

## Thermodynamic Performance of Single-Flash Geothermal Power Plants from the Point of View of Noncondensable Gas Removal Systems

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### ABSTRACT

Geothermal fluids contain Non-Condensable Gases (NCGs) at various amounts. The presence of NCGs in geothermal steam results with a dramatic decrease in net power output increasing condenser pressure and total auxiliary power consumption. Hence, NCGs should be withdrawn by a gas removal equipment to improve the performance of geothermal power plants (GPPs). The flashed-steam GPPs are a relatively simple way to convert geothermal energy into electricity when the geothermal wells produce a mixture of steam and liquid.

The primary aim of the study is to model and simulate single-flash GPPs to examine the thermodynamic performance of NCG removal systems, which are major concerns at planning and basic design stages of GPPs. Four different NCG removal systems, which are two-stage steam jet ejector system, two-stage hybrid system, two-stage compressor system and reboiler system are studied. The model is validated comparing model output with Kizildere GPP output, classified as deterministic and static. In this study, the net power output and specific steam consumption of a single-flash GPPs are evaluated depending on the separator pressure, condenser pressure, NCG fraction and wet bulb temperature of the environment.

### 1. INTRODUCTION

Geothermal power can be produced by dry steam, flashed-steam, binary and Kalina plants depending on the temperature and state of the geothermal fluid. Flashed-steam (single and double-flash) GPPs are the most commonly used power generation systems with a total share of 61% within the installed capacity in the World, mainly because most geothermal reservoirs are formed by liquid dominated hydrothermal systems (Bertani, 2010).

Geothermal steam, which flows through the entire cycle of conventional (dry and flashed-steam) GPPs, contains higher concentrations of noncondensable gases (NCGs) ( $\text{CO}_2$ ,  $\text{H}_2\text{S}$ ,  $\text{NH}_3$ ,  $\text{N}_2$ ,  $\text{CH}_4$  etc.) compared with conventional fossil-fueled power plants. The amount of NCGs contained in geothermal steam has significant impact on the power production performance of a GPP. The NCGs in geothermal steam interfere with heat transfer in the condenser by forming a 'gas-blanketing' effect, which raises the condenser temperature and back-pressure on the turbine, reducing its output. In practice, the gas effect can only be overcome by evacuating them, along with a portion of steam (Vorum and Fritzler, 2000). The power needed to extract the NCGs from the condensers and exhaust them to the atmosphere or an abatement system is supplied from the generated electricity or by steam gas exhausters or a combination of these; this seriously impairs the power production performance (Duthie and Nawaz, 1989). NCGs also decrease the exergy of the fluid reducing the available work in the plant. Thus, evaluation of the net work of the turbine should consider the NCG content (Montero, 1990). Comparing with fossil-fuelled power plants, GPPs require larger capacity NCG removal systems which occupy a large portion in total plant cost. Therefore, selection of NCG removal system becomes a major concern at planning and basic design stages which aim to maximize net power output and minimize both investment and operation and maintenance (O&M) costs of GPPs in a long-term perspective (Tajima and Nomura, 1982; Hankin et al., 1984).

Changes in the resource are usually accompanied by changes in the NCG flow. Depending on the resource, the fraction of the NCGs varies over the World from almost zero to as much as 25% by weight of steam (Hall, 1996; Coury et al., 1996). Because of the elevated NCG levels, GPPs require large capacity NCG removal systems which play a vital role in power generation occupying large portion in its total plant cost and total auxiliary power consumption. Therefore, selection of NCG removal system becomes a major concern at planning and basic design stages of geothermal power plants (Tajima and Nomura, 1982; Hankin et al., 1984).

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%) (SJEs),
- 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).

Besides, innovative upstream reboiler systems are another approach to remove NCGs from geothermal steam before they enter the turbine. Recently, in GPPs hybrid NCG removal system (SJE and LRVP) are most common.

The performance of a geothermal power cycle is influenced by geothermal fluid properties such as temperature, pressure, NCG fraction, separator/condenser pressure (Swandaru, 2006; Siregar, 2004), and wet bulb temperature of environment (Swandaru, 2006). In a specific field, temperature and pressure do not change much in the short-medium term, whereas NCG fraction may vary significantly (Bidini et al., 1999).

This study examines the performance of a single-flash GPP for four different conventional gas removal options, under various separator pressures (100-1000 kPa), NCG fractions (0-20%) and wet bulb temperatures (5-25°C). The single-flash GPP is modelled by a code written in Engineering Equation Solver (EES) (F-Chart, 2014) for two-stage steam jet ejector system (SJES), two-stage hybrid system (HS), which consists of steam jet ejector and LRV, two-stage compressor system (CS) and reboiler system (RS).

## 2. SINGLE-FLASH GPP MODEL

The schematic diagram of a representative single-flash GPP model is shown in Figure 1. The plant mainly consists of production wells, wellhead/main separator(s), turbine, condenser, NCG removal system, cooling tower and auxiliary equipment such as pumps and fans.

Geothermal fluid which is a mixture of liquid, water vapor and NCGs at the wellhead is separated into the steam and liquid phases at the separator. Steam phase is directed to the turbine contains water vapor and NCGs. A demister is employed prior to the turbine to remove the condensate from the steam and make sure dry steam is introduced to the turbine. After passing the turbine; steam, condensate and NCGs flow to the condenser. The primary purpose of the condenser is to condense the exhaust steam leaving the turbine. NCGs are accumulated and extracted by a gas removal system from the condenser. The rest is pumped to the cooling tower which helps to decrease the temperature as the fluid drops down through the cooling tower to be re-used in the condenser. Liquid phase is driven by circulation pumps and air is drawn into the cooling tower by fans.

