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# APPLICATION OF A TRANSIENT WELLBORE SIMULATOR TO WELLS HE-06 AND HE-20 IN THE HELLISHEIDI GEOTHERMAL SYSTEM, SW-ICELAND

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## ABSTRACT

The wellbore simulator *HOLA* has been used to simulate wellbore conditions (temperature, pressure, etc.) that influence the transport of fluid from the reservoir to the surface during discharge-testing of two Hellisheidi wells, HE-06 and HE-20. At first data from the wells were analyzed by the application of modern well-test analysis techniques such as derivative analysis and computer software simulation. Following that wellbore simulator analysis (*HOLA*) of discharge test data from the wells was used to estimate the productivity index (*PI*) for each well and the results compared with the injectivity indices (*II*) obtained from injection tests. The results were compared with results from three other high-temperature geothermal fields, one in Iceland and two in Japan. The relationship between *II* and *PI* for Hellisheidi wells, and wells in other high-temperature liquid dominated reservoirs, seems to indicate a general first order relationship with considerable scatter. The electrical power potential of wells HE-06 and HE-20 is estimated at 7.3 and 5.7 $MW_e$, respectively.

## INTRODUCTION

One of the basic tasks of a geothermal reservoir engineer is to measure the fluid flow from a discharging well and its energy content as well as to analyse the flow characteristics of the well. High-enthalpy wells are discharge tested after they have been allowed to heat up after drilling for 2-4 months. The well is opened up and allowed to flow to the atmosphere. Geothermal high-temperature wells are usually discharged into a silencer which also acts as a steam-water separator at atmospheric pressure.

The simulator HOLA can be used to simulate the wellbore conditions (temperature, pressure, etc.) that influence the transport of fluid from the reservoir to the surface. The simulator numerically solves a set of differential equations that describe the steady-state energy, mass and momentum flow in a vertical pipe for single or two-phase flow. The governing steady-state differential equations are those for mass, momentum and energy fluxes in a vertical well (Bjornsson et al., 1993).

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, South West 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 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 discharge tests for two wells HE-06 and HE-20 in Hellisheidi geothermal system. Details of the simulation are presented by Elmi (2008). The productivity indices (*PI*) for wells HE-06 and HE-20 (Figure 1) have been estimated by the HOLA program and then compared with the injectivity indices (*II*) obtained by a nonlinear regression method and derivative plots applied to step-rate injection test data (Daher, 2008). The results were compared with results from three other high-temperature geothermal fields, one in Iceland and two in Japan. And finally the electrical power potential EEP for both of the two wells were estimated.

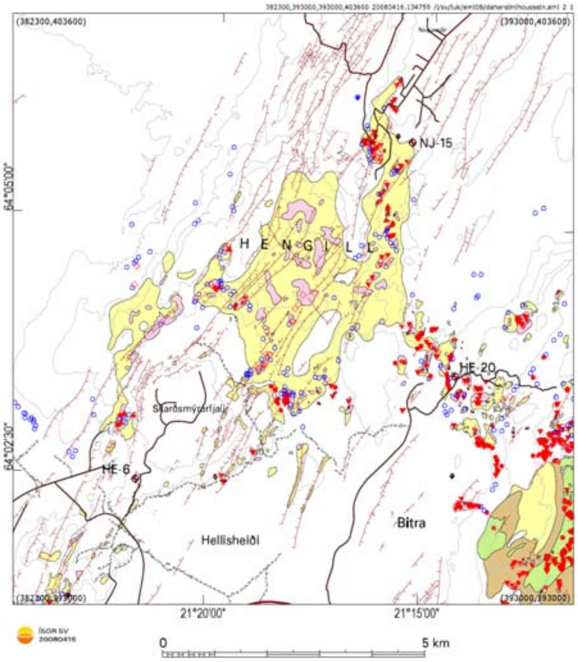


*Figure 1: Location of map of wells HE-06 and HE-20.*

## WELLBORE SIMULATION

The simulator HOLA was used to simulate the wellbore conditions (temperature, pressure, etc.) that influence the transport of fluid from the reservoir to the surface. The simulator numerically solves a set of differential equations that describe the steady-state energy, mass and momentum flow in a vertical pipe for single or two-phase flow. The governing steady-state differential equations for mass, momentum and energy fluxes in a vertical well are (Bjornsson et al., 1993):

$$\frac{dW}{dz}=0$$
$$\frac{dP}{dz}-\left[\left(\frac{dP}{dz}\right)_{fri}+\left(\frac{dP}{dz}\right)_{acc}+\left(\frac{dP}{dz}\right)_{pot}\right]=0 \qquad (1)$$
$$\frac{dE_t}{dz}\pm Q=0$$

