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On Line Determination of Production Curves of Producing Geothermal Wells, from Separation Station Flow Data Where Several Wells Converge (Miravalles Geothermal Field)

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ABSTRACT

There are 7 separation stations at the Miravalles Geothermal Field (Costa Rica). Each station is fed by 3 or more producing wells. It is possible to determine a wells production curve on line, if steam and water flow from the separation station are analyze. For the determination of the curve, the conditions of the well production under study must change, and maintain productivity with another well (or wells) from another separation station. An analysis of the differences in the flow from each station, estimates the relative contribution of the well (brine and vapor), the enthalpy, and therefore the production curve. The analysis can be complemented by geochemical studies (e.g. gases) at different flow conditions, while the well is in production.

1. INTRODUCTION

The Miravalles geothermal field is located in Costa Rica. It has about 52 geothermal wells, of which 29 are producers, 14 reinjectors and the rest are monitoring wells. The field produces fluids in two phases: 330 kg/s of steam and 1350 kg/s of brine. With those fluids it has the capacity to generate 158 MW.

Fluids from producing wells are sent to seven main separation stations. The steam and brine are separated in these stations. Each station has 2, 3 or more related wells. The Figure 1 shows a diagram of wells corresponding to the separation station 2 (SAT-02) and separation station 5 (SAT-05).

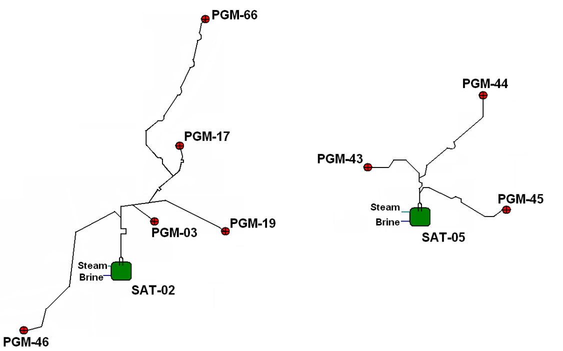

Figure 1: Diagram of the separation stations 2 and 5 with associated wells.

All producing wells have different characteristics, both chemical as thermohydraulics. The well is withdrawn for evaluation purposes in determinate periods. James is the method used for evaluation of the wells, together with geochemical and other thermohydraulics studies. However, it is possible to generate a characteristic production curve per well, from the total flows of the separation station in question, provided that certain conditions are met.

The wells PGM-17 (separation station 2) and PGM-45 (separation station 5) were evaluated simultaneously from the station flows. The results will be discussed in the subsequent sections.

2. OVERVIEW

The James' method involves a total withdrawn of the production well. The well is retired from the system during its evaluation for about 1.5 days. The geothermal fluids are not used for generation purpose during this time, but these are discharged directly into the atmosphere. Furthermore, it is not always possible to retire the well to evaluate (because of the production, or problems in the discharge system, among others).

The productivity measurement of a well is possible, on the basis that the total flows of the separation station met some conditions. This method has some advantages:

- the wells are not withdrawn from production, during most of the evaluation time (better utilization of resources)
- it is possible simultaneous evaluations of two or more wells (different stations)
- it considers the particular conditions of the interconnected system (transport losses, influences of other wells in the station, system pressure, etc.)

2.1 Conditions of the Flow Differences Method

This method is based both in differences in steam flows as in brine flows, monitored at the separation station, after each change in status of a production well. For its implementation, it is necessary to meet the following conditions:

- There must be at least two separation stations, and the wells must be evaluated in different stations.
- Reposition recourse. This is important to keep a constant generation in geothermal power plants. At the same time, this reposition should be acceptable in terms of quantity and quality. Conditions of steam with higher content of gases, could affect the generating units. In addition, the reposition wells should not be in the same separation station of the testing well (reposition wells could be other testing wells). It is possible to make such determinations without reposition recourse, reducing the generation.