Generally, condensers are operated at the lowest temperature possible results in maximum turbine work and cycle efficiency and in minimum heat rejection. The typical condensate temperature attained in practice is 45-50°C, corresponding to a condenser pressure of 9.6-12.5 kPa-abs (El-Wakil, 1984; Moghaddam, 2006).

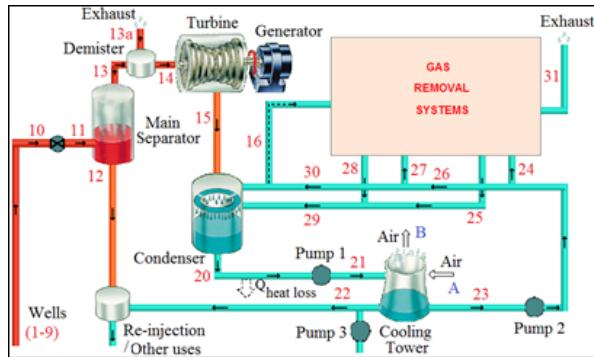


Figure 1: Schematic diagram of representative single-flash GPP.

The GPP model is simplified into sub-modules, which are separator-demister, turbine-generator, condenser, cooling tower, NCG removal system and auxiliary power (fans and pumps) modules, each with distinct mass and energy inflows and outflows and approximated into steady-state flow.

## 3. METHODOLOGY

The general assumptions and constant parameters of representative single-flash GPP model are listed in Table 1. The thermodynamic model uses the data of Kizildere Geothermal Power Plant (KGPP)-Turkey, which is a single-flash plant with extremely high NCG fraction, to allow a comparison between the results of the modelling and the operational data of an actual single-flash GPP.

Table 1: Input parameters of the thermodynamic model.

Parameters	Values	Parameters	Values
Flowrate of Wells (kg/s)	281.6	NCG removal system final stage discharge	105
Pressure of Wells (kPa)	1,800	Water temperature at cooling tower exit (°C)	29
Wellhead Pressure (kPa)	1,330	Generator efficiency (%)	90
Separator Pressure (kPa)	460	Compressor efficiency (%)	75
Temperature of Wells (°C)	204.7	LRVP Efficiency (%)	40
NCG fraction at main separator exit (%)	13	Fans/Circulation pumps efficiency (%)	70
Condenser Pressure (kPa)	10	Dead state pressure (kPa)	985
Pressure drop between main separator exit and turbine inlet (kPa)	10	Fans/Circulation pumps motor efficiency (%)	85
Pressure drop throughout the reboiler (kPa)	320	Dead state temperature (°C)	16
Pressure drop of fans/circulation pumps (kPa)	0.1	Dead state relative humidity (%)	65

The other main assumptions are;

- Geothermal fluid is a saturated vapor-liquid mixture at the wellhead.
- The presence of NCGs is treated as only CO<sub>2</sub> since it constitutes over 90% of the NCGs in most liquid dominated geothermal fields (Michaelides, 1982).
- Geothermal fluid properties at each state are determined by considering the geothermal fluid is a mixture of liquid, water vapor and NCGs stream.

- For all processes of the power plant,  $\text{CO}_2$  is considered not to dissolve in the water.
- Turbine efficiency is calculated according to Baumann Rule (DiPippo, 1982) and the calculation of isentropic quality considers the existence of NCGs.
- The temperature difference between cooling water entering the cooling tower and hot air leaving the cooling tower is  $6^\circ\text{C}$  (Siregar, 2004; Swandaru, 2006).
- The temperature drop of the condenser exit to the cooling tower entrance is  $3^\circ\text{C}$  (Swandaru, 2006).
- The temperature of  $\text{CO}_2$  gas is assumed same as to the wet bulb temperature of cooling water (Swandaru, 2006).
- NCG removal systems are considered as two-stage and each stage is assumed to use equal pressure ratios.
- The pressure drop throughout the inter and after condensers is assumed as 1 kPa.

The general equations of mass and energy balance used in the static (steady-state, steady-flow) model are summarized in Table 2.

**Table 2: General equations of the model.**

Equation	Equation Number
$\dot{m} = \dot{m}_l + \dot{m}_s + \dot{m}_{NCG}$	(1)
$x = (\dot{m}_s + \dot{m}_{NCG}) / \dot{m}$	(2)
$f = \dot{m}_{NCG} / (\dot{m}_s + \dot{m}_{NCG})$	(3)
$\sum (\dot{m}) = \sum (\dot{m})$	(4)
$\dot{m}_l = \dot{m} (1-x) \times \dot{m}_{out}$	(5)
$\dot{m}_s = x \times (1-f) \times \dot{m}$	(6)
$\dot{m}_{NCG} = x \times f \times \dot{m}$	(7)
$\dot{m} \times h = \dot{m}_l \times h_l + \dot{m}_s \times h_s + \dot{m}_{NCG} \times h_{NCG}$	(8)
$\sum (\dot{m} \times h)_{in} = \sum (\dot{m} \times h)_{out}$	(9)

