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Performance Analysis of Single-Flash Geothermal Power Plants: Gas Removal Systems Point of View

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ABSTRACT

Non-condensable gases (NCGs) are natural components of geothermal fluids and can affect the performance of a geothermal power plant (GPP) significantly. Therefore, the NCGs should be removed from the process to optimise the thermodynamic efficiency of the plant. GPPs require large capacity NCG removal systems and also occupies large portion in its total plant cost and auxiliary power consumption.

The single-flash GPP, which is commonly used throughout the world, is a relatively simple way to convert geothermal energy into electricity when the geothermal wells produce a mixture of steam and liquid. In this study, a detailed exergy analyses of a single-flash GPP is conducted for four different gas removal systems (steam jet ejectors, hybrid systems, compressors and reboiler systems) at various NCG contents, and the power output is optimised.

The obtained results show that the compressor system is the most efficient and robust system where the influence of the NCG fraction is limited. On the other hand, steam jet ejectors are highly affected by increasing NCG fraction since motive steam flowrate to the steam jet ejectors are directly related to NCG fraction. Thus this analysis shows them to be the worst case. The hybrid system responds late to the change in NCG fraction because the LRVP is more efficient since its performance lies between compressors and steam jet ejectors.

1. INTRODUCTION

The steam that leaves the separator is not pure but contains non-condensable gases (NCGs) (CO_2, H_2S, NH_3, N_2, CH_4 etc.) which are the natural components of geothermal fluids. The amount of NCGs contained in geothermal steam has significant impacts on the power generation performance of a geothermal power plant (GPP). Depending on the resource, the fraction of the NCGs can vary from less than 0.2% to greater than 25% by weight of steam (Hall, 1996; Coury et al., 1996).

The practical problems caused by elevated levels of NCGs in geothermal power plants are:

- the gases reduce the heat transfer efficiency of the condensers increasing the condenser operating pressure, which reduces turbine power output,
- NCGs contain lower recoverable specific energy than does steam,
- higher capital and operating cost for gas removal in the cost of electricity than fossil-fueled power plants,
- acid gases such as carbon dioxide and hydrogen sulphide are highly water-soluble and contribute to corrosion problems in piping and equipment that contact steam and condensate (Vorum and Fritzler, 2000).

Exergy analysis is a technique that uses the conservation of mass and energy principles together with the second law of thermodynamics for the analysis, design, and improvement of energy systems and others (Dincer and Rosen, 2005). With exergy analysis, efficiencies that are a measure of an approach to the ideal case can be evaluated, and the process steps having the largest losses can be identified (Rosen and Dincer, 2004; Ozturk et al., 2006).

Exergy analysis of geothermal power plants has been conducted by many researchers. The studies mostly are focused on determination of exergetic efficiency of the plants and sensitivity analysis of dead state properties. The authors considered that NCG content is zero through the cycle or NCGs are taken into consideration only in the gas extraction system instead of the entire cycle (DiPippo and Marcille, 1984; DiPippo, 1992, 1994, 2004; Cadenas, 1999; Cerci, 2003; Siregar, 2004; Kwambai, 2005; Aqui et al., 2005; Dagdas et al., 2005; Ozturk et al., 2006; Kanoglu et al., 2007).

The influence of NCGs on the performance of geothermal power plants was first studied by Khalifa and Michaelides (1978). The authors reported that the presence of 10% NCG in the geothermal steam, results in as much as a 25% decrease in the net work output compared to a clean steam system. Michaelides (1980) proposed a flash system at the wellhead to separate the NCGs before they enter the turbine and determined the flash temperature depending on the NCG content. It is emphasised that NCG content in the steam is an important factor for the estimation of the recoverable work. If NCG content is higher than 0.1%, separating the NCGs by flashing at the wellhead results higher amount of work recovery. It is recommended that if NCG content is high, NCG removal should be taken into account thermodynamically and economically for the construction of plants. To increase power generation performance, upstream reboiler systems are investigated as an alternative to conventional gas extraction systems (Awerbuch et al., 1984; Coury et al., 1996; Gunerhan, 2000) and applied in Italy on a commercial scale (Allegrini et al., 1989; Sabatelli and Mannari, 1995).

Yildirim and Gokcen (2004) considered the NCG content on each step of energy and exergy analysis of Kizildere Geothermal Power Plant. They emphasised the importance of NCGs on power plant performance and concluded that since geothermal power plants contain a considerable amount of NCGs, the NCG content should not be omitted throughout the process and dead state properties should reflect the specified state properties.

The studies reveal that the presence of NCGs in geothermal steam results with a dramatic decrease in the net work output compared to clean steam. Because of the elevated NCG levels, GPPs require large capacity NCG removal systems. Therefore, selection of NCG removal system becomes a major concern at planning and basic design stages of geothermal power plants (Hankin et al., 1984; Gokcen and Yildirim, 2008).

