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Adjusting the Well Output Curves of the Miravalles Geothermal Field, Costa Rica

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ABSTRACT

Estimation of the mass production of the Miravalles Field wells has been done based on the use of the James method. Well output curves were constructed by using data taken from well testing and then improved through statistical analysis. The output curves of the production wells of Miravalles are defined to be as one out of four correlation types: linear, quadratic, elliptic and Antoine (modified), based on the physical behavior of the wells and the least-squares calculation.

These correlations are input into worksheets and another piece of homemade software in order to calculate production and injection mass flowrates. Not only are special unsteady state processes like the integration of a separation station into the production system calculated but also the information is fed into a mass production database which is extremely necessary for field management and for the modeling of the geothermal field.

1. INTRODUCTION

The Miravalles Geothermal Field is the only geothermal reservoir under exploitation in Costa Rica (Figure 1). Deep drilling started in 1978, when a high-temperature reservoir was discovered. Subsequent drilling stages increased the steam production in order to supply three flash plants commissioned in 1994 (55 MW), 1998 (55 MW) and 2000 (29 MW), and one binary plant in 2004 (19 MW), totaling an installed capacity of 163 MW. Three 5 MWe wellhead units have also produced for different periods, and one of them is still in operation.

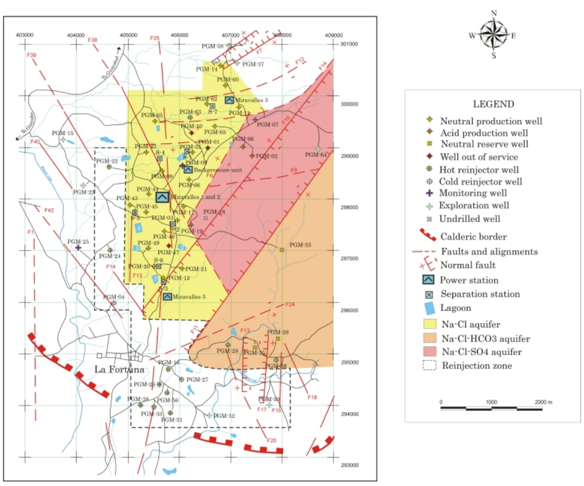

Figure 1: The Miravalles Geothermal Field Location and Facilities

The reservoir is 800-1000 m thick, high-temperature and liquid-dominated, located at about 700 m depth with reservoir temperatures naturally declining to the south and west. The main reservoir fluids have a sodium-chloride composition with TDS of 5300 ppm, a pH of 5.7 and a silica content of 430 ppm and have a tendency to form carbonate scaling in the wells. The main aquifer is characterized by a 230-255 ºC lateral flow. A shallow steam dominated aquifer is located in the northeastern part of the field, and it is formed by the evaporation of fluid from the main aquifer that moves along fractures (Vallejos, 1996). Another important sector is an acid aquifer located in the eastern-northeastern part of the field, and so far four out of five wells that have been drilled there have been systematically exploited and neutralized.

The field is associated with a 15 km wide caldera, which has been affected by intense neo-tectonic phenomena. The interior of the caldera is characterized in general by a smooth morphology. The proven reservoir area is about 13 km^2, and a similar area is classified as a sector for probable expansion. Another 15 km^2 area is identified as also having some possibilities for future development (ICE/ELC, 1995). These areas may increase as the reservoir is investigated further.

The main productive zone of the field can be seen in Figure 1 as the yellow area (7.5 km^2), where the majority of the production wells are located (26 out of 30). Other important productive zones are the acid aquifer (red zone of about 6.5 km^2) and the east-southeast zone (beige zone, not actually under exploitation and comprising 6.5 km^2). The injection zone is located to the west and the south (this last coincides with the zone where water exits the exploited reservoir and it is about 7 km^2).

2. OUTPUT CURVES

Output curves have been used in Miravalles for relating the total mass flow rate of a well to its wellhead pressure in order to get the amount of steam and brine available at that point in time and to determine an estimate of the total number of production and injection wells needed to be drilled to commission a geothermal power plant. This is important not only from the energy production point of view but also because the environmental impact studies in Costa Rica have been considered a fundamental element in the economy of any project. Due to this the disposal of waters is also an important issue of concern.

The output curve is a picture in time of the production of a geothermal well (González, 2001). This production is affected by some factors related to the normal evolution of a geothermal reservoir under exploitation: the exploitation and reinjection rates and policies, thermal breakthrough, the presence of cold shallow aquifers invading through the reservoir, seismic behavior of the region, geochemical factors such as mixing of incompatible waters, and chemical deposition such as carbonate and silica scaling.

