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Quantifying the Production of the Miravalles Geothermal Field According to the Evolution of the Productivity Characteristics and the Increasing in Installed Capacity

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ABSTRACT

Before the commissioning of the Miravalles Geothermal Field, the calculation of the amount of steam available for each well and the whole field based on the original output curves data was complicated. A way of making the procedure easier and automating the process of calculating mass flow rates and storing the results in spreadsheets was to develop software specially designed for those purposes.

As the installed generation capacity has increased and the behavior of the geothermal reservoir evolves, the calculation software should evolve too. After 15 years of continuous production the changing field characteristics forced a change in the way the calculations were made. The current parameters of the output curve were modified in order to reconcile the differences between the accuracy of the venturis measurements and the calculated steam by the output curves calculation. A new parameter called "percentage of opening" is defined based on the throttling of the side valve of the production well and is used instead of the wellhead pressure. The output curve is now redefined as the "evaluation curve". All the changes performed in the calculation software are described in the present paper.

1. OVERVIEW OF THE MIRAVALLES GEOTHERMAL FIELD

The Miravalles Geothermal Field has reached 15 years under continuous exploitation, and it is still 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 completed the steam necessary to feed 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 produced for different periods, and one of them is still in operation.

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 tend to form carbonate scale 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).

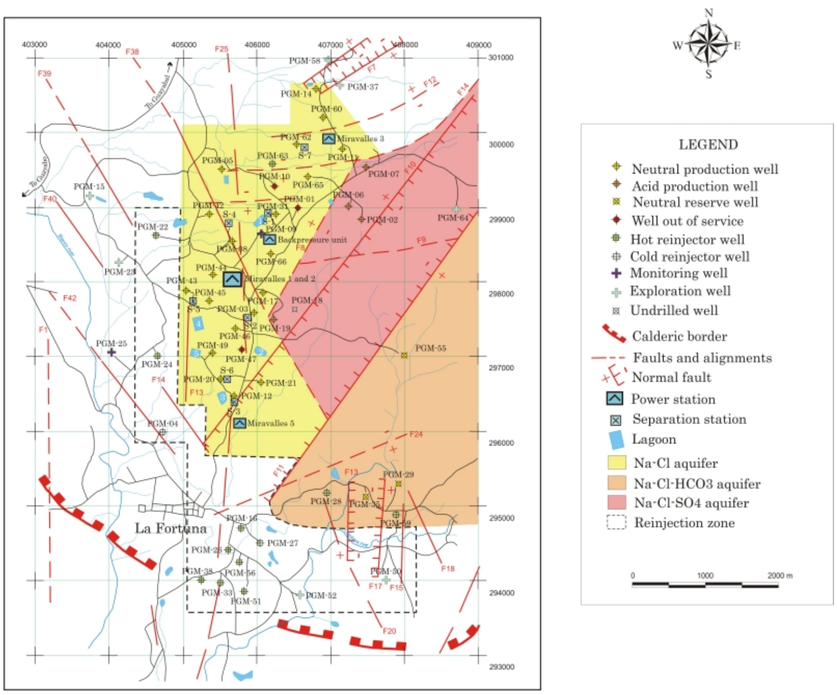

Figure 1: The Miravalles Geothermal Field Location and Facilities

Another important sector contains 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 are 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 the installed capacity of the reservoir in the future as knowledge of the reservoir increases.

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. INTRODUCTION

Prior to the beginning of exploitation of the Miravalles Geothermal Field, it was necessary to make use of statistical analysis in order to reduce the field data to polynomial equations that relate the mass flowrate and enthalpy to the wellhead pressure. This was done during the second half of 1993 and the beginning of 1994 (Bogarín and González, 2000 and González and Vallejos, 2010). These equations help to carry out five main objectives: 1- to facilitate the interpolation of massflow rates and enthalpies at every wellhead pressure of the well; 2- to do quicker calculations of the amount of steam available at each well; 3- to estimate the amount of steam delivered if some wells should be throttled under certain circumstances; 4- to do quicker calculations about the total non-condensable gas content sent to the power houses; and 5- to choose which spare wells must be produced and the amount of steam that must be supplied when a separation unit or well should be taken out of the gathering system.

