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Energy and Exergy Analysis of Sabalan Geothermal Power Plant, IRAN

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ABSTRACT

The Sabalan geothermal field in northwest of Iran is currently under development. A single flash cycle has been selected for power generation. The obtained results show that the maximum power output from the plant can be 36 MWe with pressures equal to 5.5 and 0.3 bar for separation step and condenser, respectively. Mathematical models for energy and exergy flows were developed and implemented in the Engineering Equation Solver (EES) software. A few assumptions and simplifications were made. The energy and exergy rates of the waste brine have been calculated as 54.8% and 41.4% of the total available energy and exergy rates, respectively. The separated brine can be used as a heat source for a combined power production, district heating system or some other forms of direct use. Reinjection should also be taken into account. The parts of the system with largest exergy destruction are the condenser, the turbine, and the disposed waste brine. The overall exergy efficiency for the power plant is 32.73% and the overall energy efficiency is 7.32%. Exergy analysis was found helpful and important tool for analyzing the geothermal plant from the view point of optimum usage of stored energy and should be considered at early stages of designs.

1. INTRODUCTION

The increase in energy demands, decline in energy resources and the link between energy utilization and environmental impact have resulted in calls for sustainable approach to the development and management of the earth's energy resources (Rosen, 2001). With finite energy resources and increasing energy demands, it becomes increasingly important to understand the mechanisms which degrade the quality of energy and energy resources and to develop systematic approaches to improve the systems (Gong, 1997). Systems and processes that degrade the quality of energy resources can only be identified through a detailed analysis of the whole system.

Exergy is defined as energy which can be converted into other energy forms, such as the portion of heat which can theoretically be converted into work (electricity). Exergy analysis is based on the assumption that only the exergy contained in any heat stream has value, then non-convertible part of the heat stream has no value, defined as anergy. Exergy analysis has been cited by many researchers and practicing engineers to be a powerful tool to identify and quantify energy degrading processes since it enables the types, locations and quantities of energy losses to be evaluated.

Meshkinshahr is a city in NW-Iran with a population of 164,000. Sabalan Mountain is located southeast of Meshkinshahr, 4811 m high and at 25 km distance from the city. The Meshkinshahr geothermal prospect lies in the Moil valley on the western slopes of Mt. Sabalan, approximately 16 km southeast of the Meshkinshahr city. The area includes three geothermal fields located in the northern, eastern and southern parts of the Sabalan central volcano, and a number of geothermal prospects are associated with these (Sahabi, 1999). The Meshkinshahr prospect has been identified as the best of these prospects. Geology, geothermal manifestation, geochemical, geophysical explorations have been done in the area and exploration drilling has given sufficiently good results to go into production drilling.

This paper presents the theoretical framework and mathematical formulations on which the exergy analysis is based, the steps followed in the study (methodology) are described. Then the detailed exergy analysis was done for each subsystem with the equations used, procedures and simplifying assumptions. The results of the analysis as performed in EES are presented and their significance is discussed and conclusions made.

2. METHODOLOGY

Generation of electricity using geothermal resources has been practiced for a century, since its first use at the Lardarello geothermal field in Italy, in 1904. The steam Rankin cycle has been the conventional technology used for most worldwide geothermal power generation to date. The basic technology is analogous to the steam Rankin cycle used in thermal power plants except that the steam comes from the geothermal reservoir, rather than a boiler. Various technical enhancements to the condensing steam turbines have been implemented over the years to address the differences between geothermal and boiler-quality steam. The most attractive geothermal fields for developers have been those with high resource temperatures and production fluid enthalpies. These fields can deliver at higher pressures and steam flash proportions in order to achieve more efficient operation of the condensing steam turbines, and hence lower electricity production costs. Condensing steam plants are typically used for resource temperatures in excess of 200°C. For a low-enthalpy resource, a low operating pressure is needed to obtain a reasonable steam flash, equipment size grows larger and hence more expensive, and a significant proportion of the available energy in the production fluid is rejected in the separated brine. There are several experienced and competent providers around the world for steam-turbine geothermal power plants and component equipment. Turbine-generator unit capacities are typically in the 20-80 MWe range, but are offered from less than 5 MWe up to 110 MWe.