All of the above factors could contribute to a reduction in the local permeability in the neighborhood of the production and injection wells.

The Russell James method (James 1962) is the first approach used in order to make an initial estimate of the production of a new geothermal well after an adequate recovery period. This method is preferred because it is not necessary to count on expensive installations in site to test the well. The well is discharged through an atmospheric separator. Lip pressure, wellhead pressure and weirbox levels are recorded until the parameters' stabilization are attained. During the test, chemical samples are taken from the weirbox and from the separated steam available at the discharge tube. Then, based on the James equation, the calculations are made to determine the initial production of the well corrected by the gas content.

Once the well has been integrated into the separation system at the power plant, the total amount of steam is measured at the separation stations through a venturi contraction system, annubar tubes or orifices (the use of the former one is preferred due to lower pressure losses) or at the power house. The amount of geothermal brine to be disposed of is measured through orifices. However when the separation system is in operation the steam coming from two or three wells is collected in a separation station and cannot be measured separately in each of the wells. This is a major drawback if it is detected that the steam production is declining in only one of the wells. Reading the wellhead pressure from each of the wells can be a primary way to find out which well may present a decrease in productivity.

If the well is to be tested in order to look for the causes of declining production, it must be withdrawn from the gathering system and produced to the silencer not only to evaluate production but also to log T and P surveys under a variety of conditions. The flowrate estimate would have less than 12% error once the well has reached a thermal stabilization unless the well is affected by thermal breakthrough.

The experience in Costa Rica in testing production wells based on the James method is a trade off based on economical and scientific factors. It is done at least once a year during the annual power plant maintenance period. The information gathered during these tests are the amount of geothermal brine and steam, the downhole dynamic and static temperature and pressure conditions, non-condensable gas content in the steam at maximum flowrate and also at maximum discharge pressure and the chemical composition of the separated water at the weirbox. This practice and further information analysis allows a record to be kept of the thermo-chemical and hydraulic evolution of each of the wells in Miravalles.

Most of the Miravalles production wells stabilize their productive parameters in a relative short time. A typical output curve evaluation consists of 5 evaluation points, each one lasting 4-5 hours. However, there are wells that show a lip pressure range narrow enough to force the evaluation of the well to 4, 3 or 2 data points depending on the proper characteristics of the well. Care must be taken in order to measure the lip pressure point when the differences are small because the manometer vibrations can induce an error. In the end, the lip pressure range is the parameter that is taken into account to generate an output curve that is symmetrically related to production in order to generate more accurate correlations. This cannot be performed when the wellhead pressure is taken as the main parameter for choosing each evaluation data point in equal intervals.

3. STATISTICAL ANALYSIS OF THE OUTPUT CURVES AND ITS REDUCTION TO CORRELATIONS

The information obtained from the output curves started to be collected long before the Miravalles Unit I was commissioned (March 1994). Making use of statistical analysis and the least-squares method, the production data were represented by equations (correlations of mass flowrate versus wellhead pressure) during the second half of 1993 and the beginning of 1994 (González, 2001). This task was performed in order to facilitate the interpolation of data, quicker calculations of the amount of steam available at each well under certain operative conditions, and the selection of which wells are to be produced. This was done originally by using an electronic spreadsheet at the Reservoir Engineering area.

The correlations obtained were based on a polynomial model to represent the relationship between the mass flowrate, enthalpy and the wellhead pressure. The massflow rates were normally represented through lineal, quadratic and cubic correlations. The enthalpies were also adjusted to the same type of massflow correlations. However, later on, it was observed that averaging them was enough to give an accurate value of enthalpy because the range of occurrence was within 40 kJ/kg.

In 1998, Bogarín and González (Bogarín and González, 2000) started an investigation to adapt the most suitable equations to the output physical behavior shown by the wells finding that the most representative correlations were: 1- lineal 2- quadratic 3- elliptic and 4- Antoine modified.

$$F_t = a + b * P_{cab} \quad (1)$$

$$F_t = a + b * P_{cab} + c * P_{cab}{}^2 \quad (2)$$

$$F_t = a * (1 - \frac{P_{cab}{}^2}{b^2})^{0.5} \quad (3)$$

$$F_t = a + \frac{b}{(P_{cab} + c)} \quad (4)$$

where F_t, P_{cab}, a, b and c are total massflow rate (kg/s), wellhead pressure (bar absolute) and equation constants, respectively.

At that time, the behavior shown among the output curves could be better reproduced by making use of lineal and parabolic correlations. The goodness of fit (or best representation of the data) is expressed by a high correlation coefficient and minimum least-squares calculations.