The conventional gas removal systems used in geothermal power plants are;

- Jet ejectors, e.g. steam jet ejectors, which are suitable for low NCG flows (<3%),
- Liquid ring vacuum pumps (LRVPs),
- Roto-dynamic, e.g. radial blowers, centrifugal compressors, which are mainly used for large flows of NCG (>3%),
- Hybrid systems (any combination of equipment above).

In this study a detailed exergy analysis is conducted of a single-flash GPP for four different types of gas removal systems, which are;

1. Two-stage steam jet ejector system,
2. Two-stage hybrid system (steam jet ejector and liquid ring vacuum pump)
3. Two-stage compressor system
4. Reboiler system.

The study aims to exhibit the effect of NCGs to the geothermal power plant performance since one of the most important differences between geothermal power plants and fossil-fuelled power plants is the working fluid which is not pure steam. Therefore for a confident exergy analysis of a GPP, the NCG content should be considered while determining the properties through the cycle. A parametric study is conducted to exhibit the effect of NCGs (0–25%). The objectives of the analysis are to determine the overall second law (exergy) efficiency of the plant, pinpoint the locations and quantities of exergy losses and wastes and suggest ways to address these losses and wastes.

2. OVERVIEW OF THE SYSTEM

A typical single-flash GPP mainly consists of production wells, wellhead/main separator(s), turbine, condenser, gas removal system, cooling tower and auxiliary equipment such as fans and pumps, is shown in Figure 1.

Geothermal fluid which is a mixture at the wellhead is separated into the steam and liquid phases. Steam is directed to the turbine contains water vapour and NCGs. After passing the turbine; steam, condensate and NCGs flow to the condenser where NCGs are accumulated and extracted by a gas removal system. The rest is pumped to the cooling tower which helps the temperature of the fluid drops down to the cooling water temperature to be re-used in the condenser. Liquid phase is driven by circulation pumps and air is drawn into the cooling tower by fans.

3. METHODOLOGY OF EXERGY ANALYSIS

The plant is first modelled for four conventional gas removal options using Engineering Equation Solver (EES) software (F-Chart, 2009), then exergy analysis is carried out to evaluate the net power output of the plant under a range of NCG fractions (0–25%).

For modelling, average fluid and ambient properties are kept constant and some general assumptions are made. The constant properties are taken from Kizildere Geothermal Power Plant (KGPP) which is a single-flash GPP and is a unique case in the World having highest NCG fraction as a conventional GPP. Table 1 lists the general assumptions and constant parameters which are taken from KGPP (Hall, 1996; Gokcen and Yildirim 2008; Swandaru, 2006; Siregar, 2004; Dunya, 2008; DiPippo, 1982; TTMD, 2000).

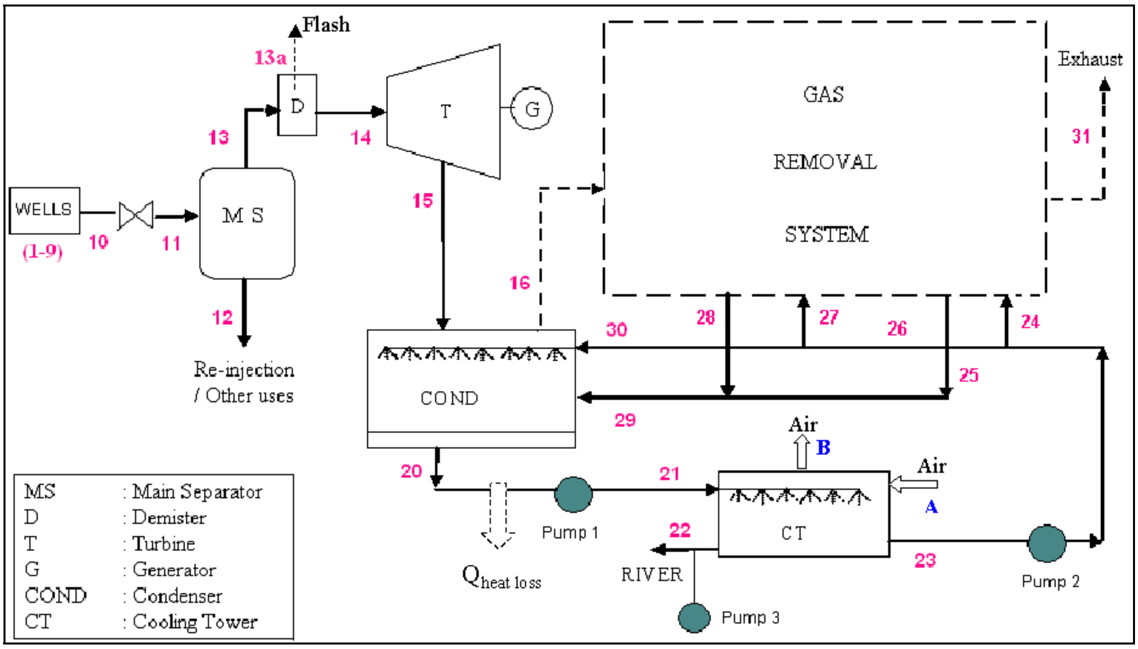

Figure 1: Schematic diagram of a single-flash GPP.