- Constant pressure throughout the system. The system pressure should be constant in order that the separation of both phases remains as invariant as possible. The system pressure will tend to be constant when the fluids are reset from other wells. On the other hand, it is possible to keep constant pressure from a separation station, increasing the pressure of separation a little more than the steam collector pressure (about 0.5 bar), using the steam valve. The pressure should be kept through all points.

- Stability of the Field. It should not have any operations, at least in other wells connected to the same separation station of the well being tested. Otherwise, the data obtained would not be valid.

- Equipment calibration. The equipments should be calibrated, both the station Venturi as the ultrasonic flowmeter.

- Separation station average conditions of thermodynamic variables. In steady-state (invariant conditions in time), the parameters of the mixture into separation station are considered as an average from individual contribution of each producer well, see equation (1). The steam fraction of the station is estimated indirectly with the separation pressure. With this pressure it calculates the enthalpies in the liquid and steam phase (equation (2)). This fraction (quality) is also applicable to individual producing wells, therefore, it is essential to have constant pressures in the system to keep the fraction invariant and therefore the enthalpies

$$\Delta H_{mixture} = \frac{\sum_{i=1}^{n}(Ft_i \cdot \Delta Ht_i)}{\sum_{i=1}^{n} Ft_i} \tag{1}$$

where:
Ft_i = Total flow of the well "i", kg/s
ΔHt_i = Mixing enthalpy of the well "i", kJ/kg
$\Delta H_{mixture}$ = Mixing enthalpy of the separation station, kJ/kg

$$x = \frac{\Delta Hl - \Delta H_{mixture}}{\Delta Hl - \Delta Hv} \tag{2}$$

where:
x = Steam fraction in saturated conditions, steam mass flow / total mass flow
ΔHl = Liquid phase enthalpy according to pressure separation (or temperature), kJ/kg
ΔHv = Steam phase enthalpy according to pressure separation (or temperature), kJ/kg
$\Delta H_{mixture}$ = Mixing enthalpy of the separation station, kJ/kg

2.2 Flows in Separation Stations

<u>2.2.1 Steam Flow Measurement</u>

The Venturi equipment is used for steam flow measurement. It is located at each station. The steam flow (kg/s) is recorded in a database. The equation used is:

$$q_{kg/s} = \frac{\pi}{4}\sqrt{2g_c} \cdot \frac{CY_1 d_f^{\,2}}{\sqrt{1-\left(\frac{d_f}{D_f}\right)^4}} \cdot \sqrt{\rho f_1} \cdot \sqrt{\Delta P} \tag{3}$$

where:
$q_{kg/s}$ = Mass flow, kg/s
g_c = Constant with a value of 1.0 Kg•m/(N•m2)
C = Discharge coefficient, dimensionless
Y_1 = Expansion factor of the gas through the reduction, dimensionless
d_f = Internal diameter of Venturi neck at operating conditions, m
D_f = Pipe diameter upstream of Venturi at operating conditions, m
ρ_{f1} = Steam density in the neck zone at operating conditions, kg/m3
ΔP = Pressure difference measured by venture, Pa

The Venturi has a smart multivariable transmitter. The transmitter automatically calculates all the variables in equation (3) and reports the flow value. However, it does external calculations for corroboration.

<u>2.2.2 Brine Flow Measurement</u>

It uses ultrasonic equipment for the brine flow measurement. This measurement is not continuous. The operators should be located with the equipment in the water pipe of each separation station to take measurements at an interval of time. The computer records the data during the study period. The data are processed later.

2.3 Methodology of Flow Differences Measurements in Separation Stations

<u>2.3.1 At the Beginning</u>

The testing well should be run in a condition of maximum production, preferably. Then the reposition well (testing well 2) should be restricted.

The pressure of separation station must have such a value that keeps it constant under each variation of the well. For this, the steam valve should have the ability to keep a stable pressure value. The pressure should be monitored on a regular basis and adjust it if there are significant changes. Variations in the steam collector pressure may change the separation pressure.

It must have a record of the initial state. The variables must be stable at all times (pressure, temperature, flow of both liquid and steam, gases, etc.).