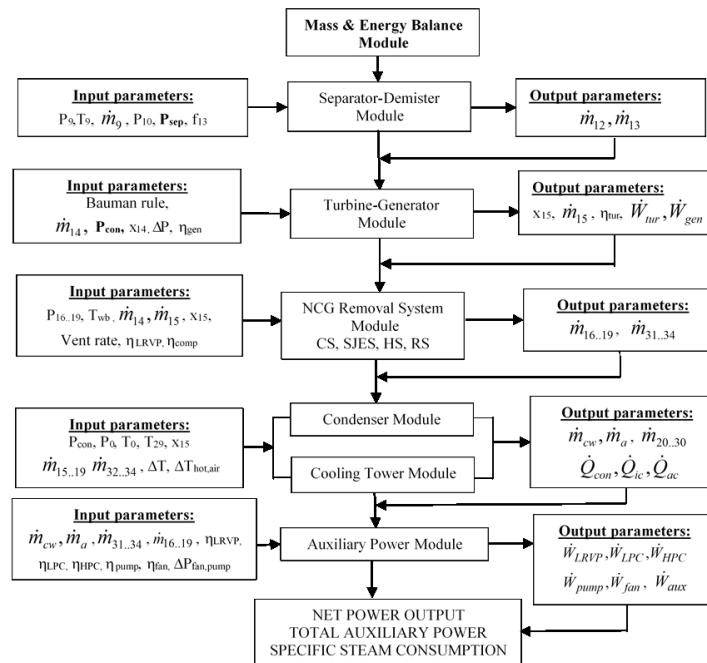
Overall mass and energy balance for steady-state conditions with reference to Figure 1, can be expressed as below (Kwambai, 2005). The subscript numbers refer to state locations on Figure 1.

$$\dot{m}_{10} + \dot{m}_{air_A} = \dot{m}_{12} + \dot{m}_{13a} + \dot{m}_{22} + \dot{m}_{31} + \dot{m}_{air_B} \quad (10)$$

$$\dot{W}_{net} = \dot{W}_{gen} - \sum \dot{W}_{aux} \quad (11)$$

$$\dot{W}_{aux} = \dot{W}_{grs} + \dot{W}_{motor,pump} + \dot{W}_{motor,fan} + \dot{W}_{other} \quad (12)$$

The flow diagram of mass and energy balance model is demonstrated in Figure 2.



**Figure 2: Flow diagram of mass and energy balance module.**

Figure 2 exhibits the input and output parameters of each sub-module. The sub-models work simultaneously using output parameters of each sub-module as input parameters of the others. The main output of the module is net power output, total auxiliary power of the plant and specific steam consumption of the plant. First step of the module is to determine the optimum separator and condenser pressures which give the maximum net power output and minimum total auxiliary power. The main equations of the sub-models except NCG Removal System Module are summarized in Table 3.

**Table 3: Main equations of the sub-modules.**

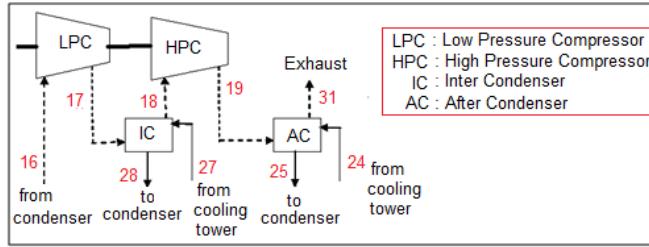
Components	Equation	Equation Number	Components	Equation	Equation Number
Separator-Demister	$h_{11} = h_{10}$	(13)	Turbine-Generator	$\dot{W}_{tur} = \dot{m}_{14} \times (h_{14} - h_{15})$	(24)
	$P_{11} = P_{12} = P_{13} = P_{sep}$	(14)		$\eta_{tur} = \dot{W}_{tur} / \dot{W}_{tur,is}$	(25)
	$x_{11} = \frac{h_{11} - h_{12}}{h_{13} - h_{12}}$	(15)		$\eta_{tur} = \frac{h_{14} - h_{15}}{h_{14} - h_{15,is}}$	(26)
	$\dot{m}_{13} = x_{11} \dot{m}_{11}$	(16)		$\eta_{tur} = 0.85 \times (1 - 1.2 \times (1 - x_{15,is}))$	(27)
	$\dot{m}_{12} = (1 - x_{11}) \times \dot{m}_{11}$	(17)		$x_{15,is} = (s_{15,is} - s_{l,15}) / (s_{15} - s_{l,15})$	(28)
	$\dot{m}_{13a} = 0.01 \times \dot{m}_{13}$	(18)		$\dot{W}_{gen} = \dot{W}_{tur} \times \eta_{gen}$	(29)
Condenser	$\dot{Q}_{con} = \dot{m}_{15} \times h_{15} - \dot{m}_{16} \times h_{16} - [\dot{m}_{l,15} + (\dot{m}_{s,15} - \dot{m}_{s,16})] \times h_{20}$	(19)	Auxiliary Power	$\dot{m}_{makeup} = 1.22 \times Evaporation loss$	(30)
	$\dot{m}_{30} = \frac{\dot{Q}_{con} - \dot{m}_{29} \times (h_{20} - h_{29})}{h_{20} - h_{30}}$	(20)		$Evaporation loss = \dot{m}_a \times (\omega_2 - \omega_1)$	(31)
Cooling Tower	$h_{a_A} + \omega_A \div h_{s_A} + W_{21} \times h_{l_{21}} = h_{a_B} + \omega_B \times h_{s_B} + W_{23} \times h_{l_{23}}$	(21)		$Drift and blowdown losses = 0.22 \times Evaporation loss$	(32)
	$\omega_B - \omega_A = W_{21} - W_{23}$	(22)		$\dot{W}_{pump} = (\dot{V}_l \times \Delta P) / \eta_{pump}$	(33)
	$\dot{m}_a = \dot{m}_{cw} / W_{21}$	(23)		$\dot{W}_{motor,pump} = \dot{W}_{pump} / \eta_{motor,pump}$	(34)

### 3.1. NCG Removal Systems Model

The study is focused on gas removal systems of single-flash GPPs. NCG removal system sub-module contains equations for four different NCG removal systems. Using the optimum separator and condenser pressures, the module runs for NCG removal systems to calculate net power output and total auxiliary power of the plant.