Table 1: Constant parameters and general assumptions (Yildirim and Gokcen, 2009).

Constant Parameters		
Wellhead pressure	(kPa)	1426
Wellhead flowrate	(t/h)	870.1
Atmospheric pressure	(kPa)	95
Yearly average outdoor temp.	(°C)	16
Wet bulb temperature	(°C)	13
Relative humidity	(%)	65
NCG fraction in steam	(%)	13
CO_2 fraction in NCG	(%)	96-99
Condenser pressure	(kPa)	10
T_{23} (Figure1)	(°C)	29
General Assumptions		
η_{comp}	(%)	75
η_{gen}	(%)	90
T_{wb}	(°C)	13
T_{21}-$T_{hot,air}$ (Figure 1)	(°C)	6
T_{20}- T_{21} (Figure 1)	(°C)	3
P_{13}- P_{14} (Figure 1)	(kPa)	10
η_{pump}, η_{fan}	(%)	70
$\eta_{motor,pump}$, $\eta_{motor,fan}$	(%)	85
ΔP_{pump}, ΔP_{fan}	(kPa)	100
P_{19}	(kPa)	105
T_{CO2}	(°C)	T_{wb}
P_{16} (Figure 1)	(kPa)	$0.90P_{cond}$
Geothermal fluid at the wellhead is saturated vapour-liquid mixture. CO_2 is an ideal gas and not to dissolve in the water Baumann Rule applies to turbine efficiency η_t At the turbine exit isentropic quality calculations consider NCGs Pressure ratios are equal at gas removal system stages.		

The net power output of the plant is defined as the difference between turbine power generation and auxiliary power consumption (Eq. (1)). Turbine power generation ($\dot{W}_t$) is calculated by Eq. (2). Auxiliary power is the sum of gas removal system (grs), circulation pumps (pump) and cooling tower fans (fan) consumption (Eq.(3)).

$$\dot{W}_{net} = \dot{W}_t - \dot{W}_{aux} \text{ (kW)} \quad (1)$$

$$\dot{W}_t = \dot{m}_{14}(h_{14} - h_{15}) \text{ (kW)} \quad (2)$$

$$\dot{W}_{aux} = \dot{W}_{grs} + \dot{W}_{pump} + \dot{W}_{fan} \text{ (kW)} \quad (3)$$

Eq. (4) is used to calculate the water circulation pump power.

$$\dot{W}_{pump} = \frac{\dot{v}_w \Delta p}{\eta_{pump} \cdot \eta_{motor,pump}} \text{ (kW)} \quad (4)$$

The cooling tower fans power $\dot{W}_{fan}$ is calculated in a similar way to $\dot{W}_{pump}$ by Eq. (4).

In all geothermal power plants, a stream of geothermal fluid is brought to the surface with a pressure and temperature, which exceeds that of the atmosphere and therefore has the ability to do work (exergy). For the analysis, the primary exergy input is the total exergy of the two-phase fluid extracted from the production wells with the reference environment being the mean ambient conditions at the power plant. The overall desired exergy output is the net electrical energy produced. The fluid from the wells undergoes a series of processes from fluid separation to steam cooling (condensation) during which some useful work is extracted.

Overall exergy balance (under steady-state conditions): The exergy entering the system consists of the exergy of the two-phase flow at the wellhead (Ex_{10}) and the exergy of air entering the cooling towers ($Ex_{air,A}$). The exergy leaving the system consists of the net electrical energy generated ($\dot{W}_{net}$), exergy of separated brine disposed (Ex_{12}), exergy loss through drains (Ex_{22}), exergy loss through flash (Ex_{13a}) exergy of gas removal system exhaust (Ex_{31}) and exergy of air leaving the cooling towers ($Ex_{air,B}$). Some exergy ($\sum I_{GPP}$) is destroyed due to the internal irreversibilities of the components, which are in the separator, turbine-generator, condenser, cooling tower, gas removal system and auxiliary equipment. With reference to Figure 1, this can be expressed as below (Kwambai, 2005):

$$Ex_{10} + Ex_{air,A} = Ex_{12} + Ex_{13a} + Ex_{22} + Ex_{heatloss,pipe} + Ex_{31} + Ex_{air,B} + \sum I_{GPP} \quad (5)$$

*Performance criteria: T*he overall objective of this system is to convert the exergy received from the wellhead into net electrical energy, which is the desired output. The rational efficiency will be the ratio of the net electrical energy produced to the total exergy of the geothermal fluids at the wellhead. This is expressed as:

$$\eta_{overall} = \frac{\dot{W}_{net}}{Ex_{10}} \quad (6)$$

In the analysis, for each node the total exergy is calculated as:

$$Ex_{total} = Ex_{liq} + Ex_{st} + Ex_{NCG} \quad (7)$$

The geothermal power plant is simplified into sub-systems, each with distinct exergy inflows and outflows and approximated into steady-state flow. The analysed components are separator, turbine-generator, condenser, cooling tower, gas removal system and auxiliary equipment such as fans and pumps. Main equations of exergy analysis of single-flash GPPs are summarized in Table 2.