<u>2.3.2 During Evaluation</u>

The flow testing well is reduced a rate of 0.5 to 1.0 bar during the determination of each point. Furthermore, the flow reposition well is increased to keep production in the generating units. With this, the system pressure should keep constant. On each restriction (and increase) it should ensure the stable condition in the separation station (keeping pressure constant). It should be given a reasonable time between each restriction (and increments) to stabilize the system (pressure, temperature, flow of both steam and liquid and gas, etc.).

2.3.3 In the End

The testing well should be completely reduced at the last point. After this point, the well is withdrawn from production to the silencers, about two hours.

It should ensure the stable condition in the separation station (keeping constant pressure).

The total withdrawn provides the productive values base of the well. It is not necessary to stabilize the system over long periods. With two hours is sufficient to obtain a representative value.

After two hours, it can proceed with the integration of the well and return to the original conditions.

2.3.4 Data Processing

With each reduction of the well, it sets new values of flow in the separation station. By restricting the well both the flow of steam as the liquid flow at the station would be decreasing. If the pressure decreases, this effect can be compensated in two ways: increased flow of another well (at another separator), and the other way it is through restriction of the station valve. When the well is totally withdrawn, the station would have flows from the other wells. This is the principle of determining flow well:

- each operating point of station, it must subtract the flow of the station when the well is totally withdrawn. This subtraction will represent the contribution of the well according to its operation status, defined by the pressure head (and/or opening percentage)

3. RESULTS AND DISCUSSION

The wells PGM-17 (separation station 2) and PGM-45 (separation station 5) were handled in August 2008 in order to determine their productivity. The diagram of the stations with the respective wells can be seen in Figure 1.

When the flow of PGM-17 was reduced at each point, the PGM-45 was increased to keep the electrical generation units, until the total withdrawn of the well PGM-17. This process took one day for every operating point. The Figure 2. shows the steam flow at the concerned stations. In the same Figure is evident the constant pressure stations in time. When the well PGM-17 is integrated again, it reverses the process: gradually increase the flow of the PGM-17 and reduce the PGM-45 at shorter time intervals (half a day). Also, the well head pressures from separation stations 2 and 5 keep themselves constant, except for wells PGM-17 and PGM-45 (Figure 3).

The liquid flow was determined at intervals of 1 to 1.5 hours each day. The Figure 4. shows a sample of fluid flow corresponding to the day August 31, for the separation stations 2 and 5. The equipment reading is in liters per second, it should be multiply by the density (depending on pressure and temperature) for flow in kg/s.

The graphs of Figures 2. and 3. show variations in flow (separation stations 2 and 5) and head pressures (wells PGM-17 and PGM-45) at different time intervals, respectively. The average values of pressure and flow for each operating point are shown in Table 1.

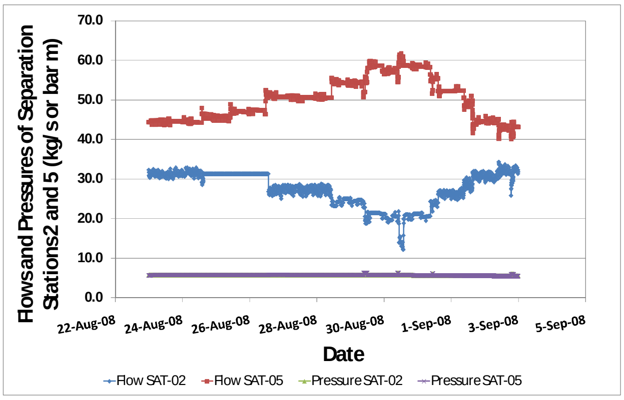

Figure 2: Steam flows and pressures of the separation stations 2 and 5 for the wells evaluation PGM-17 (SAT-02) and PGM-45 (SAT-05).