#### 3.1.1 Compressor System (CS)

Increasing NCG fraction increases steam consumption of steam jet ejectors and consequently operational cost becomes uneconomic. Centrifugal compressors although expensive to install, have overall efficiencies in order of 75%. When dealing with large quantities of NCGs this makes them the preferred option compared to the other systems (Swandaru, 2006). Centrifugal compressors are expensive to install and maintain. In some cases, compression of NCG requires up to 20% of the power produced by the plant. But they are nearly 30% more efficient than LRVPs and 250% more efficient than SJEs (Barber-Nichols, 2010). Kizildere GPP employs the compressors as NCG removal system. A two-stage CS flow diagram is shown in Figure 3.



**Figure 3: Two-stage CS flow diagram.**

Compression is ideally an isentropic process. To determine the actual enthalpy at compressor exit is quite complex since the geothermal steam is a mixture of water vapor and CO<sub>2</sub>. Therefore, the isentropic enthalpies of water vapor and CO<sub>2</sub> are calculated separately. Then, the isentropic enthalpy of the mixture is calculated using the mass flowrate of water vapor and CO<sub>2</sub> and their isentropic enthalpies.

$$h_{17,is} = \frac{\dot{m}_{s,17} \times h_{s,17,is} + \dot{m}_{NCG,17} \times h_{NCG,17,is}}{\dot{m}_{17}} \quad (35)$$

The actual enthalpy at the compressor exit is calculated using Eq. 36.

$$\eta_{comp} = \frac{h_{17,js} - h_{16}}{h_{17} - h_{16}} \quad (36)$$

### 3.1.2 Steam Jet Ejector System

The most commonly used gas removal system is steam jet ejector, which removes the NCGs from the condenser and compress them to the atmospheric pressure with the expense of steam. An ejector is a type of vacuum pump or compressor. 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.

A steam jet ejector operates on the venture principle. The motive steam is expanded through the nozzle to the design suction pressure. The pressure energy of the steam is converted to velocity energy and on leaving the nozzle at high supersonic velocities the steam passes through the suction chamber and enters the converging diffuser or entrainment, as gas and associated water vapor. Because of the capacity of a single ejector is fixed by its dimensions, a single unit has practical limits on the total compression and throughout it can deliver. For greater compression, two or more ejectors can be arranged in series (Hall, 1996; Swandaru, 2006; Birgenheier et al., 1993). In a multi-stage system, inter-condensers are typically used between the stages. By condensing the vapour prior to the next stage, the vapour load is reduced. This allows smaller gas removal systems to be used, and reduces steam consumption. An after-condenser can also be added, to condense vapour from the final stage. This will not affect overall system performance, but may ease disposal of vapour and acts as a noise suppressor (Swandaru, 2006; Birgenheier et al., 1993).

Two-stage SJES flow diagram is shown in Figure 4.

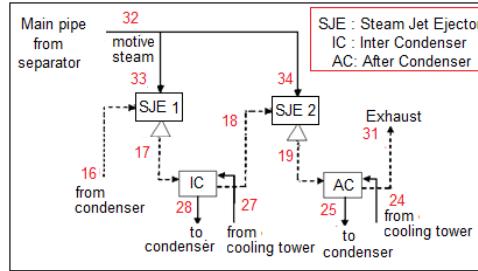


Figure4: Two-stage SJES flow diagram.

The suction and discharge pressure of each stage is determined by the following calculations (Geothermal Institute, 1996b). Each stage uses equal pressure ratios based on system suction and discharge pressure of 90% condenser pressure and 105 kPa. SJEs are feed by the motive steam, which leaves the separator. Between the stages the gas coolers are used. Dalton's laws of partial pressure and ideal gas equations are used to calculate necessary motive steam flowrate at point 33 and 34 (Hall, 1996). The air steam ratio (AS) can be found by Air to steam ratio curve (Geothermal Institute, 1996b) that has been transformed into a small program in EES called procedure ratio\_1. Inputs required for this program are the expansion ratio and the compression ratio.

The formulas in Table 4 are used to calculate in SJES model.

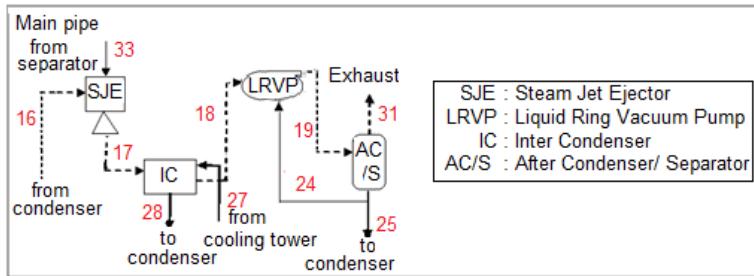
Table 4:Main equations of the SJES model.