3.1 Gas Removal Systems

3.1.1 Steam Jet Ejectors (SJES)

Ejectors remove the NCGs from the condenser and compress them to the atmospheric pressure with the expense of steam. Since an ejector has no valves, rotors, pistons or other moving parts, it is a relatively low-cost component, is easy to operate and requires relatively little maintenance but consumes a considerable amount of steam. Because of the capacity of a single ejector is fixed by its dimensions, a single unit has practical limits on the total compression and throughput it can deliver. For greater compression, two or more ejectors can be arranged in series. Two-stage steam jet ejector system is shown in Figure 2.

Table 2: Main equations of exergy analysis of single-flash GPPs.

Component	Exergy destruction	Exergetic efficiency
Separator	$I_{sep} = Ex_{10} - Ex_{12} + Ex_{13}$	$\eta_{exsep} = \frac{Ex_{13}}{Ex_{10}}$
Demister	$I_{dem} = Ex_{13} - Ex_{14} - Ex_{13a}$	$\eta_{exdem} = \frac{Ex_{14}}{Ex_{13}}$
Steam Turbine- Generator	$I_{t-gen} = Ex_{14} - Ex_{15} + Ex_{W_{gross}}$	$\eta_{ex_{t-gen}} = \frac{Ex_{W_{gross}}}{Ex_{14} - Ex_{15}}$
Condenser	$I_{cond} = Ex_{15} + Ex_{29} + Ex_{30} - Ex_{16} - Ex_{20}$	$\eta_{excond} = \frac{Ex_{16} + Ex_{20}}{Ex_{15} + Ex_{29} + Ex_{30}}$
Cooling Tower	$I_{ct} = Ex_{21} + Ex_{air,A} + Ex_{W_{fan}} - Ex_{22} - Ex_{23} - Ex_{air,B}$	$\eta_{exct} = \frac{Ex_{21} + Ex_{air,A} - I_{ct} - Ex_{22} - Ex_{exhaust}}{Ex_{21} + Ex_{air,A}}$
Water Circulation Pumps	$I_{pump} = Ex_{in} - Ex_{out} + W_{pump}$	$\eta_{ex\,pump} = \frac{Ex_{in} - Ex_{out}}{W_{pump}}$

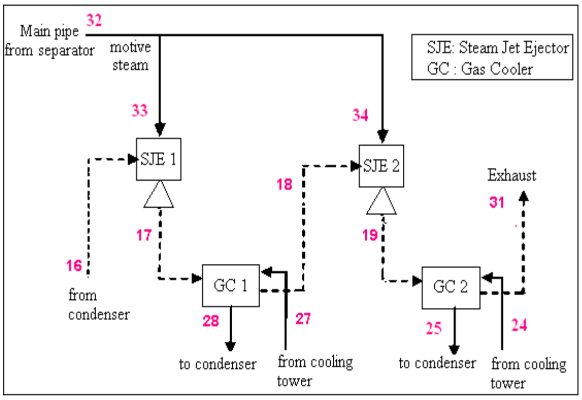

Figure 2: Flow diagram of two-stage steam jet ejector system.

Steam consumption of steam jet ejectors increases with increasing NCG fraction. Therefore, it is important to define the motive steam flow rate precisely (Eq. (8)) (Hall, 1996).

$$\dot{m}_{33} = \frac{TAE_1}{AS_1}, \dot{m}_{34} = \frac{TAE_2}{AS_2} \tag{8}$$

The corresponding work potential of steam consumed can be calculated as in Eq. (9).

$$\dot{W}_{se} = \dot{m}_{32}.(h_{14} - h_{15}) \tag{9}$$

Exergy loss of steam jet ejectors and gas coolers are the difference between exergy input and output and calculated by Eq. (10).

$$I_{sje}, I_{gc} = \sum Ex_{in} - \sum Ex_{out} \tag{10}$$

The exergetic efficiency is the ratio of total exergy output (Ex_{out}) to exergy input (Ex_{in}) of the steam jet ejectors and gas coolers.

$$\eta_{ex_{sje}}, \eta_{ex_{gc}} = \frac{\sum Ex_{out}}{\sum Ex_{in}} \tag{11}$$

3.1.2 Hybrid System (Steam Jet Ejector + LRVP) (HS)

LRVP is a rotary compressor type device and is generally used alone in low flow applications where large pressure ratios are not required. It has been proposed to use it for geothermal applications in series with a steam jet ejector, which would provide the first stage of compression (Hall, 1996). Integration of a steam jet ejector with a LRVP is commonly referred to as a hybrid system. It is one of the more efficient methods for producing a process vacuum. The flow diagram of the hybrid system is shown in Figure 3.