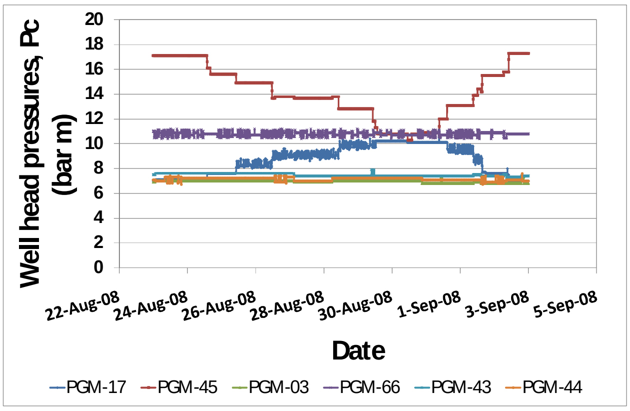

Figure 3: Head pressure of the wells associated with the separation stations 2 and 5 (Figure 1.), incorporated in the study period (late August 2008).

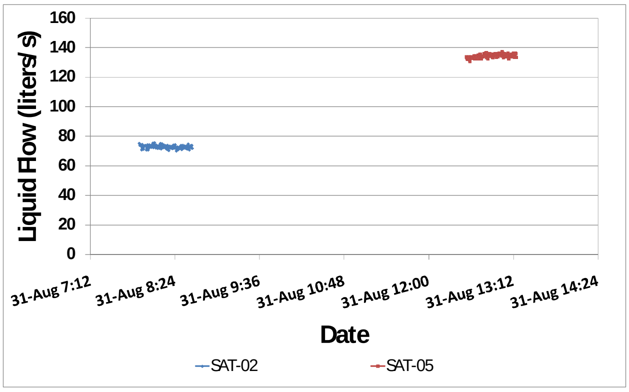

Figure 4: Example of liquid flow from separation stations 2 and 5 for August 31, 2008, during the wells evaluation PGM-17 (SAT-02) and PGM-45 (SAT-05).

To get flows from wells PGM-17 and PGM-45 it is necessary to do the subtraction: the flow values (in the Table 1) subtracted to the flow value of the specific station when the well is withdrawn completely. This way, the flows from wells are obtained. The data are tabulated in Table 2.

The data of flows show a tendency, regardless if the well is being reduced or increased to obtain the data. The Figures 5. and 6. show the tendency in the flows.

Table 1: Average values of parameters according to Figures 2 and 3.

Operation Point PGM-17 Point and (opening percent)	***Head Pressure Pc (bar m)***		***Steam Flow Separation Stations Fv (kg/s)***		***Liquid Flow Separation Stations Fl (kg/s)***		***Total Flow Separation Stations * Ft (kg/s)***	
	PGM-17	PGM-45	SAT-02 (PGM-17)	SAT-05 (PGM-45)	SAT-02 (PGM-17)	SAT-05 (PGM-45)	SAT-02 (PGM-17)	SAT-05 (PGM-45)
0 (100%)	7.1	17.1	31.3	44.5	129.1	105	160.4	149.9
1 (75 %)	7.6	15.7	31.2	45.7	125.2	89	156.4	134.9
2 (60 %)	8.3	14.9	29.5	49.0	119.1	98	148.6	147.3
3 (51 %)	9.1	13.7	27.4	50.7	99.9	110	127.2	161.0
4 (42 %)	9.9	12.8	24.3	54.3	95.5	123	119.8	177.1
5 (32 %)	10.2	10.8	20.7	57.9	72.7	138	93.4	195.4
Withdrawn (0%)**	---	10.3	13.8	60.9	37.9	148	51.6	208.5
-5 (32 %)	10.1	10.9	20.7	58.6	72.8	148	93.5	206.4
-4 (40 %)	10.1	12.0	23.6	55.2	82.6	134	106.2	189.5
-3 (47 %)	9.5	13.1	26.3	52.2	102.5	118	128.8	170.1
-2 (57 %)	8.6	14.2	28.6	49.0	117.4	122	146.0	170.9
-1 (72 %)	7.6	15.6	30.6	44.5	126.8	93	157.4	137.3
0 (100%)	7.0	17.3	31.8	42.9	133.7	92	165.5	135.0