During the first years of the field exploitation, the estimates of mass flowrate were normally represented through linear, quadratic and cubic correlations. However, the enthalpies were within a variability range of 40 kJ/kg, and there was no need for any correlation but an average.

The first attempt to calculate in a systematic mode the production of Miravalles was with a program written in the QUICK BASIC language during the first half of 1994 by the Reservoir Engineering Group (Geosciences Area). Improvements in the software were continuously done in order to develop a mass and energy balance program capable of generating a database. The objective was to systematically generate input decks for each single day of production and get in return individual output files for the production and injection data of each well, separation station and total production of the field in ASCII files. This information would be later used in the development of a mathematical model of the Miravalles reservoir (see Pham, et al, 2000 for reference on the numerical model).

The Geosciences Area was in charge of carrying out the flowrate calculations until 1997, when the Steam Supply Area took over the flowrate calculations. In doing so, the Field Operation Group belonging to the Steam Supply Area developed its own software based on the original algorithm made by the Reservoir Engineering Group but making use of other high level programming languages. However, from 1999 to 2001 changes in personnel did not allow further improvement in the calculation software and adapting it to the present and changing conditions left a gap in the processing of data. This situation forced the Reservoir Engineering Group to assume again the handling of information. These data were highly important because in 2001 the numerical model of the reservoir was conducted and updated (see Mainieri, et al, 2002 for reference on the updated numerical model).

Therefore, the Reservoir Engineering Group started to develop brand new software in 2001, making use of an innovative and flexible algorithm based on an ASCII input deck that summarizes the field configuration and allows adding a separation station or well to the modeled gathering system in such a way that no modifications to the software are necessary. The software was written in VISUAL BASIC 6.0 and the information was gathered in the commercial database MS ACCESS. Not only the Reservoir Engineering Group but also the Field Operation Group used the information generated from the steam field for their own purposes and needs.

The software has been systematically modified in order to comply with a series of requirements from the Steam Supply Group and also for the ongoing changes in the field configuration (topology) of new wells, separation stations and interchangeable pipelines connecting Miravalles I, II, III and V. Some examples of changes in the software are the addition of separation stations sending steam to other separation stations, the increase in pipeline infrastructure to supply geothermal brine to the binary power plant (bottoming cycle), and the successive increase in power plant structures. Besides the creation of the production software, there is an utility that operates in the intranet of the Centro de Servicio Recursos Geotérmicos (CSRG, Geothermal Resources Service Center) which makes use of the extensive database which contains all the relationships established for each output curve of the wells in Miravalles in order to give an estimate of production when is evaluated at certain wellhead pressure as shown in Figure 2.

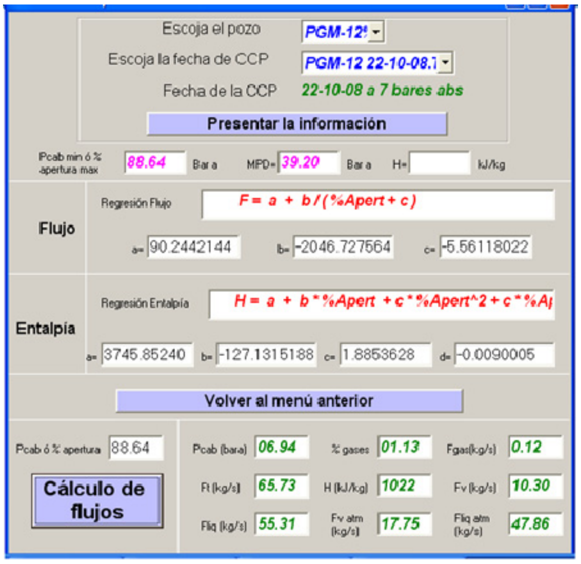

Figure 2: Example of the production calculation utility in the intranet.

With this application all the personnel involved in the production of Miravalles can do quicker calculations related to total, liquid and steam flowrates at wellhead pressures (% of opening of the lateral valve will be discussed later on), and the calculations can be done at atmospheric pressure when the discharges are sent to the silencer.

3. ESTIMATION OF THE PRODUCTIVE PARAMETERS IN WELLS

Added to the constant changes in the field production configuration, the Miravalles Geothermal Field have evolved through time and the characteristics of the production wells shifted smoothly making necessary the modification of the rules of calculation for the output curves. In the next sections this situation is described.