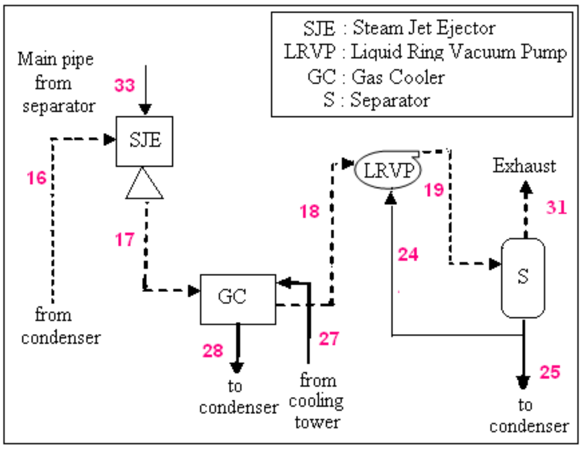

Figure 3: Flow diagram of hybrid system (SE + LRVP).

The LRVP work is calculated by Eq. (12) (Hall, 1996; Siregar, 2004).

$$\dot{W}_{LRVP} = \left[\frac{\gamma}{\gamma - 1}\right]\left[\frac{\dot{m}_{CO_2}.Ru.T_{CO_2}}{\eta_{LRVP}.M_{CO_2}}\right]\left[\left(\frac{P_d}{P_s}\right)^{\left(1-\frac{1}{\gamma}\right)} - 1\right] \tag{12}$$

For liquid ring vacuum pump, the exergy loss is:

$$I_{LRVP} = Ex_{18} - Ex_{19} + \dot{W}_{LRVP} \tag{13}$$

where $\dot{W}_{LRVP}$ is the liquid ring vacuum pump work.

The exergetic efficiency of the liquid ring vacuum pump is calculated as:

$$\eta_{exLRVP} = \frac{Ex_{19} - Ex_{18}}{\dot{W}_{LRVP}} \quad (14)$$

3.1.3 Centrifugal Compressors (CS)

Increasing NCG fraction increases steam consumption of steam jet ejectors and consequently operational cost becomes uneconomical. Centrifugal compressors although expensive to install, have overall efficiencies on the order of 75%. When dealing with large quantities of NCGs this makes them the preferred option compared to the other systems. A two-stage compressor system flow diagram is shown in Figure 4.

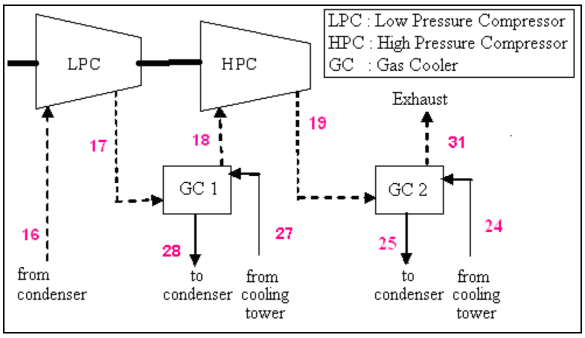

Figure 4: Flow diagram of two-stage compressor system.

Power consumption of the compressors is calculated as Eq. (15).

$$\dot{W}_{comp} = \dot{m}\ .\Delta h \quad (15)$$

Exergy loss of the compressors is calculated with reference to Figure 4 as:

$$\begin{aligned} I_{LPC} &= Ex_{16} - Ex_{17} + \dot{W}_{LPC} \\ I_{HPC} &= Ex_{18} - Ex_{19} + \dot{W}_{HPC} \end{aligned} \quad (16)$$

where W_{LPC} and W_{HPC} are the compressor work of the low and high pressure compressors.

*T*he performance criteria are:

$$\begin{aligned} \eta_{exLPC} &= \frac{Ex_{17} - Ex_{16}}{W_{LPC}} \\ \eta_{exHPC} &= \frac{Ex_{19} - Ex_{18}}{W_{HPC}} \end{aligned} \quad (17)$$

3.1.4 Reboiler System (RS)

Reboiler systems offer the only technology available for removing NCGs from geothermal steam upstream of the turbine. Reboiler technology (vertical tube evaporator type) has been applied at the pilot level at the Geysers, California. During more than 1000 h of accumulated test time, the average H_2S removal efficiency obtained was 94% (Coury and Associates, 1981). Later the same reboiler system was tested at the Cerro Prieto Geothermal Field in Mexico. The nominal capacity of the equipment was 0.4 ton/h of steam and after more than 200 test runs and 3000 operating hours, a mean value of 94% of gas removal efficiency was obtained (Angulo et al., 1986).

A tray-type direct contact reboiler system was applied to 40 MWe Latera Geothermal Power Plant in Italy where the NCG content is 3.5% at the wellhead. This is the first application to the geothermal industry in the world of the reboiler concept on a commercial scale. It was started up in early 1999 and abundant in 2003 because of the environmental problems (Bertani, 2006).

