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EXERGY ANALYSIS FOR THE AHUACHAPAN AND BERLIN GEOTHERMAL FIELDS, EL SALVADOR

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ABSTRACT

This paper in based on the results obtained from the exergy analysis done in the Ahuachapán and Berlín geothermal fields. Plotting the thermodynamic conditions of both fields on the Molliere diagram and computing the specific exergy index (SEI) the fields are classified on the medium high exergy zone. Also, the analysis of the characteristic curves by comput the utilization efficiency ratio at higher wellhead pressure related to the maximum flow conditions, indicates that higher wellhead operation can improve the thermodynamics in a production well. The study of the output characteristics curves from all the production wells in the Ahuachapán field, shows that the low enthalpy wells AH-1 and AH-24 can improve its thermodynamic conditions if they operate under higher pressure. The utilization energy (exergy) at wellhead conditions has been considered to compute the utilization efficiency (η_u) of the geothermal field power plant system instead of the extracted thermal energy. The reported production data over 1998, gives a values of 41 % for Ahuachapán (condensation system). As comparisson, in the Berlín geothermal field where two wellhead unit of 5 MW (back pressure system) are operated, is observed a utilization efficiency of 21 %.

1. INTRODUCTION

Currently the Ahuachapán Geothermal Field (AGF) has 16 production wells with an average wellhead pressure (WHP) of 6.4 bar-a. A total mass flow capacity around 783 kg/s is gathered with a double flash system into a geothermal plant of an installed capacity of 95 MW. Using the total flow capacity, the output power performed by the power plant is approximately 82 MW, which represents 86 % of the total capacity. In the long term it is not possible to operate at this output because the productive wells are located in an area of about 1 km^2 (Fig. 1). This limitation originates a concentrated mass extraction provoking a great pressure drop in the reservoir that could affect the operation of some production wells.

The experience gathered in field operations and the results from the lumped modeling of the geothermal system shows that a stabilization in the reservoir pressure can be reached if it is worked with a mass extraction of about 410 kg/s (Quijano J., 1994). Generally, the field is operated with this mass extraction using the high enthalpy wells maintaining the reservoir pressure (200 m a.s.l.) close to 19.5 bar. This field management limits the output power to 55 MW and the utilization factor to 58 %. To increase the utilization factor, CEL is rehabilitating of the power plant, planning the reinjection of residual water into the Chipilapa area (Fig. 1) and expanding the extraction area drilling 9 wells at the southern part of the actual geothermal field (ELC, 1993).

This work explores the possibility of increasing the utilization factor by improving the thermodynamic conditions in the low enthalpy wells using higher WHP operation. The study is based on the analysis of the output characteristic curves of a production well computing the ratio of the utilization efficiency at higher WHP to the utilization efficiency at the lowest pressure conditions (maximum discharge).

2. BASIC CONCEPTS

Exergy is a measure of the maximum useful work that can be done by a system interacting with an environment which is at a constant pressure p_o an temperature T_o. The simplest case to considered is that of a reservoir with a heat source of infinite capacity and invariable temperature T_o . It has been considered that the maximum efficiency of heat withdrawal from a reservoir that can be converted into work is the Carnot efficiency (Rogers, 1980). Then, the availability of a reservoir at T_o providing a rate of heat transfer Q, in a surrounding at To can be obtained by starting with the first law as follows (Freeston, 1991):

$$\dot{Q} - \dot{W} = \dot{m}(h_1 - h_0) + \tfrac{1}{2}(v_1^2 - v_0^2) + g(z_1 - z_0) \qquad (1)$$

where Q = heat flow rate
W = rate of work
m = mass flow rate
h = enthalpy
v = velocity
z = vertical position