The suction and discharge pressures	$\frac{P_{17}}{P_{16}} = \frac{P_{19}}{P_{18}}$	(37)
The entrainment ratio for NCG	$E_{NCG} = \left[ \left( 5.73 \times 10^{-4} + 18.36 \right) + \frac{\left( 2.01 \times (M_{NCG}^{0.86}) \right)}{\left( 18.36 + (M_{NCG}^{0.86}) \right)} \right]$	(38)
The entrainment ratio for steam	$E_s = \left[ \left( 5.73 \times 10^{-4} + 18.36 \right) + \frac{\left( 2.01 \times (M_{H_2O}^{0.86}) \right)}{\left( 18.36 + (M_{H_2O}^{0.86}) \right)} \right]$	(39)
Total air equivalent	$TAE = \left[ \frac{\dot{m}_{NCG}}{E_{NCG}} + \frac{\dot{m}_s}{E_s} \right]$	(40)
Expansion ratios	$Er_1 = \frac{P_{33}}{P_{16}} \quad Er_2 = \frac{P_{34}}{P_{18}}$	(41)
Motive steam mass flow rate	$\dot{m}_{33} = \frac{TAE_1}{AS_1} \quad \dot{m}_{34} = \frac{TAE_2}{AS_2}$	(42)

### 3.1.3 Hybrid System

Liquid ring vacuum pumps (LRVPs) belong to the group of positive displacement pumps. The characteristic feature of this pump type is the energy transmission from the impeller to the fluid pumped by means of a liquid ring. LRVPs have relatively high efficiency but high capital cost and are generally used alone in low flow applications where large pressure ratios are not required. To increase the gas removal system efficiency LRVPs are used in series with a steam jet ejector, which would provide the first stage of compression. Integration of a steam jet ejector with a LRVP is commonly referred as a hybrid system. LRVP is a rotary compressor type device and can be used alone in low flow applications where large pressure ratios are not required ((Hall, 1996).

The flow diagram of HS which is a combination of SJE and LRPV is demonstrated in Figure 5.



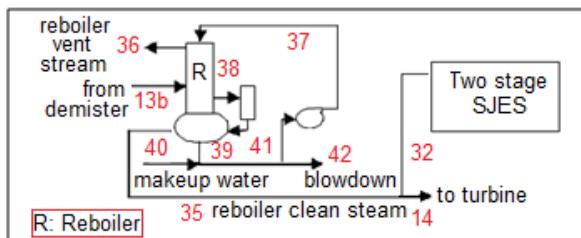
**Figure 5:**The flow diagram of HS.

The power of the LRPV is calculated by the following equation (Siregar, 2004):

$$\dot{W}_{LRVP} = \left[ \frac{\gamma}{\gamma-1} \right] \frac{\dot{m}_{NCG} \times Ru \times T_{NCG}}{\eta_{LRVP} \times M_{NCG}} \left[ \left( \frac{P_{19}}{P_{18}} \right)^{1-\frac{1}{\gamma}} - 1 \right] \quad (43)$$

### 3.1.4. Reboiler System

RSs offer the only technology available for removing NCGs from geothermal steam upstream of the turbine. In this study, a vertical tube evaporator reboiler is used (Figure 6). Wellhead steam enters the shell side of the exchanger near the bottom. The shell side is at a pressure and temperature slightly higher than the tube side. The temperature difference will result in steam condensing on the shell side and condensate evaporating on the tube side. Most of the NCGs will be exhausted in the vent stream. Condensate from the sump is pumped to the heat exchanger tubes where a fraction of the liquid flowing down will evaporate in a single pass (Awerbuch et al., 1984). Vertical tube evaporator reboiler technology has been applied at the pilot level at the Geysers, California. During more than 1000h of accumulated test time, the average H<sub>2</sub>S removal efficiency obtained was 94% (Coury and Associates, 1981).



**Figure 6: RS flow diagram.**

The rejection of NCGs to vent stream and steam/NCG weight ratio in vent gas are taken as 98% and 50%-50%, respectively. Blowdown is taken as 1%. RS 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).

$$\dot{m}_{NCG,36} = 0.98 \times \dot{m}_{NCG,13b} \quad (44)$$

$$\dot{m}_{s,36} = \dot{m}_{NCG,36} \quad (45)$$

$$\dot{m}_{s,42} = (\dot{m}_{s,13b} - \dot{m}_{s,36}) \times 0.01 \quad (46)$$

### 3.1.5. Inter and After Condensers

In a multi-stage system, inter and after condensers are typically used between the stages. By condensing the vapor prior to the next stage, the vapor load is reduced. This allows smaller NCG removal systems to be used, and reduces steam consumption. After

condenser can also be added to condense vapor from the final stage. Adding an after condenser will not affect overall system performance, but may ease disposal of vapor and acts as a noise suppressor. (Birgenheier et al., 1993; Swandaru, 2006).

#### 4. RESULTS

For the given data of KGPP and the assumptions made, thermodynamic analysis is carried out and the impacts of separator pressure, NCG fraction, wet bulb temperature on the net power output and specific steam consumption are discussed. Then, the results are compared with the operational data of KGPP.

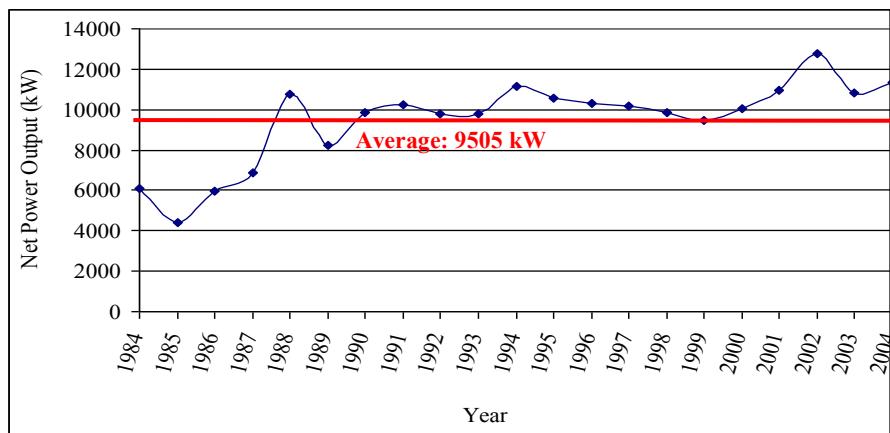
The main results of the mass and energy balance of the plant are presented in Table 5.