A packed bed direct contact reboiler test process was applied to Kizildere GPP in Turkey. A 3-month test program with an accumulative test run time of approximately 260 hours was completed in January 1999 demonstrating the performance of a bench-scale packed bed direct contact reboiler. The test unit located at the KD 14 wellhead where the NCG content is at the design level (10%). During the tests CO2 removal efficiency was obtained as 76.3±22.6% for a wide range of reboiler parameters (Gunerhan and Coury, 2000).

In this study, a vertical tube evaporator reboiler is used (Figure 5). A vertical tube evaporator is a heat exchanger where the entering geothermal steam is condensed on the shell side. A small amount of the uncondensed steam flows out from the top of the shell side in a vent stream. The condensate is pumped to the top of the heat exchanger, where it enters the tube side and evaporates through the tubes. The clean steam leaving the reboiler contains a small amount of NCGs that the capacity of steam ejector system is reduced. The rejection of NCGs to vent stream and steam/NCG weight ratio in vent gas are taken as 98% and 50%-50%, respectively. Reboiler system requires at least 330 kPa pressure drop between the separator and turbine inlet according to a study for KGPP (Coury, et al., 1996; Vorum and Fritzler, 2000; Gunerhan, 1996).

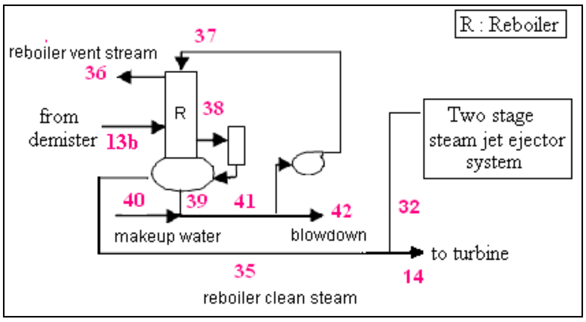

Figure 5: Flow diagram of reboiler system.

The exergy loss of the reboiler is:

$$I_{reboiler} = Ex_{13b} - Ex_{35} - Ex_{36} \quad (18)$$

and the exergetic efficiency of the reboiler is calculated as:

$$\eta_{exreboiler} = \frac{Ex_{35}}{Ex_{13b}} \quad (19)$$

4. RESULTS

For the given data of KGPP and the assumptions made, an exergy analysis is conducted to evaluate four different conventional gas removal options under a range of NCG fraction (0-25%).

Representing the operational conditions of KGPP, NCG content and turbine inlet pressure are taken as 13% and 450 kPa, respectively. Exergy distribution throughout the plant for each gas removal option is evaluated and an example is shown in Figure 6 for compressor gas removal option.

As can be seen in Figure 6, production wells provide a total exergy of 52968 kW at the wellhead. Major exergy destruction occurs due to the separation of steam from geothermal fluid, discharge of the geothermal fluid from the separator, turbine, and generator, cooling tower, condenser and gas removal system.

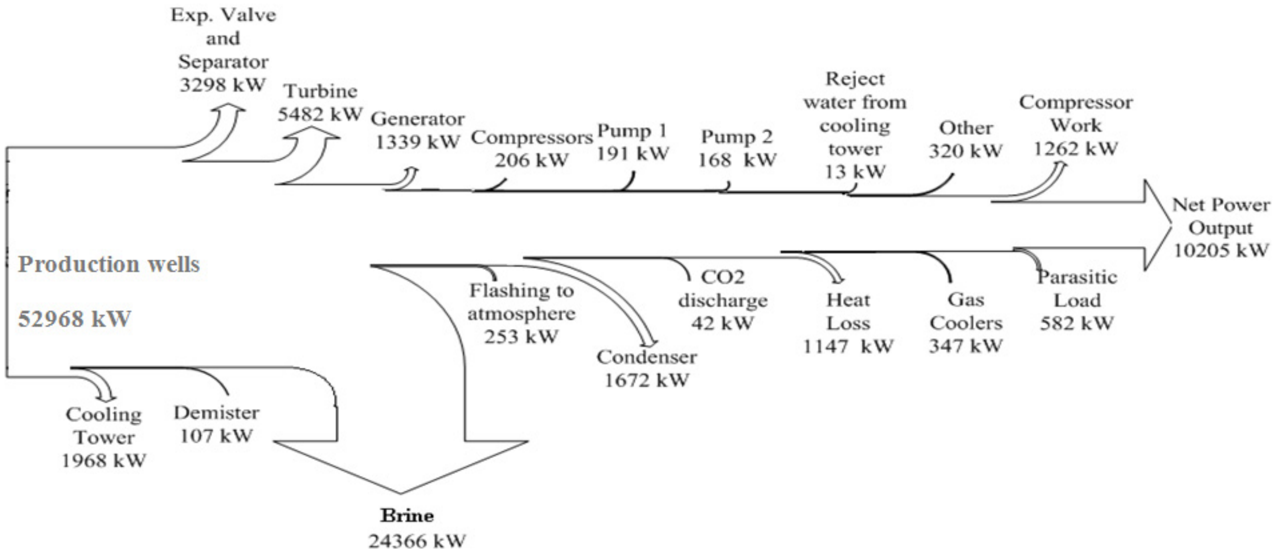

Figure 6: Exergy flow chart of the geothermal power plant with compressor gas removal system.