Neglecting the changes in kinetic and potential energy

$$\dot{Q} - \dot{W} = \dot{m}(h_1 - h_0) \qquad (2)$$

The second law for open systems is

$$\dot{\Theta} = \dot{m}(s_1 - s_0) - \frac{\dot{Q}}{T_0} \qquad (3)$$

where s is the specific entropy, T_o is the temperature of the surrounding and Θ is the entropy production, which reduces to zero for a reversible operation,

$$\dot{Q} = \dot{m} T_0 (s_1 - s_0) \qquad (4)$$

This ideal operation represent the upper limit and the performance of a plant for a given initial and final states. Combining the equation (2) an (4) the expression for maximum thermodynamic work is the following:

$$\dot{W}_{max} = \dot{m}(h_1 - h_0) - mT_0(s_1 - s_0) \quad (5)$$

If the system is designed so that the final state of the fluid is identical to the surrounding then the maximum possible work extracted from the fluid for a given initial state is called exergy. Equation 5 is rewritten as

$$\varepsilon = \dot{m}[(h_1 - h_0) - T_0(s_1 - s_0)] \quad (6)$$

And the specific exergy defined as $e=\varepsilon/m$ is

$$e = (h_1 - h_0) - T_0(s_1 - s_0) \quad (7)$$

Equation (6) will be used to compute the utilization energy at wellhead conditions and also to compute the average exergy and SEI for the Ahuachapán and Berlín geothermal fields.

3. ANALISYS OF GEOTHERMAL RESOURCES AND WELLS BY EXERGY

Geothermal energy is already in the form of heat, and from the thermodynamic point of view, work is more useful than heat because not all the heat can be converted to work. Considering the ability of a geothermal resource to do work, Lee (1966), introduced the term specific exergy index (SEI) for its classification. The equation is the following:

$$\text{SEI} = \frac{(h - 273s)}{1192} \quad (8)$$

To map the geothermal resources, straight lines for SEI = 0.5, 0.2 and 0.05 are plotted on the Molliere diagram. The area above the line of SEI = 0.5 is the high exergy resource zone, the area below SEI = 0.5 and above SEI = 0.2 is the medium high exergy zone, the area bellow SEI = 0.2 and above SEI = 0.05 is the medium low exergy zone and the area bellow SEI 0.05 is the low exergy zone (Fig. 2).

The entropy and enthalpy at wellhead condition in the production wells of Ahuachapán and Berlín Geothermal Fields have been mapped on the Molliere diagram. The most production wells are located inside the medium high exergy zone, and only the well AH-17 is located into the high exergy zone. The wells AH-19, AH-31, AH-21, AH-28, AH-24 and AH-1 remain in stand due to its low enthalpy and dryness (less than 14 %). This wells are mapped on the boundary between the medium high exergy zone and the medium low exergy zone (Fig. 2).

In order to map the Ahuachapán and Berlín geothermal fields on the Molliere diagram the average value for the enthalpy and entropy are computed by following equation.

$$h_{field} = \frac{\sum_{i=1}^{n} m_{wi} h_{wi}}{\sum_{i=1}^{n} m_{wi}} \quad (9)$$

where h_{field} = average field enthalpy
x_{field} = average dryness
h_w = wellhead flow enthalpy
m_w = wellhead mass flow

If h_{field} and X_{field} are given, can be computed the values for h_f and h_g from steam tables to satisfy the following equation.

$$h_{field} = x_{field} h_g + (1 - x_{field}) h_f \quad (10)$$

with the thermodynamic state identified, the field entropy is computed by the equation

$$s_{field} = x_{field} s_g + (1 - x_{field}) s_f \quad (11)$$

For comparison, the Ahuachapán and Berlín Geothermal Field and some other geothermal fields around the world are plotted on the Molliere diagram (Fig. 3).

The evolution of the Ohaki and Cerro Prieto fields can be observed where they change from the medium high exergy to the high exergy zone. This behavior is a product of a gradual expansion of the steam zone at the top of the hot water reservoir caused by commercial exploitation. The AGF has also a steam cap which is intersected by wells AH-17, AH-6 and AH-26 (Fig. 1). This steam cap has not experienced any notable expansion, probably due to the maintained mass extraction (about 410 kg/s) in order to keep the reservoir pressure over 19 bar. This condition fixes the free surface water reservoir and does not allow expansion of the steam cap.

3.1 Improvement of thermodynamic condition in some wells in the Ahuachapán geothermal field

Presently the AGF has 16 productive wells with a total flow capacity of 783 kg/s. Due to limitation of the mass extraction pointed out before, the output power is restricted to 55 MW, corresponding to an utilization factor of 58 %. The on line production wells are selected in order of its exergy, starting from the high exergyy well until the value of 410 kg/s is cumulated (Fig. 8).