3.1 First Period: Constant Enthalpy (1994-2005)

Since the beginning of the exploitation of the Miravalles Field there has been an evaluation of each of the production wells at least once a year. This information is useful for observing the evolution of every single production well and the Miravalles field as a whole. The evaluation consisted of taking the production well out of the gathering system for 30 hours, preferably during the maintenance of the geothermal power plants and making use of the Russell James method (James, 1962) for production estimation purposes (González and Vallejos, 2010).

Liquid saturated, two phase and steam wells have been evaluated. During this period the wells at Miravalles showed enthalpy values constant enough to calculate the steam and power output as an average of the enthalpy, as mentioned before. As the reservoir evolves, the two phase wells have been increasing in number and the enthalpy difference between the maximum flow rate (MFR) and the maximum discharge pressure (MDP) increased by a significant amount.

3.2 Second Period: Variable Enthalpy (2006-2007)

After the year 2000, some wells at Miravalles started to show a variable enthalpy, and this condition became important, but the average production of wells did not affect the comparison between the calculated steam and the steam flowrate measured at the power plants. In the year 2005 however, there was a shift in the behavior of the steam calculated by output curves and the steam measured at the power plants and this made it necessary to change the calculation method.

Due to this, there was an important change in the calculation software to account for variable enthalpy. It was also necessary to modify the production calculation utility in the intranet (Figure 2) to account for changes in this parameter. It was also observed that running an output curve for wells once a year had become inadequate in certain cases .Some wells behaved smoothly, but others had important changes in mass flow rate and enthalpy. Once the changes were implemented, the estimations of steam delivered to the power houses were improved, but over a couple of years, there was a continuous increase in difference between the calculated steam by the output curves method and the processed steam measured at the power plants.

Studies were made in order to solve this problem and to get a closer agreement between the mass flow rates calculated by the output curves. At this point, the field counted on venturi devices to compare the steam supply to the power houses. From the point of view of the field engineers, these data were very valuable to properly check with steam measured at the power houses regardless of the differences present according to the calibration method of these devices.

It was found out that when considering the production with the opening of the side valve rather than the wellhead pressure, the agreement between both figures (estimated and measured) was better (see section 4). While making some changes again in the calculation software and running some simulations afterwards, it was necessary to use a different kind of curve which correlates the mass flowrate versus the percentage of the opening of the side valve (González 2007(1) and (2)) (see appendix A). According to the kind of valve and the total number of turns in the side valve, an empirical number can be calculated denoted as “percentage of opening”. This poses new cares that must be followed during the production test of a well, reflecting the fact that the main parameter (wellhead pressure) was changed by the percentage of opening.

When testing a well based on the wellhead pressure, it is a rule of thumb in actual practice to evaluate the maximum flow rate with the side valve fully opened. However, when using the percentage of opening, it is necessary to play with the side valve to detect at which point the throttling of the side valve starts to change the weirbox levels, wellhead and lip pressures. This point is when the maximum flowrate is established. Further opening of the valve does not change the amount of fluid producing to the silencer.

4. CALCULATING THE OUTPUT CURVE BASED ON THE % OF OPENING OF THE LATERAL VALVE VERSUS WELLHEAD PRESSURE AS A MAIN VARIABLE

Sometime after the development of the Variable Enthalpy Method for calculating the production of the Miravalles field, some doubts arose about the uncertainty of the data, especially in wells that showed some noticeable production decline. It was necessary after some tests (Appendix A) to recalculate the behavior of some wells because even though they were producing relatively steadily, they changed the wellhead pressure in a declining pattern during the year. To account for this effect, it was necessary to correct the output production calculation so that the constant decline in wellhead pressure did not affect the production, because it was observed according to the measurements of the power house venturi devices that the mass flowrate stayed steady.

The most direct way to account for that behavior was to consider that the opening of the side valve controls the process in principle. When establishing the % of opening, some simulations were taking into account and the conclusion was that this parameter is better suited to describe the phenomenon and to adequately keep pace with the steam supply amount delivered to the power house.

Prior to consider this new parameter, the difference between the steam supply calculated by the output curves method and the steam measured by venturies in some cases exceeded 15-18%. After beginning to use the new parameter, the difference was reduced to 5-8% maximum as had been the normal behavior during previous 12 years.