The elliptic correlation (in the first quadrant of polar coordinates) is applicable to curves which show very small variations near the maximum flowrate and a steep change in the data relationship near the maximum discharge pressure including a reversal at the MDP (maximum discharge pressure), as shown in Figure 2. This kind of relationship is used to adjust data in the wellbore simulator Wellsim (GENZL, 1991). The general form of the correlation is:

$$\frac{F_t^{\ 2}}{A^2} + \frac{P_{cab}^{\ \ 2}}{B^2} = 1 \tag{5}$$

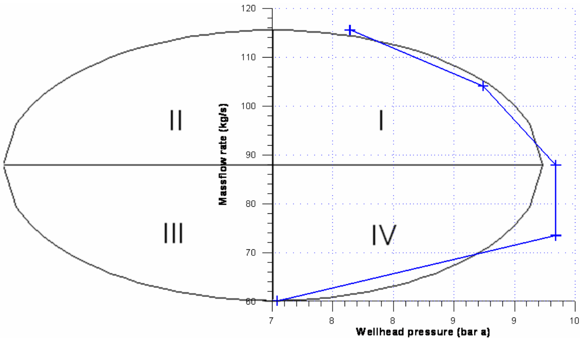

Figure 2: Ellipse correlation adjusted to a field data

The modified Antoine correlation is based on the Antoine equation, which is based on the Clausius-Clapeyron correlation (Himmelblau, 1988) that derived the form of the equation based on the thermodynamic relationship between the slope of the steam pressure and the molar heat of vaporization for various substances linearizing the equation in the following way:

$$\frac{dp}{dT} = \frac{\Delta H_v}{T*(V_g - V_l)} \tag{6}$$

where p, T, ΔH_v, V_g and V_l are steam pressure, absolute temperature, molar heat of vaporization and the molar volumes of gas and liquid, respectively.

However, the steam pressure empiric correlations (as shown in Figure 3) are frequently denoted in the following Antoine equation form:

$$\log(p^*) = b - \frac{-m}{(T+a)} \tag{7}$$

where m is the slope of the curve.

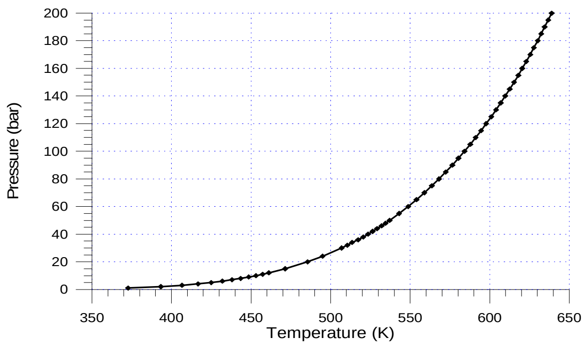

Figure 3: Example of vapor pressure versus temperature plot

The data are linearized in order to be straight lines in a plot where the x-axis is the inverse of the temperature and the y-axis is the logarithm of the steam pressure. The general form of the equation is:

$$\log(y) = a + b*\frac{1}{X} \tag{8}$$

It should be noted that the difference between Equation (7) and (8) is a minus sign, which in the end does not impact the final results; this sign difference is why the equation is called the modified Antoine. During the development of the numerical method each data pair is used as a "pivot point" in which all the other data are evaluated in order to achieve a correlation based on least-squares. Then, each set of data (5 for an output curve of 5 data points) are compared to obtain the minimum least-squares based on each "pivot point", obtaining 5 data of least-squares and choosing the minimum of them.

Figures 4 and 5 show a couple of examples of adjusting output curves based on the four correlations previously discussed. For both examples, it can be seen that the difference among each set of field data supplied and the data provided for the different correlations do not differ much one each other at first sight even though there are important differences in the calculation of the least-squares. In the case of well PGM-10 (Figure 4) the modified Antoine correlation is the best (minimum least-squares) that suits the field data but the quadratic correlation is very close to it. In the case of well PGM-45 (Figure 5), the best correlation is the quadratic one even though the lineal correlation is very close. The output curve correlation data can be seen in the Appendix.