* The total flow is obtained by adding the steam flow and liquid flow according to the operation point

** Flow of the separation station 5 with PGM-45 completely retired: Fv = 17.9 kg/s and Fl = 90 kg/s

Table 2: Flow values of wells according to analysis of separation stations

Operation Point	PGM-17				PGM-45			
	Reducing the well				Increasing the well			
	Head Press. Pc (bar abs)	***Steam Flow*** Fv (kg/s)	***Liquid Flow*** Fl (kg/s)	***Total Flow*** Ft (kg/s)	***Head Press. Pc (bar abs)***	***Steam Flow*** Fv (kg/s)	***Liquid Flow*** Fl (kg/s)	***Total Flow*** Ft (kg/s)
0	8.04	17.6	82.6	100.1	18.04	26.6	0.0	26.6
1	8.54	17.4	79.1	96.5	16.60	27.8	0.0	27.8
2	9.21	15.8	73.5	89.3	15.84	31.1	7.5	38.6
3	10.03	13.6	56.1	69.7	14.68	32.8	18.4	51.2
4	10.81	10.5	52.2	62.7	13.74	36.4	29.7	66.1
5	11.14	6.9	31.6	38.5	11.74	40.0	43.0	83.0
---	Increasing the well				Reducing the well			
0	7.94	18.0	86.8	104.8	18.24	25.0	1.9	26.9
-1	8.55	16.8	80.5	97.3	16.49	26.6	2.5	29.1
-2	9.58	14.9	72.0	86.9	15.09	31.1	28.9	60.0
-3	10.46	12.5	58.5	71.0	14.04	34.3	25.2	59.5
-4	11.04	9.8	40.5	50.3	12.94	37.3	40.2	77.4
-5	11.04	6.9	31.6	38.5	11.80	40.7	52.3	93.0

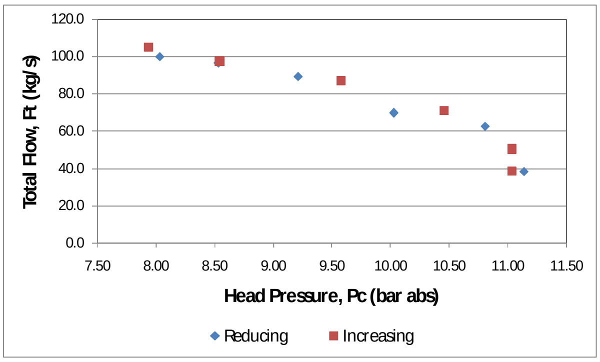

Figure 5: Flow tendency of the well PGM-17.

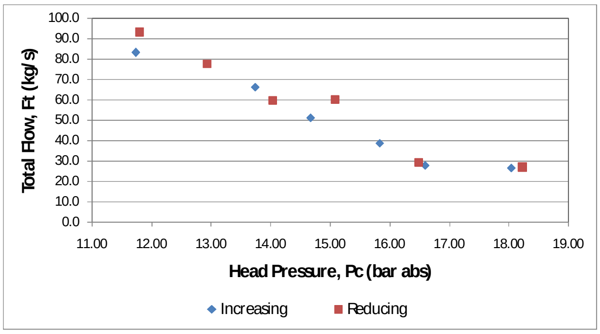

Figure 6: Flow tendency of the well PGM-45.

The final productive curves are shown in Figures 7. and 8. for the wells PGM-17 and PGM-45, respectively. Some data can be eliminated statistically to improve the curve. To determine the equation of the curves, the method of least squares is used in different forms of equations (linear, logarithmic, Antoine, quadratic, etc.). Table 3 summarizes the variables in the best fit equations applied to each well.