5. SOFTWARE FOR THE CALCULATION OF THE MIRAVALLES GEOTHERMAL FIELD PRODUCTION AND INJECTION

The software developed for running these calculations has been developed to fulfill the needs of the areas involved in the exploitation and modeling of the Miravalles Geothermal Field and has been evolved according to the evolution observed without it being necessary to modify the code each time the configuration of the field changes (González, 2001 through 2008).

In Figure 3 is shown an input deck of only one separation station producing to the Power House 1.

```
Campo Geotermico Miravalles
PRODUCTORES
SAT-02 PGM-03
SAT-02 PGM-17
SAT-02 PGM-66
COLECTORES
SAT-02 COL-04 1.00
INYECTORES
COL-04 PGM-24 1.00
CCPPRODUCTORES
PGM-03 27-10-07.TR3
PGM-17 03-11-07.TR3
PGM-66 27-11-07.TR3
BINARIA
1   3        1- SIN PLANTA BINARIA 2- CONDENSACION + BINARIA 3-
BINARIA
COL-01 OEC-11 0.43 158.0 143.0 08.36 08.18
COL-01 OEC-21 0.32 162.0 138.0 08.65 08.17
COL-01 OEC-22 0.25 162.0 136.0 08.68 08.23
CASAMAQUINASSATELITES
CMA-01 SAT-02 1.00
CONTENIDOGASESPOZOS
PGM-03 REG
PGM-17 REG
PGM-66 REG
FINDEARCHIVO
01-01-2008
02-01-2008
00:00
00:00
SAT-02
 6.64, 24, 0
PGM-03
 59, 8.44, 24, 0
PGM-17
 36, 11.14, 24, 0
PGM-66
 41, 12.54, 24, 0
PGM-24
 5.64, 24
```

Figure 3: Example of a configuration for one separation station at Miravalles.

The input deck is divided into sections. The first row defines the geothermal field name. The second row is the “productores” section that indicates which separation station each well is producing to. In the present example there is only one separation station shown for presentation purposes.

The “colectores” section specifies which separation stations the water collectors are connected to. The number “1.00” represents that all the water from the separation station is collected in “colector4”.

The “inyectores” section shows how the collectors are related to the injection wells. The number “1.00” indicates that all the water from the collector is injected into well PGM-24.

The section “CCPProductores” indicates which output curves are being used to make the calculations. Each line has the format: well, day, month and year of the output curve.

The “Binaria” section correlates different modules of the Miravalles bottoming cycle with each one of the collectors of water or steam at the separation stations. Each cycle can generate electricity according to a previous input correlation. The figures in each row indicate: collector, module involved generating electricity, input and output temperature (°C) and input and output pressure (bar abs).

The section “casamaquinassatelites” relates how the steam of the separation stations is converted to power in each of the power plants according to the actual consumption index, which has been previously input. There is a percentage involved which indicates that a separation station (satellite) can supply steam to various power houses.

The section “contenidogasespozos” relates the total amount of non-condensable gases (NCG) in the steam for each of the production wells. This allows not only simulation of the electric generation produced by the power houses but also simulation of the total gas content to be sent to the power houses in accordance with the available NCG extraction system. In the case of the Miravalles Geothermal Field this element poses an important constraint in the system (Sánchez, 2009), since the NCG have a significant influence on the electrical generation (ICE is actually looking to increase the NCG processing installed capacity). The word “reg” indicates that the program takes the percentage of non-condensable gases from the server correlations, but it is also possible to input any valid NCG percentage to account for a certain condition.

The word “findearchivo” indicates that the topology of the system has been input, and now the operation conditions must be input as well.

The next 4 rows represent the date and time (beginning and end) of production or injection based on a 24 hour base.

The following two rows state the name of the separation station, amount of time spent delivering to the power house and amount of time venting to the atmosphere.

Afterwards, in two consecutive rows comes the name of the production wells, the percentage of opening of the side valve, the wellhead pressure, time spent delivering to the separation station and time spent venting to the atmosphere. At the end of the file is written in two consecutive rows information from the injection wells: wellhead pressure and injection time.