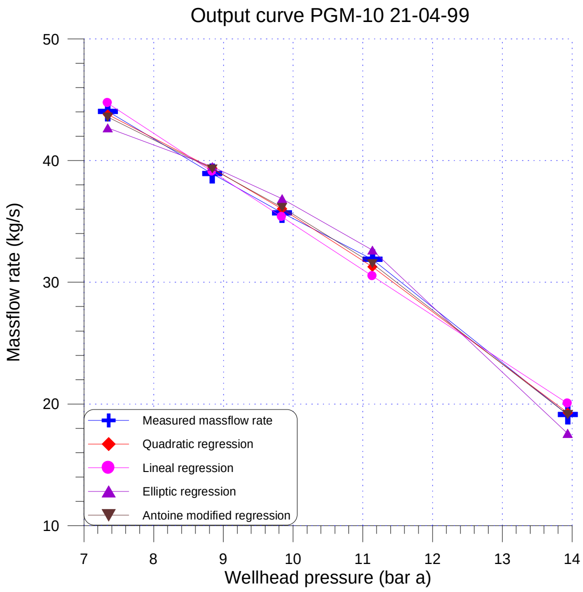

Figure 4: Output Curve Correlation Adjustment for Well PGM-10

4. UTILIZATION OF THE OUTPUT CURVE CORRELATIONS TO CALCULATE PRODUCTION AND INJECTION MASSFLOW RATE

The first set of correlations of mass flowrate versus wellhead pressure were obtained during the second half of 1993 and beginnings of 1994 (González, 2001). This task was performed in order to facilitate the interpolation of data, to do quicker calculations of the amount of steam available at each well under certain operative conditions, and to choose which wells to be produced.

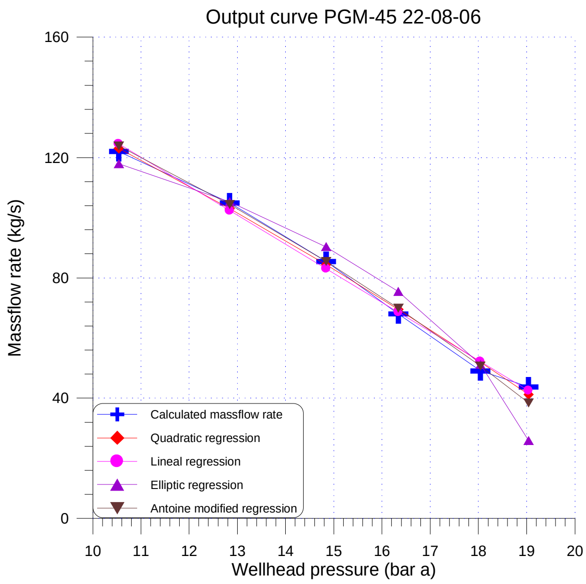

Figure 5: Output Curve Correlation Adjustment for Well PGM-45

At the very beginning of the field exploitation, there was no steam measuring devices in the field, only at the power house. Once a new relationship for the flowrate had been attained after the evaluation of each well, it was input into the electronic spreadsheets to update information and perform calculations of production and injection of the steam field. It was possible then to simulate some production scenarios, but there are limitations in the way that the information could be managed. The next step was to develop a simple calculation program to start the management of the information. This program was made in the QUICK BASIC language during the first half of 1994 by the Reservoir Engineering Group (Geosciences Area).

The software was continuously improved in order to develop a mass and energy balance program capable of generating a database base on the output curves (see González and Vallejos, 2010).

5. COMPARISON BETWEEN THE PRODUCED AND MEASURED STEAM

Figure 6 compares the steam measured through orifice plates at the power plants and the calculation based on the output curves for one year set of data.

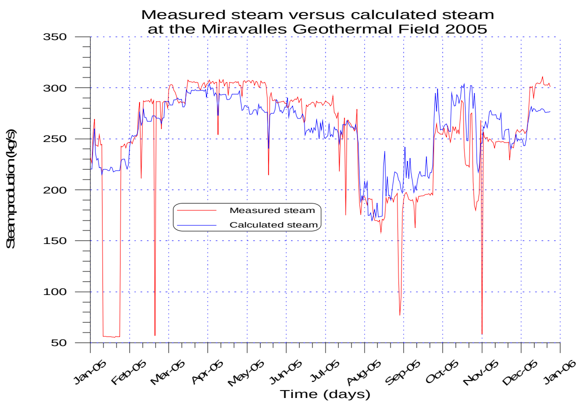

Figure 6: Calculated and measured steam for the Miravalles Geothermal Field in 2005

It can be seen from Figure 6 that prior to August the calculated steam was less than the measured steam in the power plant. From August to December, the steam calculated was greater than the steam measured.

The most important factor that relates the observable differences prior and after August is that the output curve have been updated with the new period of well evaluations. In addition, the calculations after August consider a variable enthalpy approach rather than the average enthalpy considered in the old fashion correlations calculated prior to 2005 (see González and Vallejos, 2010).