**Table 5: Main results of the mass and energy balance of the plant with Kizildere operational data.**

NCG Removal System		CS	SJES	HS	RS
Separator Pressure (kPa)	460	460	460	460	
Condenser Pressure (kPa)	10	10	10	10	
Auxiliary Power (kW)	Compressor /LRVP	1262		1299	
	Steam Jet Ejector *		6666	3038	180
	Water Circ.Pumps	346	372.4	360.3	192
	Cooling Tower Fans	86.3	91.5	89.8	47.2
	Other	150	150	150	150
	TOTAL	1844	7279	4936	569.2
Net Power Output (kW)	10235	5466	7447	5667	

#### 4.1 Validation of the Model

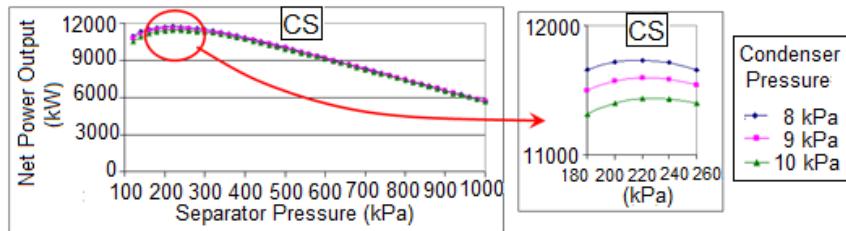
The model is validated only with the annual average electricity production capacity (net power output) of Kizildere GPP, which uses compressors as NCG removal system, since the recorded data of the plant components are limited. Figure 7. indicates that the average net power output of Kizildere GPP in 1984-2004 is 9505 kW (DPT, 2001; Yildirim and Gokcen, 2004). By using actual annual operational data of Kizildere GPP, listed in Table 1, net power output of CS is computed by the model as 10235 kW (Table 5), which is within 7.7% in recorded data.



**Figure 7: Annual average net power output of Kizildere GPP (Source: DPT, 2001; Yildirim and Gokcen, 2004)**

#### 4.2 Impact of Separator Pressure

To evaluate the effects of condenser and separator pressures on thermodynamic performance of the plant net power output of the plant is calculated for condenser and separator pressures of 8-10 kPa and 100-1000 kPa, respectively. The net power output versus separator pressures are shown in Figure 8 at 13% NCG fraction. It is seen that from Figure 8 increasing separator pressure increases the net power output upto a peak value, which corresponds to optimum separator pressure. Further increase in separator pressure shows a dramatic decrease in net power production caused by a consequent decrease in steam flow rate. Optimum separator pressures obtained from the Figure 8 is 220 kPa for CS, 500 kPa for SJES, 340 kPa for HS and 580 kPa for RS at 13% NCG fraction.



**Figure 8: Net power output of the plant for various separator and condenser pressures at 13% NCG fraction.**

Generally, GPPs operate at off-design conditions. To be able to compare thermodynamic performance of the plant with operational and optimum separator pressures, net power output and auxiliary power of the plant are calculated at optimum separator pressure for each NCG removal system and the results, which are summarized in Table 6, show that the net power outputs are increased as 0.2-11.7% by using optimum separator pressures. As an example, the net power output of the CS is calculated as 11436 kW at optimum separator pressure of 220 kPa at 13% NCG fraction. An average operational separator pressure of KGPP is as high as 360 kPa. The decrease in net power output is approximately 1.2 MW (11.7%) because of the elevated operational separator pressure.

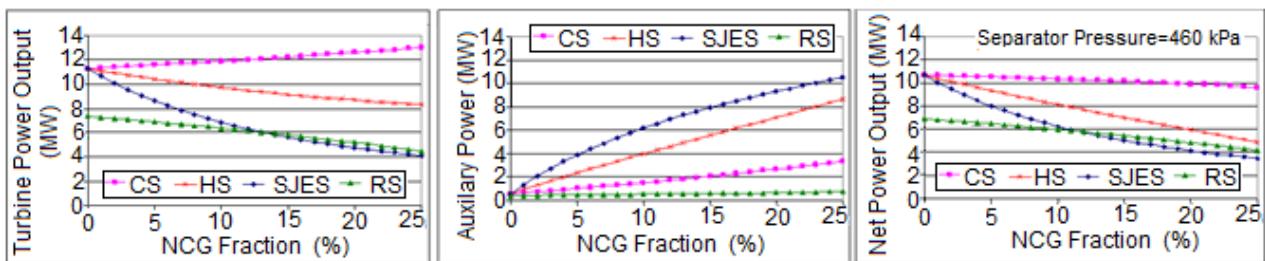
**Table 6: Main results of mass and energy balances of the plant at optimum separator pressures.**

NCG Removal System	CS	SJES	HS	RS
Optimum Separator Pressure (kPa)	220	500	340	580
Condenser Pressure (kPa)	10	10	10	10
Auxiliary Power (kW)	Compressor /LRVP	1749		1518
	Steam Jet Ejector *		6239	3645
	Water Circulation	486	353	424
	Cooling Tower Fans	121	87	106
	Other	150	150	150
	TOTAL	2506	6829	5843
Net Power Output (kW)	11436	5476	7712	6294

\* Consumed motive flow rate is converted into power in kW.