The software works by making the calculations on a 24 hour base. The times in each well and separation station must add up to 24 hours. If the sum is less than 24 hours it means that the well or separation station was closed for the remaining time.

In Figure 4 can be seen the output of the Miravalles mass and energy balance for the example of one separation station shown in Figure 3, representing the operational conditions set for the first of January of 2008.

6. RESULTS FROM THE NEW TYPE OF CORRELATIONS

Two important changes in the way the output curves are reported in Miravalles were: 1- accounting for variable enthalpy and 2- taking into account the % of opening of the side valve. The results can be seen in Figures 5 and 6.

When comparing the steam measured in the venturies (steam delivered) and the steam calculated by the output curves method, the average difference was of 5.6% with a standard deviation of 1.9% for the average steam supplied to the power houses during the year 2008. It is important to notice that the steam delivered should be less than the calculated due to a restriction effect at some separation stations because the total mass flowrate delivered from the wells exceeds the design value.

BALANCE DE MASA BASADO EN CCP PARA EL Campo Geotermico Miravalles
TOMANDO EN CUENTA EL CO2

entre el 01-01-2008 a las 00:00 y el 02-01-2008 a las 00:00

Pozos del SAT-02

	% Aper valv o Pcab (% ó Pcab)	Flujo Total (kg/s)	Entalpia (kJ/kg)	Contenido gases %P/P
PGM-03	59	28.78	1193	1.650
PGM-17	36	50.43	1018	0.600
PGM-66	41	55.01	1339	0.980

SAT-02

Psep (bar a)	Ft (kg/s)	Fl (kg/s)	Fv+Fg (kg/s)	H (kJ/kg)	H'CO2 (kJ/kg)	X	%Gases %P/P
6.64	134.2	102.1	32.0	1187	1179	0.236	1.033

Pozos inyectores

	Presion Cabezal (bar a)	Flujo inyect. (kg/s)
PGM-24	5.64	102.1

Flujos totales del Campo Miravalles a C.M.
(el líquido reportado es de la inyección en caliente)

Flujo total (kg/s)	Flujo líquido (kg/s)	Flujo vapor (kg/s)
134.2	102.1	32.0

Flujos de vapor distribuidos a las diferentes C.M.

Casa de máq.	Flujo liq o vap (kg/s)	Potencia (MWe)	Gases incondensables % P/P
CMA-01	32.02	14.42	1.033

Figure 4: Output of the Miravalles mass and energy balance for 01-Jan-08.

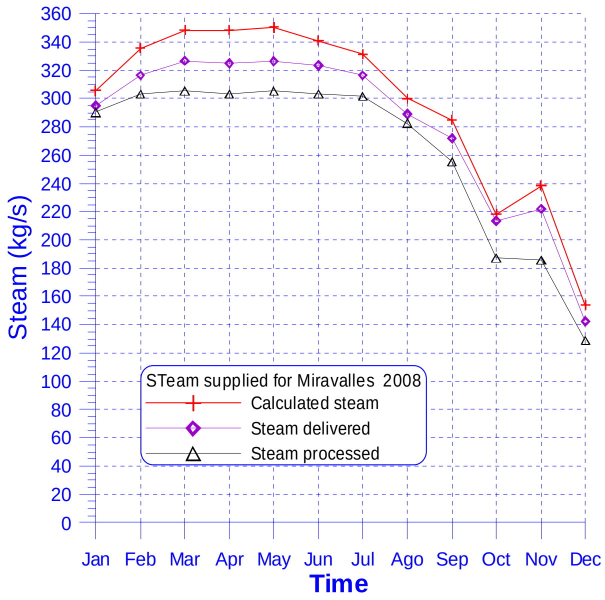

Figure 5: Steam supplied to the power houses at Miravalles 2008 (Nietzen, 2009(1)).

In Figure 6 there is a comparison between the water flowrate measured and calculated for the first four months of 2009.

It can be seen that in a couple of measurements the water measured is higher than the water calculated, but these are exceptions. The water calculated is higher than the water measured at an average value of 5.5% with a standard deviation of 4.7% for the first four months of 2009.