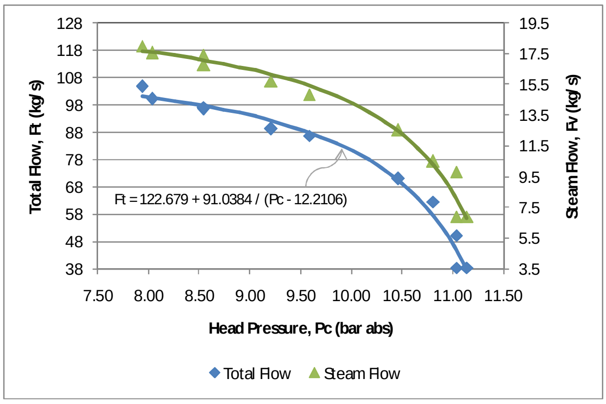

Figure 7: Productive curve of the well PGM-17.

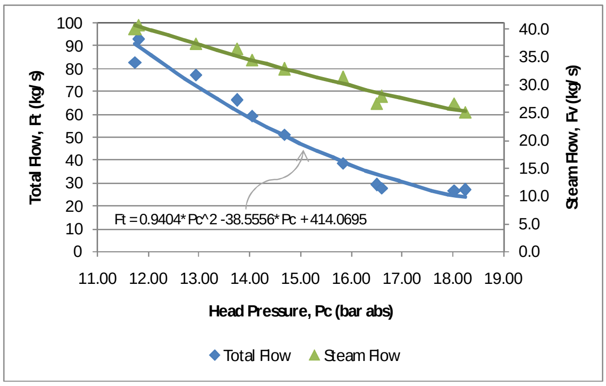

Figure 8: Productive curve of the well PGM-45.

Table 3: Parameters of best fit equations, for determining the total flow per well

Well	PGM-17	PGM-45
Type of Equation	Antoine	Quadratic
Form	$Ft = A + \frac{B}{Pc + C}$	$Ft = A \cdot Pc^2 + B \cdot Pc + C$
Value A	122.679105	0.94044548
Value B	91.038438	-38.5556513
Value C	-12.2106175	414.069582

Enthalpy and Gases

Among the assumptions is to keep a constant pressure in the separation station. This helps calculating the enthalpy of the well according to the head pressure. For this, the equation (2) is changed to:

$$\Delta H_{mixture} = x(\Delta Hv - \Delta Hl) + \Delta Hl \tag{4}$$

where:
x = Steam fraction in saturated conditions, steam mass flow / total mass flow
ΔHl = Liquid phase enthalpy according to pressure separation (or temperature), kJ/kg
ΔHv = Steam phase enthalpy according to pressure separation (or temperature), kJ/kg
$\Delta H_{mixture}$ = Mixing enthalpy of the well, kJ/kg

If the steam fraction obtained under conditions at the station is high, the value of the well enthalpy will also be high.

In the case of a separation pressure of 5.6 bar manometric (6.54 bar absolute) and a saturated condition (Perry, 1999):

- ΔHl = 685.4 kJ/kg
- ΔHv = 2760.3 kJ/kg

For point 0 (initial) of the well PGM-17:

Fv = 17.6 kg/s

Ft = 100.1 kg/s

With x = Fv/Ft = 17.6 / 100.1 = 0.175

Then:

$\Delta H_{mixture}$ = 0.175 * (2770.3 kJ/kg – 685.4 kJ/kg) + 685.4 kJ/kg = 1049 kJ/kg

The enthalpy calculations are repeated for all operating conditions. The summary of this variable is shown in Tables 4 and 5, PGM-17 and PGM-45 respectively. The enthalpy of the well PGM-17 could be considered constant (average of 1049 kJ / kg). However, it is not the same situation for the well PGM-45, when the well is reduced the enthalpy is increasing, until it produces only steam.

Other variables may be considered during the evaluation of the wells on line, such as gases, associated with the quality of steam. Gas data during the evaluation are shown in Table 6.

Graphics of enthalpy and gas are shown in Figure 9. Both the enthalpy and gas remain constant in the PGM-17 throughout operational points, but the enthalpy and gases are increased by reducing the well PGM-45. These variations in enthalpy and gases are considered in the balance sheet at the time of scheduling the production of fluid to the generating units (Suwana, 1991).