On the Molliere diagram the on line production wells are classified as medium high exergy wells. In a decreasing order these wells are the following: AH-17, AH-6, AH-26, AH-4b, AH-23, AH-22, AH-27, AH-16a, AH-20 and AH-7 (Fig. 2). The remainder of the wells are mapped in the boundary between the medium high exergy zone and the medium low exergy zone. Regularly these wells are used when some medium high exergy well goes into maintenance.

As pointed out before the other possibility to increase the power plant utilization factor is trying to improve the thermodynamic conditions in some wells of the medium low exergy group, by operating them at higher WHP. Then, to evaluate if production will improve its thermodynamics conditions, an analysis of the output characteristic curves is achieved. In the analysis the ratio of the utilization efficiency at higher WHP to the utilization efficiency of the lowest WHP (maximum discharge) is computed.

The term utilization efficiency (η_u) is introduced by DiPippo (1997). This efficiency is based on the second law of thermodynamics and it is defined as follows.

$$\eta_u = \frac{W}{\varepsilon} \tag{12}$$

where W is the power generated (usually net) and ε is the rate of exergy supplied to the plant from the resource. The latter quantity may be found from equation (6). In this case, s_0 ,h_0 and T_0 are entropy, enthalpy and the absolute temperature of the dead state respectively. Since the thermodynamic dead state is the lowest temperature to which heat can be theoretically be rejected, it is usually taken as the design wet-bulb temperature for systems with wet cooling towers such as in the Ahuachapán geothermal power plant.

In the AGF the production wells are connected to feedzones distributed along the reservoir thickness. It is possibly that a geothermal well has its feedzone or feedzones connected with the water, the two phase or the steam cap zone. Then, during a wellhead operation from low WHP to high WHP, depending where the feedzone is there, could be an increase or decrease in the flowing enthalpy. A methodical study in the low enthalpy wells (stand by group) could change the WHP operation and increase the total efficiency of the geothermal field. To analyze the case, the ratio of the utilization efficiency in two point of an output curve of a hypothetical well can be considered (Fig. 4).

In a higher wellhead operation it is expected that the water flow and vapor flow decrease by the same ratio. But depending where the feedzones of the wells are, a higher WHP operation could originate a higher increase in the water flow than the vapor flow ratio, originating a decline in thermodynamic conditions. The opposite is when the vapor flow ratio increases over the water flow ratio, which improves the thermodynamic conditions.

If a source consisting of a reservoir with temperature T and pressure p is considered, the reservoir variables enthalpy h_R and entropy s_R are constant. Then, during an isoenthalpic process the utilization energy (equation 6) become.

$$\varepsilon = \dot{m} C \tag{13}$$

When C is a constant, then the exergy at the two operation point is $\varepsilon_1 = m_1 C$, and $\varepsilon_2 = m_2 C$, if $m_2 = 0.8 m_1$ then $\varepsilon_2 = 0.8\varepsilon_1$

The calculation of power generation in an isentropic process from p1 = 5 bar and p2 = 8 bar to the pressure of the condenser p_c = 0.85 bar (Fig. 5) is computed by

$$W_1 = m_{v1}(h_{v1} - h_{1c}) \tag{14}$$

$$W_2 = m_{v2}(h_{v2} - h_{2c}) \tag{15}$$

where the subindex v means vapor and the subindex c means the conditions at the condenser.

if $h_{v1} - h_{1c} \approx h_{v2} - h_{2c} = K$ then $W_1 = K m_{v1}$, and $W_2 = K m_{v2}$. If $m_2 = 0.8 m_1$ and again $W_2 = 0.8 W_1$

The utilization efficiency ratio ($\Re$) for the two operation points is

$$\Re = \frac{\eta_{u2}}{\eta_{u1}} = \frac{W_2}{W_1}\frac{\varepsilon_1}{\varepsilon_2} \tag{16}$$