W = total mass flow (kg/s),
P = pressure (Pa),
$E_t$ = total energy flux in the well (J/s),
z = depth coordinate (m),
Q = ambient heat loss over unit distance (W/m).

The plus and minus signs indicate down-flow and up-flow, respectively. The pressure gradient is composed of three terms: wall friction, acceleration of fluid and change in gravitational load over depth interval (*dz*).

The governing equation of mass flow between the well and the reservoir, through a given feed-zone, is:

$$W_{feed}=PI\left[\frac{k_{rw}\rho_w}{\mu_w}+\frac{k_{rs}\rho_s}{\mu_s}\right]*\left(P_r-P_{well}\right) \qquad (2)$$

$W_{feed}$= feedzone flow rate (kg/s),
PI = productivity index of the feedzone ($m^3$),
$k_r$ = relative permeability of the phases (subscripts w for liquid and s for steam),
μ = dynamic viscosity (Pa.s),
ρ = density (kg/$m^3$),
P = pressure (Pa), subscripts r for reservoir and well for well.

Hola programme calculates *PI* at a feed zone by

$$PI=\left(\frac{q_\beta}{P_\beta-P_{wb}}\right)\left(\frac{\mu_\beta}{k_{r\beta}\rho_\beta}\right) \qquad (3)$$

PI = productivity index ($m^3$),
$q_\beta$ = inflow mass rate (kg / $m^3$) at the feed zone of the phase β (liquid, gas),
$P_\beta$ = pressure reservoir (Pa) at the feed zone,
$P_{wb}$ = bottomhole pressure at that depth,
$\mu_\beta$ = viscosity ( Pa·s),
$k_{r\beta}$ = dimensionless relative permeability,
$\rho_\beta$ = density (kg / $m^3$).
Here the PI will be calculated by summing up PI's for each feed zone

$$PI=\sum_{j=1}^{N}PI_j=\sum_{j=1}^{N}\frac{Q_j}{\Delta P_j} \qquad (4)$$

Where N is the number of feed zones, $Q_j$ the flow rate through feed-zone *j* (kg/s) and $\Delta P_j$ is the difference between the reservoir pressure and down-hole pressure at feed-zone j (Grant et al., 1982).

## FIELD DATA INTERPRETATION

### 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 the Hellisheidi geothermal field (Jonsson et al., 2002).

The temperature and pressure profiles measured on April 28, 2003 were selected to be simulated with the HOLA program. After a lengthy process of trial-and-error, and least-squares fitting by HOLA, a successful simulation was achieved. The results are presented in Figure 2.

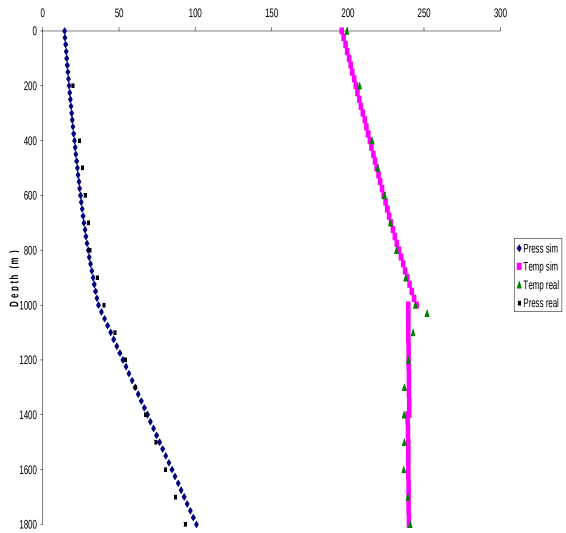


*Figure 2: Wellbore simulation (HOLA) of pressure and temperature log-data from well HE-06 logged during discharge testing of the well on 2003-04-28.*