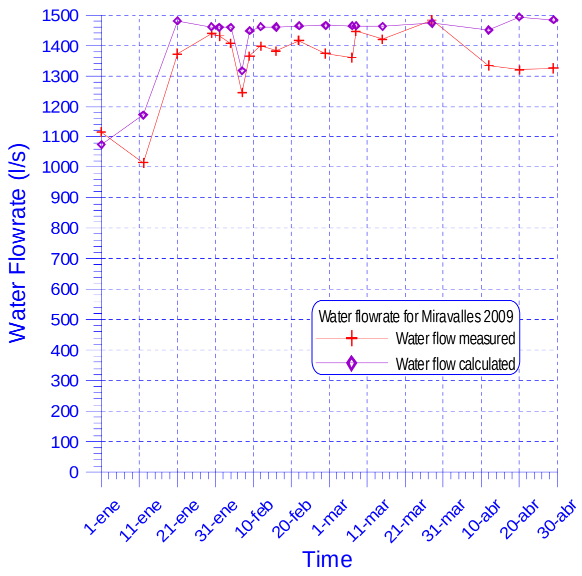

Figure 6: Comparison between the water measured and calculated at Miravalles 2009 (Nietzen, 2009(2)).

7. CONCLUSIONS

The production parameters of the Miravalles Geothermal Field have evolved through the years. This has forced changes in the calculation methods applied to estimate the power output in order to keep pace with the measured steam. These calculations are performed in order to have an independent method of checking the accuracy of the venturi devices.

During the first decade of the field production, the constant enthalpy approach was good enough to calculate the steam produced by the wells with an adequate degree of accuracy. The wells were considered to produce at a constant enthalpy rather than a variable one.

After that, the normal evolution of the wells to two phase production due to continuous mass extraction and the increase in the difference between the measuring devices and the calculation methods made it necessary to develop a modified method to maintain a good degree of accuracy in the estimation of the steam supplied to power houses from the Russell James method.

Therefore, it was necessary to consider variable enthalpy as a method of improving the accuracy of estimating the steam at different operation conditions. Later on, it was necessary to reconsider the method again because there was an additional increase in the amount of deviation between the steam calculated and the amount processed by the power houses.

To improve the method some observations were made and it was found that the throttling of the side valve provided better results than the wellhead pressure as the main parameter. At this point, the calculation method was improved by also taking into account the non-condensable gas content and doing simulations of the amount of gas to be sent to the power houses.

So far the method and the calculations made by the developed software show a good agreement with the measured steam and have proven to be a good tool for measuring the mass production, checking the consistency of the venturi devices, and for maintaining a recorded history of the field's production.

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APPENDIX

During October-2006, one of the power houses was set off line for maintenance purposes and then integrated to the national electric power grid. At that moment, it was performed a comparison between different correlation methods (González 2007(2)).

The curves represented in Figure A.1 were worked out taking into account the wellhead pressure as main variable (in blue), the % of opening of the side valve at constant enthalpy (in purple), the % of opening of the side valve at variable enthalpy (in green) compared all of them against the steam supplied to the power houses (in red) and some differences can be noted.

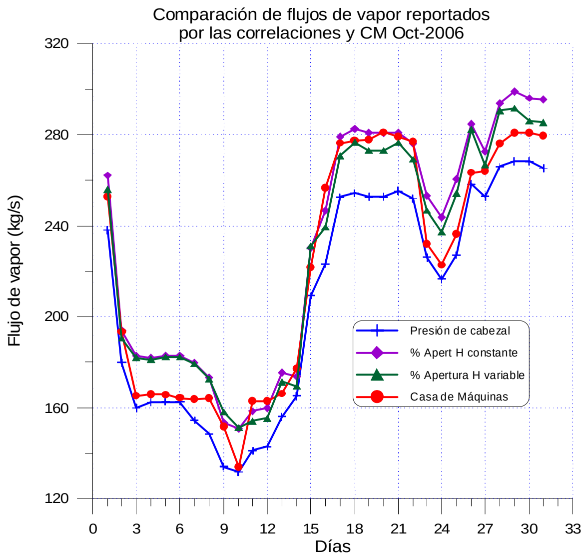

Figure A.1.: Steam data comparison between methods in October-2006 (González 2007(2)).

As can be seen, the correlations that take into account the % of aperture bring about closer data related to the power house steam consumption than the wellhead pressure as a main variable and yield to data above the power house steam consumption in an opposite way than wellhead correlations do.