For the hypothetical example $\Re = 1$, it means thet there was no change in resource utilization, but the power output was reduced by 20 %. Rewritins equation 19 using equations 15 and 18 we arrive at

$$\Re = \frac{\dot{m}_{v2}}{\dot{m}_{v1}}\frac{\dot{m}_{T1}}{\dot{m}_{T2}} \tag{17}$$

Generally, subindex 1 means conditions at maximum discharge and subindex 2 means any other point in the output characteristic curves at higher WHP. The $\Re > 1$ means improved thermodynamic utilization of the resource under high pressure operation while $\Re < 1$ means lower thermodynamic. However, the power output will always be lower for a higher pressure operation (DiPippo, 1998, pers.com.).

To improve the total power-plant system efficiency the output characteristics curves of each productive well have been analyzed by computing the utilization efficiency ratio $\Re$. The preliminary results show a progress in thermodynamic condition in wells AH-1, AH-4b, AH-6 and AH-24 (Fig. 6). Because wells AH-4b and AH-6 belong to the medium high enthalpy group it is preferred to leave them operating at maximum discharge while the low enthalpy wells AH-1 and AH-24 are left to operate it at higher WHP with orifice plates. In the other productive wells the operation at higher well head pressures decrease the thermodynamic conditions, an example is well AH-7 (Fig. 7).

3.2 Analysis of the utilization efficiency at the Ahuachapán Geothermal Field

Before 1997, the efficiency at the geothermal power plants was computed base on the extracted energy at wellhead conditions, discharging the residual water was to the surrounding at 25 ºC. DiPippo (1996) suggested to incorporate the utilization efficiency criteria (η_u), because not all the heat extracted in the mass flow from the reservoir can be converted into work, as a limitation pointed by the second law of thermodynamics.

To compute the utilization energy a open cycle system with an input given by the wellhead conditions is considered. The output conditions of the cycle in the Ahuachapán power plant is characterize by the wet bulb temperature of 21 ºC (Fuji Electric Co., 1981). The output conditions of the cycle in the Berlín geothermal field is an ambient temperature of 25 ºC, because it operates with back pressure turbines.

In summary, the output power generated by both geothermal fields during 1997 was 430.4 GWh with a mass extraction of about 16.7 Mton. Considering a final water discharge to an environment of 25 ºC the thermal energy equivalent is 18.6×10^{15} Joules. Consequently, the thermal efficiency of the Ahuachapán and Berlín field-plant systems is 10.6 and 5.4 respectively (Table 1) (Quijano, 1997).

Handling the second law of thermodynamic criteria, in Ahuachapán and Berlín the utilization energy at wellhead conditions is 1,026 GWh and 319.1 GWh respectively. Similarly, the utilization efficiency (η_u) for the Ahuachapán field-plant system is 41%, while for the Berlín field-plant system is 21% (Table 1).

Furthermore, as pointed out before in the AGF the residual water is delivered to the Pacific Ocean through a channel. The estimation of the utilization energy in the residual water gives an average value of 16 GWh/month. With this energy a binary plant with an efficiency of 12 % could operate (DiPippo, 1997), getting an output power of about 2.6 MW.

CONCLUSIONS

To estimate the efficiency of the power plant geothermal field system in Berlín and Ahuachapán the second law of thermodynamic principle is applied, computing the utilization energy (ε) instead of the thermal energy. Handling the utilization efficiency factor η_u to evaluate the performance at the power plants of Ahuachapán and Berlín, higher efficiency values are obtained due to exergy being always less than the thermal energy. Computing the production data over 1998, values of 41 % and 21 % are obtained in the Ahuachapán and Berlín geothermal fields respectively. The Ahuachapán system gives a higher value because it has a condensation system while Berlín has a back pressure system.

From the analysis of the output characteristics curves computing the ratio ($\Re$) of the utilization efficiency at higher well head pressure to the utilization efficiency of the maximum discharge (minimum pressure), it can be recognized that higher wellhead pressure operation improve its thermodynamic conditions ($\Re$ >1). An analysis of the output curves in the production wells of the AGF concluded that wells AH-1, AH-4b, AH-6, AH-24, and AH-26 improve their thermodynamic conditions. Since the higher pressure operation always reduce the output power, the high enthalpy wells AH-4b, AH-6 and AH-26 are not considered, but for the for low enthalpy wells Ah-1 and Ah-24 it is better to set a new higher pressure operation to be connected to the power plant.