#### 4.3 Impact of NCG Fraction

The effect of NCG fraction on the turbine power output, auxiliary power and net power output at the conditions, given in Table 1, for a 0-25% range of NCG fraction are plotted in Figure 9. The Figure indicates that, auxiliary power increases and net power output decreases with increasing NCG fraction. The plant which is employed with compressors generates highest net power output at each NCG fraction. Increment in NCG fraction (1%) causes a net power output loss of 0.4% for CS, 2.2% for HS, 2.5% for RS and 2.7% for SJES. Especially, SJES has a dramatical decrease on net power output by NCG fraction. On the other hand, it is interesting to see, the turbine power output of CS increases with increasing NCG fraction. The reason for that is increment in steam quality at the separator by considering NCG in the steam. Therefore, separator pressure has vital importance for maximizing the net power output.



**Figure 9: Turbine power output, net power output and auxiliary power of the plant vs. NCG fraction.**

In Figure 10 separator pressure versus net power output of the plant for various NCG fractions (0-25% by weight of steam) is demonstrated at 10 kPa condenser pressure. The Figure 10 indicates that each option exhibits the same behavior for zero NCG fraction except RS. Because RS requires at least 330 kPa pressure drop between the separator and turbine inlet, while the other NCG removal systems require 10 kPa.

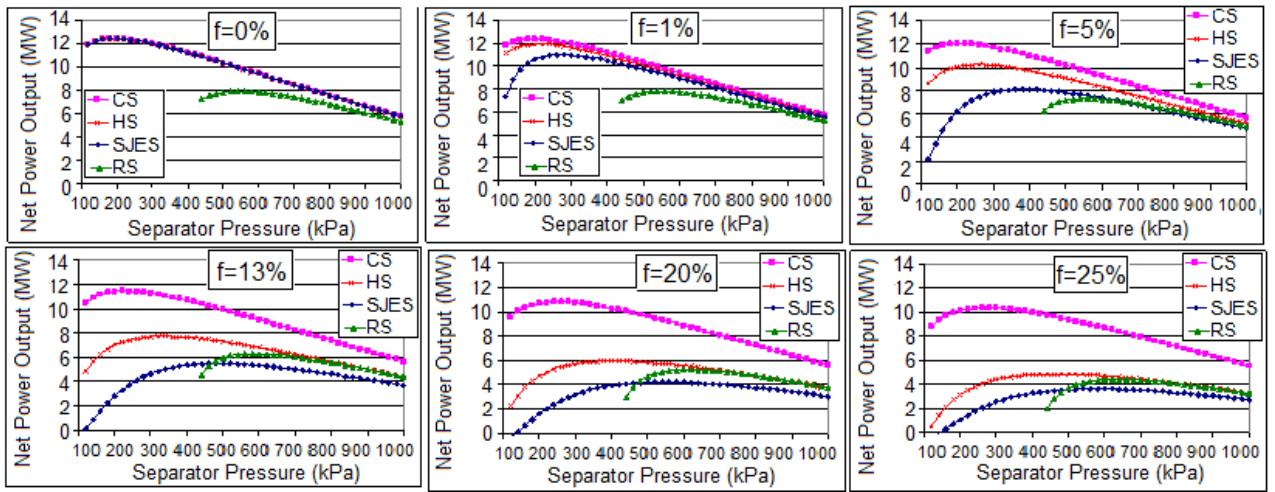


Figure 10: Separator pressure vs net power output of the plant for various NCG fractions.

Figure 11 gives a better insight of the optimum separator pressures depending on NCG fraction. Increasing NCG fraction increases optimum separator pressures for each NCG removal system.

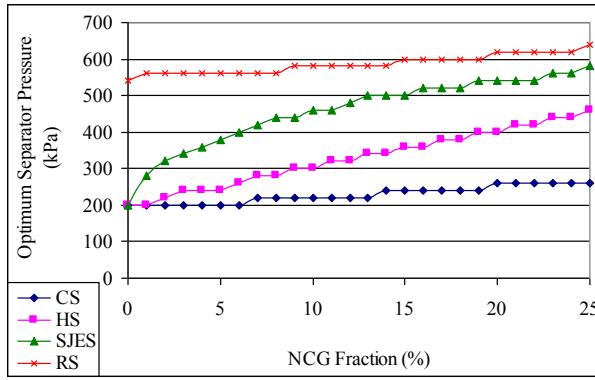


Figure 11: Optimum separator pressures vs. NCG fraction.

#### 4.4 Impact of Wet Bulb Temperature

Wet bulb temperature is an important parameter to determine the motive steam flowrate for the NCG removal system. The performance of power plants changes throughout the year depending on the wet bulb temperature as a function of outdoor temperature and relative humidity. Wet bulb temperature is the most important controlling parameter on cooling towers. Since cooling towers are parts of the gas removal systems, which maintain the cooling water for condenser where the NCGs are extracted from, the influence of wet bulb temperature should be studied closely. In Figure 12 and Table 7, wet bulb temperature vs. net power output and auxiliary power of the plant at optimum condenser and separator pressures are shown.

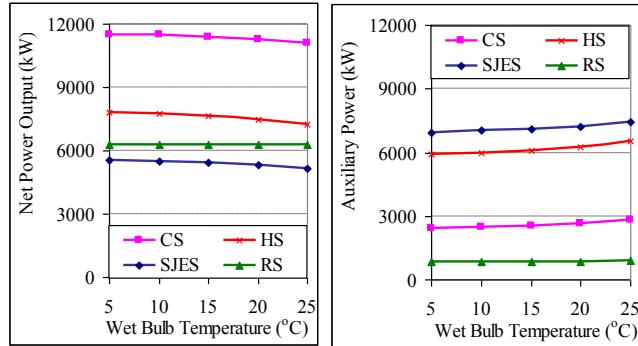


Figure 12: Net power output and auxiliary power of the each system vs. wet bulb temperature.