The modelling results indicated two main feed zone at 1000 and 1400 m depth, each with approximately the same flow rate (18.5 and 13.5 kg/s respectively) and productivity index, *PI*, equalling $10^{-12}$ $m^3$. The total flow rate simulated was 32.0 kg/s at a well-head pressure of 14.4 bar-g and the discharge enthalpy is 1020 kJ/kg. These values are very close to the results of discharge measurements by Reykjavik Energy, 33.0 kg/s at 14 bar-g, at the same time. But there is difference between the values of enthalpy as the enthalpy measured by Reykjavik Energy is around 1350 kJ/kg. This discrepancy could be due to insufficient separation in the silencer, during lip pressure measurement, where part of the water is carried with the steam leading too low water flow the weir-box. After the flashing started a gain of enthalpy can occurs with the time then it can expected to have higher enthalpy value .

According to the modelling result, the total (combined) *PI* equals 2.25 (l/s)/bar. If we compare this with the injectivity index, *II* = 5.58 (l/s)/bar obtained by Daher (2008) the ratio between *II* and *PI* is 2.5. Some uncertainty may arise from the model simulation as the data are very sensitive to variations in *PI*. To increase the accuracy of the *PI*-value it may be better to use a more accurate method for discharge measurements (e.g. through spinner logging) in order to be able to measure flow rate at the feed zones.

According to the simulation for HE-06 steam-flow at 14.4 bar is 14.6 kg/s. Assuming that the steam flow is converted to electricity at a steam rate of 2 (kg/s)/$MW_e$, the electrical power potential of the well corresponds to 7.3 $MW_e$.

**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 temperature and pressure profiles measured on March 16, 2006 were selected to be simulated with the HOLA program. After a lengthy process of trial-and-error, and least-squares fitting by HOLA, a successful simulation was achieved. The results are presented in Figure 3.

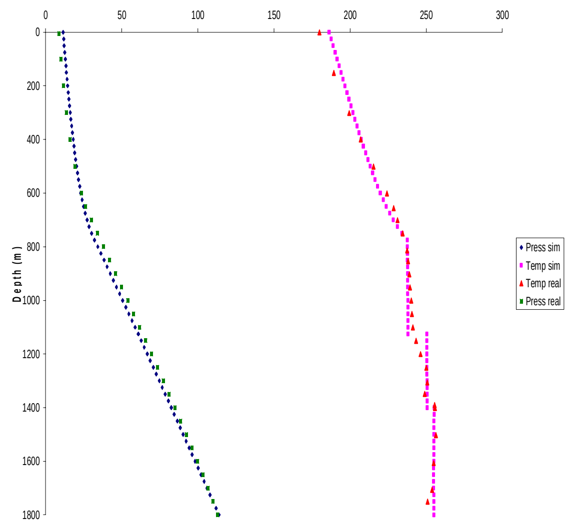


*Figure 3: Wellbore simulation (HOLA) of pressure and temperature log-data from well HE-20 logged during discharge testing of the well on 2006-03-16.*

The model results indicated three main feed zone at 1125, 1800 and 1400 m. The total flow rate obtained for 10.5 bar-g required is 32.7 kg/s. This value is close to the one obtained during discharge measurements by Reykjavik Energy (35.5 kg/s for 10.1 bar-g). The flow rate from a feed-zone at 1125 m depth (21.8 kg/s) is twice higher than the flow rate of feed-zones at 1400 and 1800 m depth (7.7and 3.1 kg/s, respectively). The wellhead enthalpy corresponds to 1018 kJ/kg.
From the model result, the *PI* = 4.1 (l/s)/bar. Comparing this with the injectivity index *II* 3.2 (l/s)/bar), (Daher, 2008) the ratio between *II* and *PI* is 0.8.

Downhole simulations indicate three main feed points, the more dominant one at 1125 m. A maximum temperature of about 250°C is attained and the corresponding enthalpy of liquid water is 1085 kJ/kg.