As the geothermal fluid is flashed into steam and brine in the separators, a total exergy of 3298 kW is destroyed during the separation process itself, and this loss corresponds to 6.2% of the total exergy input. The remaining brine at relatively low temperature and pressure is first sent to the silencer and then is re-injected or directed to the other direct use applications. A total exergy of 24366 kW, which amounts 46% of the total exergy input is brine. The demister is located between separator and turbine. Assuming a 10 kPa pressure drop between separator and turbine, the exergy loss of the demister is calculated as 107 kW and 1% of the steam is flashed in the demister wasting 253 kW of exergy. The exergy loss of the turbine is 5482 kW, which amounts to 10.3% of the total exergy input. More exergy is destroyed in the generator during the conversion of the mechanical shaft work to the electrical energy. This accounts for 2.5% of the total exergy destruction. Cooling tower and condenser are the other vital components with 1968 and 1672 kW exergy destruction, respectively. The pipe between the condenser exit and cooling tower inlet is assumed to have 3°C temperature drop. Therefore, the exergy destruction with heat loss is calculated as 1147 kW. For the gas removal system, the exergy loss is 206 kW for the compressor and 347 kW for gas coolers. The total exergy loss of the gas removal system is 554 kW, which is 1% of the total exergy input. A further usage of exergy output is consumed by internal devices such as auxiliaries, pumps, fans and control systems. This parasitic load is calculated as 582 kW and compressor work is 1262 kW. The total exergy destruction of the plant totals as 42763 kW, which is 80.7% of the total exergy input. The remaining 10205 kW leaves the plant as the net power output.

Exergy distribution of the plant components for each gas removal option are summarised in Table 5 (in kW) and 6 (in %), respectively.

In Figure 7, overall exergetic efficiency of gas removal systems depending on NCG fraction at operational turbine inlet pressure of the KGPP is exhibited. Among the gas removal options, the compressor system accounts the highest overall exergetic efficiency. Reboiler system is the worst option for low NCG fractions, for high NCG fractions it becomes more efficient than steam jet ejector system.

Table 5: Main results of the exergy analysis for all gas removal system alternatives.

Exergy (kW)	Gas Removal System			
	CS	**SJES**	**HS**	**RS**
Exergy losses of main equipment	**38591**	**34543**	**36760**	**40401**
Expansion valve and Separator	3298	3298	3298	1215
Brine	24366	24366	24366	33339
Demister	107	107	107	41
Turbine	5482	2760	4242	2935
Generator	1339	674	1036	672
Condenser	1672	841	1293	911
Cooling tower	1968	2111	2045	1090
Pumps	359	385	374	199
Reject to atmosphere or river	**308**	**307**	**307**	**3238**
Heat loss	**1147**	**1233**	1193	**637**
Other	**320**	**1703**	**348**	**921**
Gas removal system	**554**	**9117**	**5037**	**1738**
Steam jet ejectors	-	3618	2424	93
Liquid ring vacuum pump	-	-	541	-
Compressors	206	-	-	-
Reboiler	-	-	-	1505
Gas coolers	347	5499	2072	141
Auxiliary power	**1844**	**613**	**1899**	**389**
Parasitic load (pumps, fan etc.)	582	613	599	389
Compressor work	1262	-	-	-
Liquid ring vacuum pump	-	-	1300	-
Net power output (kW)	**10205**	**5452**	**7423**	**5655**

Table 6: Overall exergy distribution of all gas removal system alternatives.

	Overall exergy distribution (%)			
Component	**CS**	**SJES**	**HS**	**RS**
Brine	46	46	46	62.9
Expansion valve and separator	6.2	6.2	6.2	2.3
Demister	0.2	0.2	0.2	0.1
Turbine	10.3	10.3	8.0	5.5
Generator	2.5	1.3	2.0	1.3
Condenser	3.2	1.6	2.4	1.7
Cooling tower	3.7	4.0	3.9	2.1
Heat loss	2.2	2.3	2.3	1.2
Gas removal system	1.0	17.2	9.5	3.3
Auxiliary power	3.5	1.2	3.6	0.7
Other	1.9	4.5	1.9	8.2
Net power output	**19.3**	**10.3**	**14.0**	**10.7**

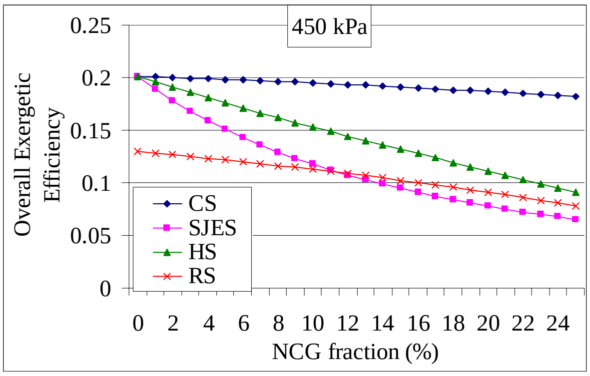

Figure 7: Overall exergetic efficiency of gas removal systems depending on NCG fraction at operational turbine inlet pressure of KGPP.