2.1 Power Plant Classifications

Total installed capacity worldwide has been classified under the following plant categories: dry steam; single flash; double flash; binary/combined cycle/hybrid and back pressure (Table 1 and Figure 1). The largest installed capacities correspond to dry steam and single flash units, with 2/3 of the total. Binary units, despite their low position in this ranking because og their smaller capacity ratings, are becoming increasingly more common (Ruggero Bertani, 2006).

There were a total of 490 geothermal units operating in early 2005 (Table 1). The distribution of units over the different categories are shown in Figure 1. The maximum corresponds to 208 binary units (42%), with a total installed capacity of 682 Mwe (i.e 3.3 MWe per unit). The average size of single flash units is 26.2 MWe, followed by the 34.2 MWe for double flash units, and 43.9 MWe for dry steam plants. (WGC 2005).

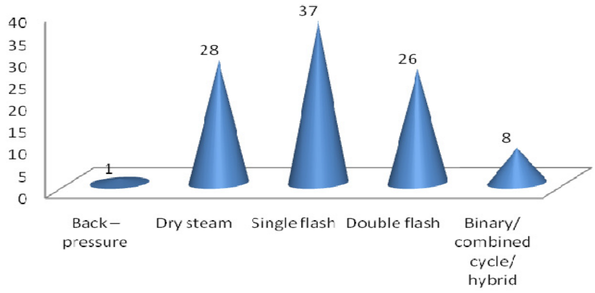

Figure 1: Distribution of units over the different categories.

2.2 Flash Plants

Single flash steam technology is used where the hydrothermal resources are of liquid dominated type. The produced fluid goes into a separator which separates steam from two – phase mixture (Figure 2). The steam is then passed through a turbine coupled to a generator as for dry steam power plants. The majority of the geothermal fluid remains as water phase, and this liquid is re-injected into the reservoir or used in a local direct heat application. Alternatively, if the liquid from the separator has sufficiently high temperature, it can be passed into a second separator (low pressure separator), where a pressure drop induces further flashing to steam.

This steam, together with the exhaust from the turbine, is used to drive a second turbine or the second stage of the principal turbine to generate additional electricity. Typically, a 20-25% increase in power output is achieved, with a 5% increase in plant costs (Australian Renewable Energy, 2003). Flash steam plant generators range in size from 10 to 55 MW, but a standard size of 20 MW is used in some countries, including the Philippines and Mexico (Australian Renewable Energy, 2003). The run-off fluid can be used for direct use applications.

This paper contains performance analysis and optimization of the single-flash power plant (Figure 2). Mathematical models for exergy and energy were developed and analyzed using the Engineering Equation Solver (EES) software to perform the calculations. The results from well testing and exploration drilling in the Sabalan geothermal field was used to evaluate the initial values to perform more accurate analysis. Reservoir fluid enthalpy and mass flow rate are 1000 kJ/kg and 500 kg/s respectively (SKM, 2005).

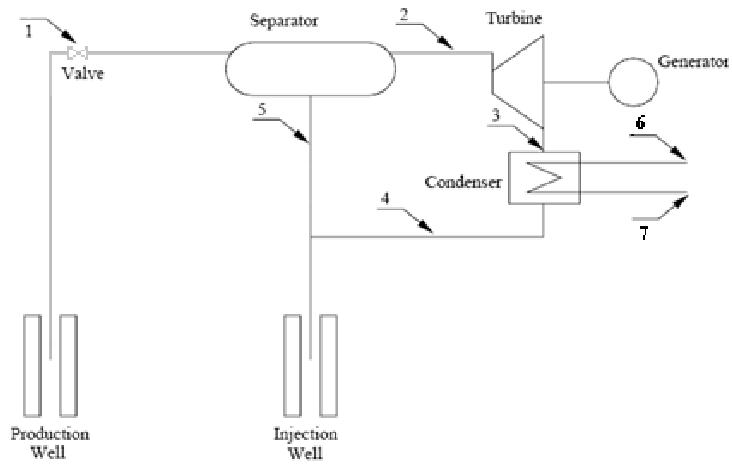

Figure 2. A process diagram of a single flash cycle.