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NOMENCLATURE

AGF: Ahuachapán Geothermal Field
SME: Stabilized mass extraction
SEI: specific exergy index [unit less]
WHP: Wellhead pressure
Q : Rate of heat transfer [J/s]
W: Work [J]
W_{max}: Maximum thermodynamic work [J]
M: Mass flow [kg/s]
H: Enthalpy [kJ/kg]
h_{field}: Average enthalpy [kJ/kg]
x_{field}: Dryness average [unit less]
h_w: Mixture enthalpy [kJ/kg]
m_w: Total mass flow at wellhead [kg]
m_v: Vapor mass [kg]
Θ: Production entropy [kJ/s/ºC]
s: Entropy [kJ/kg ºK]
T: Temperature [ºC]
P: Pessure [bar]
ε: Exergy [kJ/s/kg]
v: Velocity [m/s]
e: specific exergy [kJ/kg]
η_u: Utilization efficiency [unit less]
$\Re$: Utilization efficiency relation [unit less]

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Table 1. Mass, thermal and utilization energy extracted from Ahuachapán and Berlín geothermal fields during 1997/(1996)

Field-plant	Extracted Mass	Thermal Energy		Output Power	ThermEfficiency (η_{th})	Utilization Energy	Uefficiency (η_u)
	(Mton)	(10^{15} J)	(GWh)	(GWh)	(%)	(GWh)	(%)
Ahuachapán	12.7 (12.5)	14.22 (14.0)	3949.1	420.4 (370.1)	10.6 (9.5)	1026.16 (1006.4)	41.0 (38.0)
Berlín	4.0 (3.7)	4.4 (4.1)	1221.8	65.9 (60.3)	5.4 (5.3)	319.1 (277.7)	20.7 (21.7)
Total	16.4 (16.2)	18.62 (18.2)	5170.9	486.3 (430.4)		1345.26 (1284.1)	

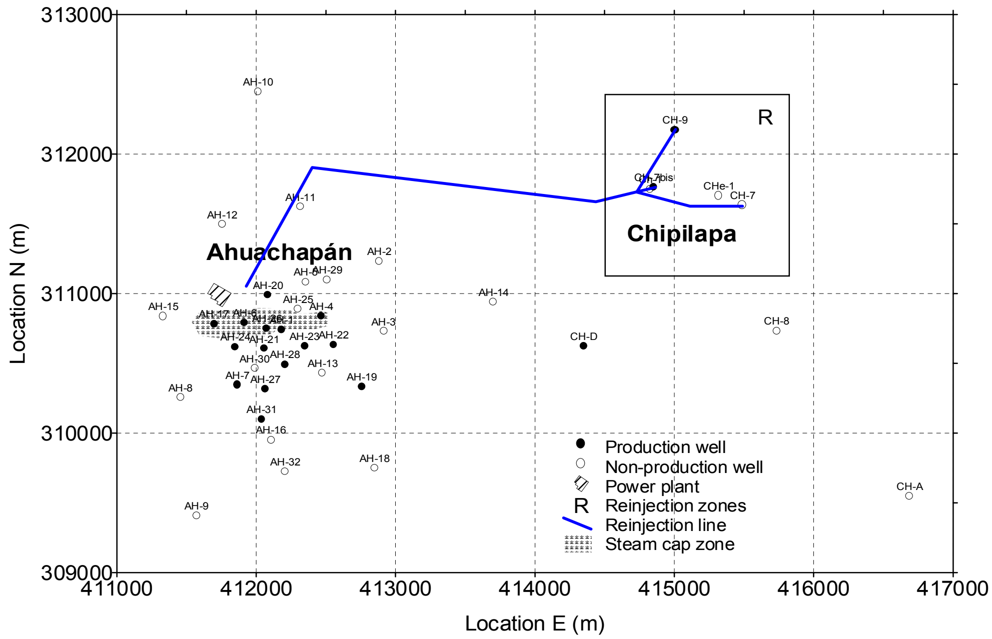

Figure 1. Distribution of geothermal wells in the Ahuachapán-Chipilapa geothermal field. Actually the residual water is discharged to Pacific ocean through a channel, but in 1999 it will be reinjected into the Chipilapa area.