Table 7: Comparison of exergetic efficiencies of the main components of the plant for different gas removal options at 13% NCG fraction 450 kPa turbine inlet pressure.

Component	Exergetic Efficiency (%)			
	CS	**SJES**	**HS**	**RS**
Turbine-Generator	0.638	0.638	0.638	0.626
Condenser	0.769	0.882	0.821	0.788
Cooling Tower	0.606	0.607	0.607	0.607
Overall	**0.193**	**0.103**	**0.14**	**0.107**

5. CONCLUSIONS

The main conclusions derived from the analysis are:

1) NCG fraction is the most influential factor and net power output of GPPs decrease with increasing NCG fraction.

2) The compressor system is the most efficient and robust system where the influence of the NCG fraction is limited. On the other hand, steam jet ejectors are highly affected by increasing NCG fraction since motive steam flowrate to the steam jet ejectors are directly related to NCG fraction. Thus they prove to be the worst case. The hybrid system responded late to the change in NCG fraction because the LRVP is more efficient since its performance lies between compressors and steam jet ejectors.

3) While the pressure drop between the separator and turbine inlet is as low as 10 kPa for the first three options, 330 kPa should be maintained for the reboiler system. Therefore, the separator pressure is the highest for reboiler option at the same NCG fraction. Increase in separator pressure results in a decrease in steam flowrate thus yielding a lower power output per unit of steam feeding the turbine. This makes the situation more dramatic for reboiler system in a feasibility study. To increase the power output, steam flowrate should be increased by drilling more wells which leads the higher costs of field development.

4) An examination of the exergy destruction throughout the plant reveals that the largest exergy destruction occurs from the brine discharge after flashing processes in the separators. For operational turbine inlet pressure of 450 kPa and 13% NCG fraction, it accounts for 62.9% for the reboiler system and 46% for the other systems of the total exergy input. Therefore, alternative cycles (such as combined cycle, double flash, binary plant etc.) should be considered in order to save considerable amount of the exergy lost in the brine discharge.

5) Exergy analyses indicate that the exergetic efficiency is 60.7% for the cooling tower and around 63% for turbine-generator couple for 450 kPa turbine inlet pressure and 13% NCG fractions. The results show that the cooling tower and turbine-generator couple are the major exergy consumers and they have the largest improvement potential.

6) According to the results of the exergy analyses, the compressor system has the highest overall exergetic efficiency of 19.3% and steam jet ejector system has the lowest overall exergetic of 10.3% for operational condition of KGPP. The overall exergetic efficiencies of hybrid and reboiler gas removal systems are 14% and 10.7% respectively.

7) Besides technical analysis, to better frame the distinction and possible range of NCG fraction for each option, economic analysis should be carried out.

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Nomenclature

Cp : Constant pressure specific heat (kJ/kg K)

Cv : Constant volume specific heat (kJ/kg K)

Ex : Exergy (kW)

h : Enthalpy (kJ/kg)

I : Exergy loss (kW)

M : Molar mass (kg/kmol)

$\dot{m}$: Mass flowrate (kg/s)

P : Pressure (kPa)

Ru : Universal gas constant, 8.314 kJ/(kmol K)

T : Temperature (K)

$\dot{W}$: Power (kW)

TAE : Total air equivalent (kg/s)

AS : Air-steam ratio (-)

Greek symbols

η : Efficiency (-)

$\dot{\upsilon}$: Volume flowrate (m^3/s)

ΔP : Pressure drop (Pa)

γ : The ratio of the Cp_{CO2}/Cv_{CO2} (-)

Subscripts

aux : Auxiliary

comp : Compressor

cond : Condenser

CO_2 : Carbon dioxide

ct : Cooling tower

d : Discharge

dem : Demister

ex : Exergy

fan(s) : Fan(s)

gc : Gas cooler

gen : Generator

grs : Gas removal system

hot,air : Hot air

i : Indice for steam jet ejectors

in : Inlet

liq : Liquid

motor, pump : Motor pump

motor,fan : Motor fan

NCG : Non-Condensable Gas

net : Net

out : Outlet

overall : Overall

pump(s) : Pump(s)

s : Suction

st : Steam

sep : Separator

sje : Steam jet ejector

t : Turbine

t-gen : Turbine-generator

total : Total

wb : Wet bulb

Abbreviations

CS : Compressor System

GPP : Geothermal Power Plant

HPC : High pressure compressor

HS : Hibrid System

LPC : Low pressure compressor

LRVP : Liquid ring vacuum pump

NCG : Non-Condensable Gas

RS : Reboiler System

SJES : Steam Jet Ejector System