Table 1: Worldwide classification of geothermal plant cycles (Ruggero Bertani, 2006)

Plant type	Installed capacity (MWe)	Percent (%)	Installed capacity (number of units)	Percent (%)
Back – pressure	119	1	29	6
Dry steam	2545	28	58	12
Single flash	3294	37	128	26
Double flash	2293	26	67	14
Binary/ combined cycle/ hybrid	682	8	208	42
Total	8933	100	490	100

2.2.1 Parameters of the separator

For calculations, the mass flow and at least two other parameters of the fluid need to be known. Enthalpy is given and it is assumed that the wellhead pressure is known. With these parameters all the other parameters of the fluid such as entropy and temperature can be determined. The fluid goes to the separator to separate steam and water because only steam should enter the turbine. With enthalpy and pressure, the quality of the fluid can be calculated and then the mass flows of steam and brine can be calculated. The temperature of steam and brine are the same as that of the geothermal fluid that enters the separator, or:

$$T_2 = T_1 = T_5 \tag{1}$$

The pressure of the steam and brine are also the same as the pressure of the geothermal fluid that flows into the separator, or:

$$P_2 = P_1 = P_5 \tag{2}$$

where the numbers refer to Figure 2. The enthalpy of the steam is determined as saturated steam enthalpy at pressure P_2. Similarly, the enthalpy of the brine as saturated water enthalpy at P_5. The entropy of the steam and the brine can be calculated from temperature and enthalpy, and then all the parameters of the fluid are known in the separator.

2.2.2 Parameters of the turbine

Ideally, the entropy of the fluid after the turbine is the same as the entropy of the fluid before the turbine (as shown in Figure 2), i.e.:

$$S_3 = S_2 \tag{3}$$

With a fixed pressure after the turbine and S_3 known, the enthalpy of the fluid after the turbine can be calculated with the EES software. Thus, the power of the turbine can be calculated as:

$$W_t = (h_2 - h_3) * m_2 * \eta_t \tag{4}$$

where η_t is the isentropic efficiency of the turbine. The mass flow after the turbine equals the mass flow before the turbine. If in addition to the main cycle (Figure 2), a flash vessel is employed to generate secondary steam from the brine at stage 5, the resulting double-flash plant will be more efficient than a single-flash plant. Either a dual-admission turbine or two separate tandem compound turbines could be used. The pressure of the water at stage 5 is the same as the wellhead pressure and is lowered isenthalpically through a throttling valve, generating a mixture of water and steam at a lower pressure level. The steam is then separated from the mixture and fed into a low pressure turbine along with the steam from the high pressure turbine outlet (Jalili, 2007).

2.3 Optimization

The separation pressure is very important and a critical parameter to get optimal values for the plant performance. The pressure that yields maximum total net power output has been calculated using EES and selected as optimum separation pressure. According to calculations, optimum separation pressure value is 5.5 bar. Exhaust steam quality (x2) at exit of turbine is another important parameter to be taken into account; it has very effective influence on turbine operation and maintenance cost, it was assumed to keep this value higher than 0.86. To avoid scaling problem at plant component, lower wellhead pressure wasn't selected as an optimum value. Figure 3 illustrates explained process.

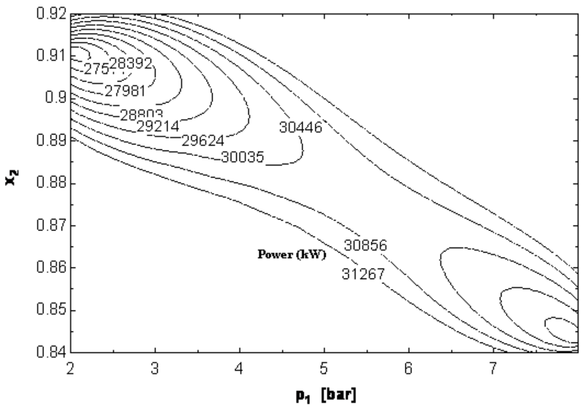

Figure 3: Pressure optimization.