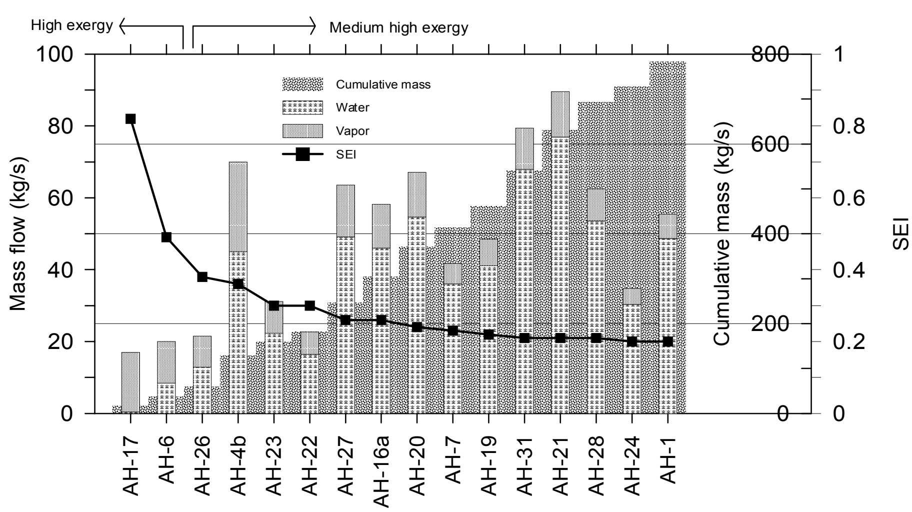

Figure 8. Arrangement by specific exergy index SEI of the production wells in the Ahuachapán geothermal field.

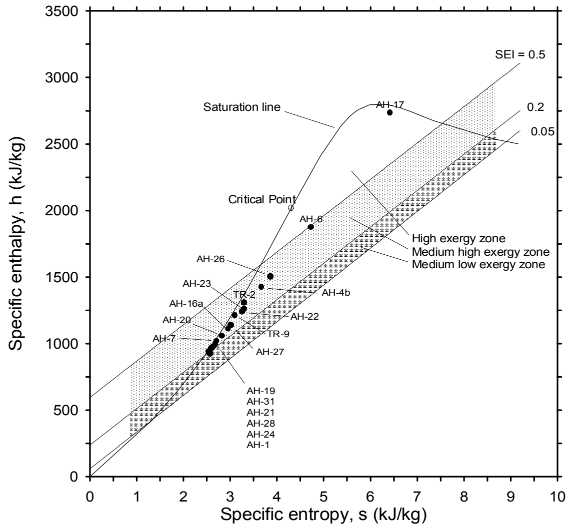

Figure 2. Classification of production geothermal wells on the Ahuachapán and Berlín geothermal fields. The most production wells are located in the medium high exergy zone.

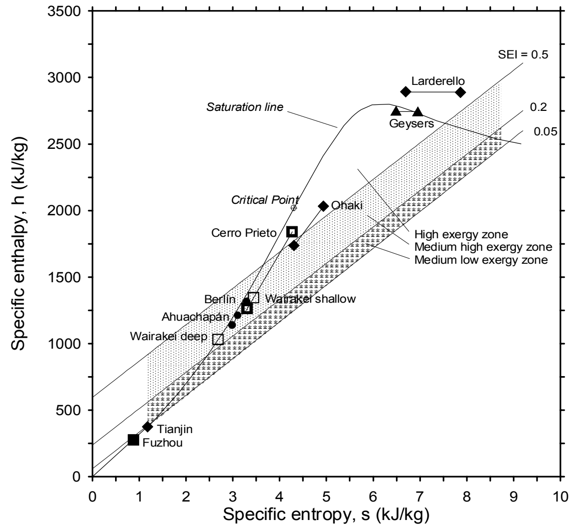

Figure 3. Classification of geothermal resources by specific exergy indices (SEI) on Mollier Diagram for water. High exergy: SEI > 0.5, medium high exergy: 0.5 < SEI > 0.2, medium low exergy: 0.2 < SEI > 0.05, low exergy: SEI ≤ 0.05 (Taken from Lee, 1966).