According to the simulation for HE-20 steam-flow at 10.5 bar-g is 11.4 kg/s and then the electrical power output of the well is expected to be about 5.7 $MW_e$.

## Comparison between *II* and *PI*

To compare the *PI* and *II* indices for high-temperature wells, the values for 34 wells from different geothermal high-temperature fields have been compared. These are:

- Three wells from the Hellisheidi area in Iceland; wells HE-05 (Mahnaz, 2003), HE-06 and HE-20.
- Six wells from Reykjanes in Iceland; wells RN-10, 13, 15, 18, 21 and 22 (Axelsson et al., 2006).
- Seven wells from Oguni in Japan; wells GH-10, 11, 12, 15, 20, IH-2 and N2-KW-3 (Garg and Combs, 1997).
- Seven wells from Sumikawa in Japan; S-2i, 2, 4, SA-1, SA-4, SC-1 and SD-1 (Garg and Combs, 1997).
- Eleven wells from Takigami in Japan; NE-4, 5, 6, 11, 11R, TT-2, 7, 8, 8S1, 8S3 and TT-13S (Garg and Combs, 1997).

To summarize all the data a plot of *II* versus *PI* is presented in Figure 4. It appears from the figure , to the first order, that the *PI* and *II* for all the boreholes are more or less equal, but there is considerable scatter.

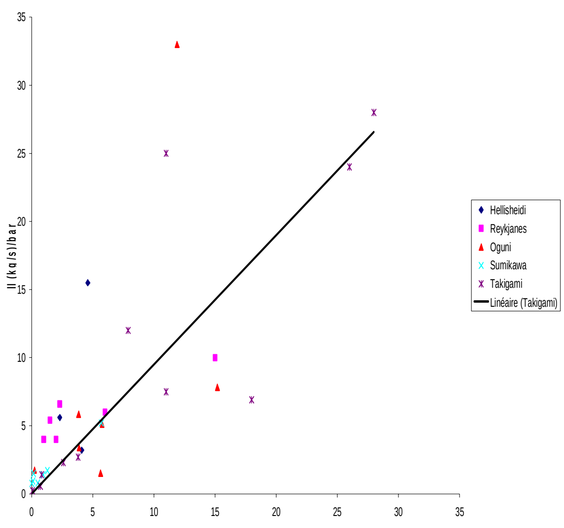


*Figure 4: Productivity index (PI) vs. injectivity index (II) for selected liquid feed-zone wells in Hellisheidi, Reykjanes, Oguni, Sumikawa, and Takigami.*

## CONCLUSIONS

In summary, the main results of the analysis of transient wellbore simulator test data from wells HE-06 and HE-20, and comparison with other high-temperature geothermal wells worldwide, are:

- The estimated ratio between *II* (5.58 (l/s)/bar) and *PI* (2.25 (l/s)/bar) for well HE-06 is 2.5. The well has two main feed zones around 1000 and 1400 m depth. The EPP of the well is estimated to be 7.3 $MW_e$.
- The ratio between *II* (3.2 (l/s)/bar) and *PI* (4.1 (l/s)/bar) for well HE-20 is 0.8. There are three main feed zones in the well, around 1125 and 1400 m depth. The EPP of the well is estimated to be 5.7 MWe.
- The ratio between *II* and *PI* for Hellisheidi wells, and in other high-temperature liquid dominated reservoirs used for comparison, seems to indicate a general first order relationship with considerable scatter.

Some of recommendations can be made to improve data quality, and consequent data interpretation, such as:

- As it was difficult during this study to get good data for the total mass output plotted against wellhead pressure from wells HE-06 and HE-20, it shows how important it is to have accurate data in order to get physical parameter estimates close to reality. One important recommendation is to use detailed down-hole flow-meter measurements (spinner logging) in order to get accurate information on feed-zone locations and on the amount of loss or gain between well and formation.
- In order to determine the maximum discharging pressure, the enthalpy and flow rates measurements should be done with care. It is recommended before connecting the wellhead pressure to the power plant, to run a completely of lip pressure program. May be it's better to use chemical tracers for flow-rate measurements, because of greater accuracy, even if it is more expensive.

## ACKNOWLEDGEMENTS

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