2.4 Exergy and Energy

Exergy analysis has been applied for each component such as separators, turbines, condenser, etc. For a stream of fluid, the total exergy flow can be expressed as:

$$E_{total} = E_{KE} + E_{PE} + E_{PH} + E_O \tag{5}$$

where:

E_{KE}	:	Kinetic exergy
E_{PE}	:	Potential exergy
E_{PH}	:	Physical exergy
E_O	:	Chemical exergy

Both E_{KE} and E_{PE} are associated with high-grade energy and are fully convertible to work, while E_{PH} and E_O are low-grade energy where the stream has to undergo physical and chemical processes while interacting with the environment. For this study, only physical-exergy shall be considered since the process involves only fixed composition flows (Rosen, 1999). Therefore, the exergy will be expressed as equal to the maximum work when the stream of substance is brought from its initial state to the environmental state defined by P_0 and T_0 by physical processes involving only thermal interaction with the environment (Kotas, 1995).

$$E_{total} = E_{PH} = m_i[(h_i - h_o) - T_0(s_i - s_0)] \tag{6}$$

where:

i	:	Refers to state points
0	:	Refers to the environmental state
m	:	Refers to mass flow rates (kg/s)
h	:	Enthalpy (kJ/kg)
s	:	Entropy (kJ/kg-K)
T_0	:	Temperature (K)

For a control volume, an exergy balance equation can be expressed as:

$$E_{input} = E_{desired} + E_{waste} + E_{destroyed} \quad (7)$$

where:

E_{input} : Total exergy inflow into the control volume (kW)

$E_{desired}$: Total desired exergy output (net work output) (kW)

E_{waste} : Sum of exergy from the system other than the desired (kW)

$E_{destroyed}$: Sum of exergy lost in the system as a result of irreversibility (kW).

3. RESULTS AND DISCUSSION

Analysis of the single–flash geothermal power plant was conducted using energy and exergy concepts for Sabalan, Iran. Reservoir fluid enthalpy and mass flow rate are 1000 kJ/kg and 500 kg/s respectively. EES software was used to model the plant. Optimization was done to maximize the net power output of the plant. Optimum pressure value for separation is 5.5 bar. With these optimum pressure values the net power output of the plant is calculated to be 36594 KW_e. Pumps and compressor will use 843 KW_e and 3350 KW_e, respectively. Table 2, illustrates important parameters at major stages of power plant at optimal pressure. The overall first and second law efficiencies of the power plant are 7.32% and 32.73% respectively. The reference conditions for exergy analysis are 15ºC and atmospheric pressure. Figure 4 shows exergy destruction at different stages of the plant. 1.38% of the total exergy destruction is due to transmission from the reservoir to wellhead. 1.09% of the exergy is destroyed at the separation step. 4.91% is lost at the steam expansion unit. 23.35% are destroyed in the condenser, 13.19% and 41.44% are the waste brine from condensing steam and separator respectively. Finally the remainder is 32.73%, which is the fraction of the initial exergy that the plant turns to power.

In reality, the waste fluids should only be accepted as exergy lost in geothermal power plant applications if this exergy cannot be made use for other applications such as space and district heating, greenhouse, pool heating or aquaculture.

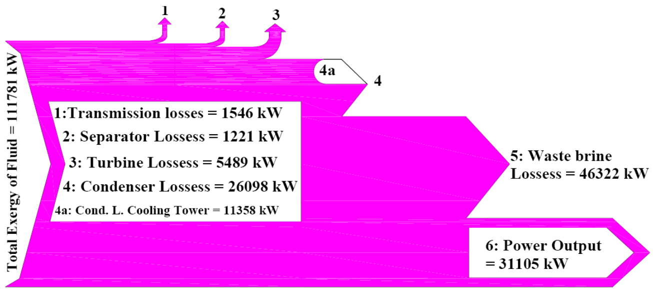

Figure 4. Grassman presentation of the overall exergy flow.

The other approach to waste fluid is reinjection. Reinjection of the used geothermal brine is a legal obligation in the USA and other developed countries (Dagdas, 2007). There are some important points concerning the reinjection process. For example, brine must be reinjected in a suitable location in reservoir for reheating. When the geofluid has returned to its original reservoir, it should have reached the original temperature and pressure. Thus the reservoir is replenished with water, and the exploitation gets as close to being renewable as possible.