Table 4: Summary data, well PGM-17

Head Pressure Pc (bar abs)	Steam Flow Fv (kg/s)	Liquid Flow Fl (kg/s)	Total Flow Ft (kg/s)	Enthalpy H (kJ/kg)
7.94	18.02	86.79	104.81	1042.11
8.04	17.56	82.59	100.15	1049.20
8.54	17.43	79.10	96.53	1060.05
8.55	16.80	80.49	97.29	1043.67
9.21	15.75	73.52	89.27	1051.55
9.58	14.85	72.01	86.86	1040.21
10.46	12.54	58.49	71.03	1051.78
10.81	10.51	52.18	62.69	1033.24
11.04	6.93	31.62	38.54	1058.31
11.04	9.84	40.49	50.33	1090.94
11.14	6.93	31.57	38.49	1058.76
			Average	1049
			Deviation	9

Table 5: Summary data, well PGM-45

Head Pressure Pc (bar abs)	Steam Flow Fv (kg/s)	Liquid Flow Fl (kg/s)	Total Flow Ft (kg/s)	Enthalpy H (kJ/kg)
11.74	39.96	43.03	82.98	1684.51
11.80	40.66	52.32	92.98	1592.76
12.94	37.26	40.17	77.43	1683.84
13.74	36.43	29.69	66.12	1828.64
14.04	34.35	25.17	59.52	1882.77
14.68	32.76	18.40	51.16	2014.11
15.84	31.14	7.49	38.63	2357.95
16.49	26.63	2.47	29.10	2584.39
16.60	27.82	0.00	27.82	2760.28
18.04	26.62	0.00	26.62	2760.28
18.24	24.97	1.91	26.88	2612.83

Table 6: Gases during the evaluation of wells PGM-17* and PGM-45

Head Pressure Pc (bar abs)	Gases in PGM-45 (% p/p)
14.94	1.71
13.94	1.67
12.24	1.49
12.14	1.44

* gases of the well PGM-17 practically constant during the evaluation, 0.47 % w/w (Sánchez, 2008)

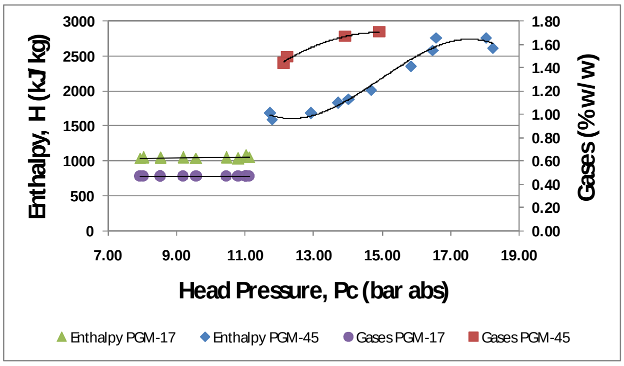

Figure 9: Enthalpy and gases during the wells evaluation PGM-17 and PGM-45.

4. CONCLUSIONS

This method considers the fluid energy losses that occur during transport from the well to the separation station. Also, the effect on the system (other wells, separation stations, steam collector, plants, etc.) is taken into account.

Steam and liquid graphs are obtained independently, which can relate-graph in order to observe their behavior. If the curves are not parallel at all, it means that there is a change in enthalpy of the well according to its operational; greater steam fractions could exist according to head pressure of the well. This might be closely related to higher gas production.

The method also allows simultaneous evaluation, under the policy of resource replenishment. While a well is reduced, other well could gradually increase its flow, performing the same analysis for the determination of points, on a reverse way.

The testing wells were so different. One of them (PGM-17) had a stable condition throughout the operational points (enthalpy, gas, it always produced two phase fluids). Furthermore, the other one (PGM-45) increased the enthalpy and gases when it was reduced (at one point it only produces steam). Despite these differences between the wells, the method gives acceptable results. However, the plant conditions varied somewhat, as well as reinjection fluids to the wells reinjectors.

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