The variable enthalpy approach counts for the actual evolution stage observed in the Miravalles Field, where the reservoir had suffered an important pressure drop and some parts of the field have developed steam caps and thus the average enthalpy at any separation station varies depending on the well contribution.

6. OTHER CONSIDERATIONS.

It is also important to notice that there is a slight difference in production of the wells when they are connected to the steam-brine pipelines and when they are producing to the silencer.

This behavior has been seen since the beginning of the commercial production of Miravalles, but it has been noticeably increasing through time.

This behavior is a minor problem in determining the accuracy of the output curves in the production wells. With the variable enthalpy approach and other operation methodologies designed to evaluate wells, the accuracy of the output curves has been improved (González and Vallejos, 2010).

It is always expected that the calculated steam will be greater than the measured steam in the power plants due to various reasons: 1) the correlations used prior to the new evaluation of the wells are no longer valid (not updated); 2) the fact that the James method has an error by itself of around 10-12% that can affect the measurements; 3) there must be some mass losses due to small condensation in the steam lines prior to its arrival to the power plant; 4) Miravalles Units I and II use a significant quantity of steam in order to manage a high non condensable gases content (by the continuous use of ejectors).

6. CONCLUSIONS

Prior to the commissioning of Miravalles Unit I (March 1994) it was foreseen that there would need to be available mathematical correlations for the output curve of production wells in order to simulate different field exploitation scenarios and to estimate the steam available to supply to the power plant. At the same time it is possible to estimate the amount of water injected in each part of the field.

The main purpose of determining output curves is to have a simple tool for estimating the total mass flow rate produced by each individual well. This information is used for various purposes:

i- To supply the adequate mass production data for a mathematical model of the geothermal reservoir;

ii- To observe and evaluate the behavior of production and injection wells and the field as a whole under exploitation in order to take the mitigation measures needed to overcome any decrease in production;

iii- To improve the field management by selecting the right combination of production and injection wells, taking into account the individual analysis of each well and the numerical modeling analysis.

iv- In combination with a non condensable gas content calculation tool used in Miravalles (Sánchez, 2009 and González and Vallejos, 2010), to simulate the right combination of wells to send the adequate steam quality to the power houses.

The process of adjusting the well output curves to mathematical curves correlations have been modified in order to maintain accuracy. The process has been successful in providing reliable production data in an easy way.

The fact that during the 2005 output curves introduced a new variable into the calculation (variable enthalpy) does allow for an effective point of comparison with the output curves run during 2004 which took into account January to August 2005, in the sense that it showed an effective change in the mass flowrate determination. On the other hand, the flowrates calculated cannot be compared as a way to determine the well evolution in time, since they are made with two different calculation methods.

It can be seen from Figure 6 that the tendency to adjust the steam supplied to the power houses kept pace with the steam calculated based on the output curves.

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APPENDIX

Well PGM-10 Output Curve Correlation Adjustment Data

Well PGM-10

DATE: 21-Apr-1999

Chosen Correlation: ANTOINE

Quadratic:

$Y= A(1) + A(2)*X + A(3)*X^2$

A(1) = 55.67702

A(2) = -0.518602

A(3) = -0.1501171

ERROR = 0.7598314

Lineal:

$Y= A(1) + A(2)*X$

A(1) = 72.1796

A(2) = -3.741056

ERROR = 3.306077

Elliptic

$X^2 / A(2)^2 + Y^2 / A(1)^2 = 1$

A(1) = 49.00976

A(2) = 14.93339

ERROR = 6.528453

Antoine Modified

$Y = A(1) + A(2) / (X + A(3))$

A(1) = 104.8341

A(2) = 1418.248

A(3) = -30.49012

ERROR = 0.6985602

Well PGM-45 Output Curve Correlation Adjustment Data

Well: PGM-45

Date: 22-Ago-2006

Td = 231 °C 700<PE<800 Boiling in formation

Chosen Correlation: Quadratic

Quadratic:

*Y= A(1) + A(2)*X + A(3)*X^2*

A(1) = 000194.261732

A(2) = -000005.165355

A(3) = -000000.151038

ERROR = 22.650986

Lineal:

*Y= A(1) + A(2)*X*

A(1) = 000226.196033

A(2) = -000009.647929

ERROR = 29.893866

Elliptic

X^2 / A(2)^2 + Y^2 / A(1)^2 = 1

A(1) = 000140.514067

A(2) = 000019.372098

ERROR = 418.056997

Antoine Modified

Y = A(1) + A(2) / (X + A(3))

A(1) = 000463.264300

A(2) = 014334.807426

A(3) = -000052.779372

ERROR = 37.986457