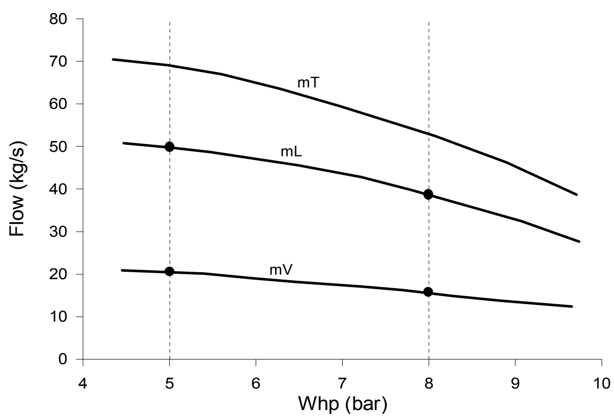

Figure 4. Typical output characteristic during a well test discharge.

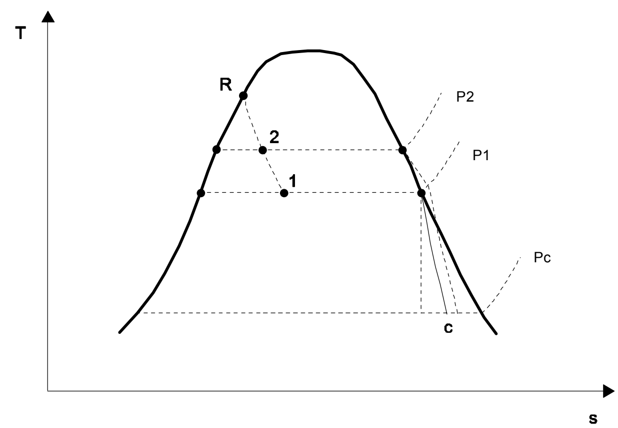

Figure 5. Schematic diagram showing two well head pressure operation points to explain and hypothetical the power output. The Point C means conditions at the condenser.

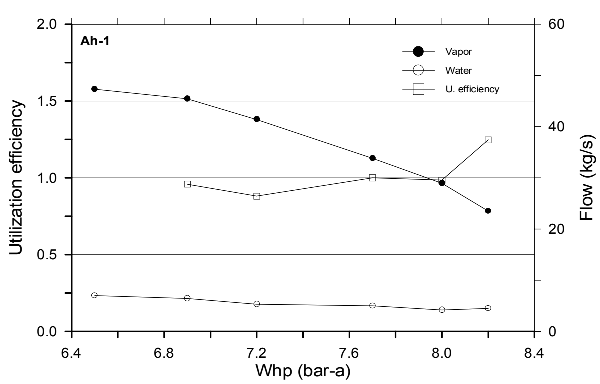

Figure 6. Output curves of wells AH-7 in. The utilization efficiency decreases as higher WHP is operated using as a reference the maximum discharge operations conditions.

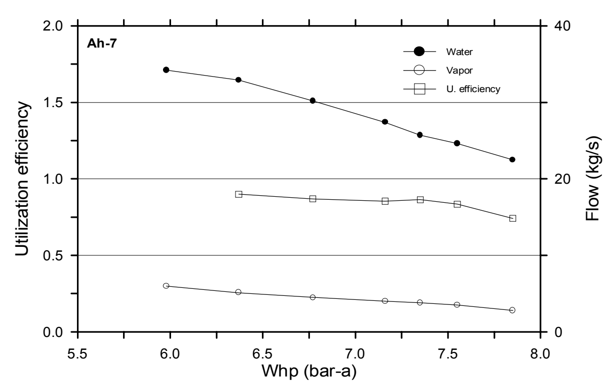

Figure 7. Output characteristic curves of well AH-1. The utilization efficiency analysis shows an improvement in thermodynamic conditions by operating the well at higher WHP.