predictions using water level data from 1997 to 2002 and two-tank closed model estimated a water level draw down of around 20 m per year. This can be seen in the 2002 – 2005 observed data. The model presented here, using data from 1997 to 2005, likewise predicts a water level decline of around 20 m per year. A two-tank open model using 1997-2002 data gave a prediction of ~10m decline per year. Although the closed and open model results are the optimistic and pessimistic view of the reservoir behavior, the observed data points are closer to the closed model prediction. This reveals the fact that the Hofsstadir reservoir is a confined reservoir. The longer data series also improved the calibration of the models and the reliability of the predictions.

The total surface area estimated on the basis of liquid-formation compressibility is too large and it is possible that some free-surface storativity is included in this case.

The draw-down in well HO-1 is not obviously critical for 18-20 l/s production but for more hot water supply and long-term use, the developer has to anticipate management options like lowering the downhole pump, as well as increasing the amount of fluid reinjected back into the reservoir. This should maintain the pressure in the reservoir quite well and help to sustain future production. Computer monitoring and observation data which is collected automatically in well HO-01 is the most powerful tool for future studies and management. Continuous revisions of the model will be needed for long term management of the reservoir.

TRACER TEST IN THE HOFSSTADIR GEOTHERMAL FIELD

On 29.08.2007 a tracer test was started to provide better understanding of the reservoir characteristic of Hofsstadir geothermal system. Na-Fluorescein, which has been successfully used in many other low temperature fields in Iceland, was used (Hauksdóttir *et al*., 2000).

Ten kg of Na-Florescence were diluted and injected into the ongoing injection of the geothermal field. The average production rate has been 30 l/s and the injection rate has been about 13 l/s. The distance between the production and injection wells is about 1200 m and the tracer started to show up after 2 months. The tracer recovery is very slow and in fact only about 10% have been recovered during last 4 months. This is believed to indicate that the injected water diffused to a very large volume and the wells not directly connected.

The preliminary result of the tracer test analysis, using the TRINV computer code (Arason *et al.*,1993), are shown in Figure 7, Table 3 illustrates the results; the flow channel area (Aφ), dispersion coefficient (D), velocity (u), longitudinal dispersivity (α_L) and the calculated mass recovery of tracer through the corresponding flow channel, until infinite time over the total injected tracer. The reinjection started at the end of April 2007, while the tracer was injected at 14:30 on August 29th 2007. To estimate the effective flow paths in the reservoir the sampling process will be continued.

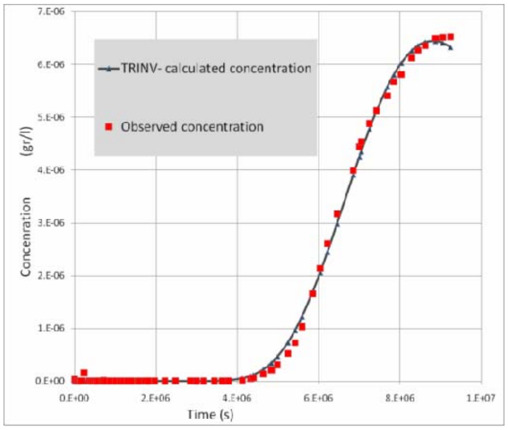

Figure 7. Observed and simulated Na-Florescein recovery in well HO-1 at Hofsstadir.

Well distance	u	D	Aφ	αL	Mi/M
1200	1.E-04	7.E-03	12.62	55	14.84
m	m/s	m2/s	m2	m	%

Table 3. Model parameters used to simulate the tracer recovery.

CONCLUSIONS

The total surface area of the Hofstadir system, estimated on the basis of liquid-formation compressibility, appears too large. Some free-surface storativity also has to be taken into account. The data observed following the 2002 modeling shows that the reservoir is most likely a confined reservoir. Reinjection will play a most important role in sustaining utilization of the reservoir over a long period of production. In the case of the Hofsstadir geothermal field, and well HO-01, draw-down is not obviously critical for up to 20 l/s production but for more hot water supply the developer will be required to lower the down hole pump in HO-1. Computer monitoring and observation data collected automatically in well HO-01 well is the most powerful tools for future studies and management. Continues revising of the lumped parameter model will be needed for long term use of the reservoir.

AKNOWLEGMENTS

The authors would like to thank Orkuveita Reykjavíkur (Reykjavik Energy) for the permission to use the Hofsstadir data. This work has been done for M.Sc. degree of Mahnaz Rezvani with supervision of Dr. Gudni Axelsson. The authors acknowledge the support of the UNU-GTP, which supports the MSc-studies of the first author at the University of Iceland. The first author would like to thank Dr. Ingvar Birgir Fridleifsson director of UNU-GTP for his continuous support.

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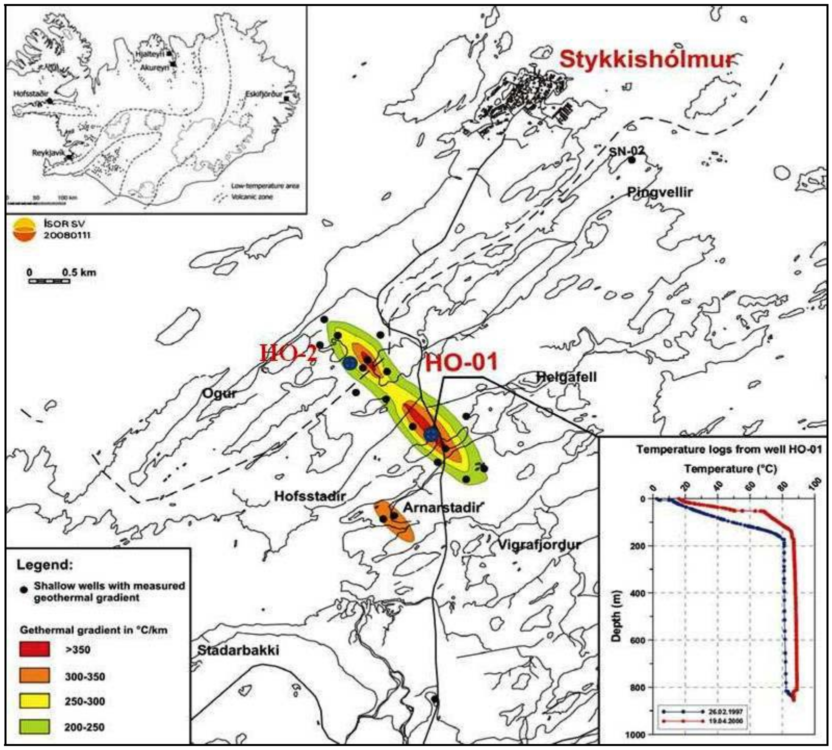

Figure 8. Location of Stykkisholmur town and Hofsstadir geothermal field, W-Iceland. Also shown are a geothermal gradient anomaly based on measurements in shallow drillholes, locations of production well HO-1 and injection well HO-2 and temperature logs from well HO-01.