Ideally the heat in the rejected brine from separator and condenser should be utilized in a cascade of applications, each making the most of the available heat, before the fluid is reinjected into the reservoir. A reservoir can be limited by the natural inflow of heat and water. If the natural inflow of heat is sufficient, then the reservoir will not cool down. In most cases the reinjection will create a cold plume around the reinjection well, and the lifetime of the project is limited to the time it takes for this plume to grow into the production wells.

Reinjection will always solve the limited water inflow problem. To avoid of well clogging problem, possible need for filtering the brine before reinjection should be taken into account. If the waste fluid is reinjected to the reservoir carefully, it will contribute to preserving the pressure and temperature of the resource. In that case, this process should not be considered as an exergy destruction process. Table 3, summarizes important optimum values of power production process.

Table 2. Important parameters at major stages of power plant at optimal pressure.

State	Enthalpy (kJ/kg)	Mass flow (kg/s)	Energy (kW)	Energy (%)	Temparature (ºC)	Exergy (kW)	Exergy (%)
0	1000	500	500000	100	170 [SKM, 2005]	111781	100.00
1	1000	500	500000	100	155.45	110235	98.62
2	2748	82.05	225473.4	45.09	155.45	64238	57.47
3	2302	82.05	188879.1	37.78	69.05	27644	24.73
4	289.2	82.05	23728.86	4.75	69.05	1545	1.38
5	656	418	274208	54.84	155.45	46322	41.44
6	41.99	729.8	30644.3	6.13	10	61.94	0.06
7	268.2	729.8	195732.4	39.15	64.05	11420	10.22

Table 3: Optimum values of analysis.

Parameter	Value
Quality of steam at separation	16.41%
Mass flow rate after separation	82.05 kg/s
Quality of steam at turbine exit	86.17%
Total net power produced by	36594 kW
Power used by pump	842.9 kW
Overall first law efficiency	7.32%
Overall second law efficiency	32.73%

The reason for high exergy loss in condenser is due to heat transfer from the turbine exhaust steam to the environment via cooling water. In geothermal power plants, the waste heat of the condenser should be recovered if it is possible and economy allows. Some low-temperature applications could be added to this system for heat recovery. Another important location for exergy destruction in the plant is the turbine. This is also evident from the low value of second law efficiency of the turbine-generator system.

The main reason for this result is low temperature and pressure values at the turbine inlet (Dagdas, 2007). Waste brine discharged from the power plant has important energy and exergy content. The energy and exergy rates of the waste brine have been calculated as 274208 kW and 46332 kW, respectively. These values represent 54.84% and 41.44% of the total energy and exergy flow from the reservoir, respectively. The waste geothermal fluid must be carefully reinjected into the reservoir to ensure sustainability.

4. CONCLUSIONS

From the results, the following conclusions have been drawn:

1.The exergy analysis of Sabalan geothermal power plant has pointed out the locations and quantities of exergy losses, wastes and destructions in the different processes within the plant. The exergy analysis was found to be very helpful tool where the thermodynamical solutions (energy analysis) is not sufficient. It increases the accuracy of the analysis and makes it possible to determine the key parameters of processes. The total exergy available from production wells at Sabalan power plant has been calculated to be 111 MW.

2. The overall exergy efficiency for the power plant is 32.7% and the overall energy efficiency is 7.3% in both cases with respect to the exergy from the connected wells, assuming an environment temperature of 15ºC.

3. The exergy lost in the transmission system amounting to 1.5 MW should be taken into account when the site for the power plant is selected. It seems to be one of the parameters in the site selection and decision making.

4. The locations with largest exergy destruction are the condenser, the turbine, and the disposed waste brine with 23.35%, 4.91%, 41.44% of total exergy destruction in the plant.

5. The rejected water from separator with mass flow rate of 418 kg/s and temperature of 155°C, can be beneficial to be used as a heat source for a combined power cycle. Cascade use of this section should be taken into account carefully. District heating system for the population in the Sabalan area (winter temperature around -5ºC) is another possible option for more optimum utilization.

6. A detailed exergy analysis and plant optimization studies should be done using actual operating condition, based on real plant data. Exergy analysis should be incorporated in future designs of geothermal plants.

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