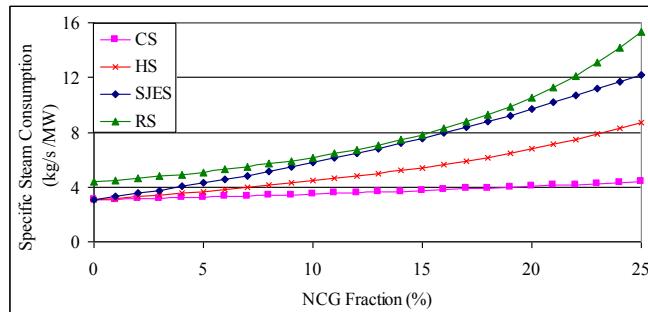
**Table 7: Wet bulb temperature vs net power output and auxiliary power of the plant.**

Wet Bulb Temperature (oC)		5	10	15	20	25
CS	Net Power Output (kW)	11514	11464	11391	11280	11104
	Auxiliary Power (kW)	2428	2478	2551	2662	2838
SJES	Net Power Output (kW)	5561	5507	5430	5316	5144
	Auxiliary Power (kW)	6955	7015	7101	7228	7419
HS	Net Power Output (kW)	7819	7748	7643	7485	7236
	Auxiliary Power (kW)	5897	5977	6093	6269	6545
RS	Net Power Output (kW)	6302	6297	6289	6276	6257
	Auxiliary Power (kW)	824	831	840	853	875

As it can be observed from Figure 12, the net power output of the plant decreases with increasing wet bulb temperature. This is because increasing the wet bulb temperature, increases the motive steam flowrate, since the auxiliary power increases. The results of Table 6 is depicted that net power output is decreased as 0.18% for CS, 0.37% for SJES and HS and 0.04% for RS, while auxiliary power is increased as 0.84% for CS, 0.33% for SJES, 0.55% for HS and 0.31% for RS by 1°C increment in wet bulb temperature.

#### 4.5 Specific Steam Consumption

Specific steam consumption, which is the ratio of steam flowrate at separator exit to net power output of the plant, is one of the criteria to evaluate the performance of GPPs. Specific steam consumption depending on NCG fraction for 360 kPa operational separator pressure of KGPP is plotted in Figure 13. RS has the highest and CS has the lowest specific steam consumption among NCG removal systems. Specific steam consumption is increased as approximately 1.73% for CS, 7.38% for HS, 10.07% for RS and 11.94% for SJES by 1% increment in NCG fraction and it is observed that, while specific steam consumption of CS does not change very much by increasing NCG fraction, specific steam consumption of SJES changes dramatically.

**Figure 13: Specific steam consumption for various NCG fractions.**

#### 4. CONCLUSIONS

The results of modeling and simulation of flashed- steam GPPs have been summarized. The model has been confirmed using data of Kizildere GPP as input parameters. Simulation parameters are wet bulb temperature, separator pressure, condenser pressure and NCG fraction.

Main conclusions are listed below:

- Optimum condenser pressure for each NCG removal system is determined as 10 kPa.
- Optimum separator pressures are determined as 220 kPa, 340 kPa, 500 kPa and 580 kPa for CS, HS, SJES and RS, respectively.
- Thermodynamic performance of single- flash plant can be improved by 0.2-11.7% running the separator and condenser pressures on their optimum values. GPPs should be urged to operate around design conditions to generate optimum net power.
- Net power output is decreased by 0.18% for CS, 0.37% for SJES and HS and 0.04% for RS by 1°C increment in wet bulb temperature.
- Specific steam consumption is the highest for RS and lowest for CS. As an example at 460 kPa separator pressure; for 2% NCG fraction, RS consumes 47.4% more steam than CS, for 13% NCG fraction it is 97.4%.
- 1% increment in NCG fraction results a decrement on net power output as 0.4% for CS, 2.2% for HS, 2.7% for SJES and 2.5% for RS.
- Based on the results of the thermodynamic modeling, CS is the best gas removal option in terms of the highest net power output and lowest auxiliary power for Kizildere GPP operational conditions. On the other hand, RS is the worst option for

entire NCG fraction range. HS is responded late to the change in NCG fraction because the LRP is more efficient since its performance lies between CS and SJES.

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## NOMENCLATURE

AS : Air-steam ratio (-)

$C_p$	: Constant pressure specific heat (kJ/kgK)
$C_v$	: Constant volume specific heat (kJ/kgK)
$E$	: Entrainment ratio (-)
$Er$	: Expansion ratio
$f$	: Noncondensable gas fraction (% weight of steam)
$h$	: Enthalpy (kJ/kg)
$M$	: Molar mass (kg/kmol)
$\dot{m}$	: Mass flowrate (kg/s)
$P$	: Pressure (kPa)
$R_u$	: Universal gas constant, 8.314 kJ/(kmol K)
$\dot{Q}$	: Heat load (kW)
$T$	: Temperature (K)
$TAE$	: Total air equivalent (kg/s)
$\dot{V}$	: Volume flowrate (m <sup>3</sup> /s);
$W$	: Mass of circulating water per unit mass of dry air (-);
$\dot{W}$	: Power/Work (kW)
$x$	: Quality (-)

Greek letters

$\eta$	: Efficiency (%)
$\mathcal{V}$	: the specific volume of the water vapor (m <sup>3</sup> /kg)
$\Delta P$	: Pressure drop (Pa)
$\gamma$	: $C_p/C_v$ (-)
$\Delta T$	: Temperature difference (°C)
$\omega$	: Humidity ratio (-)

Subscripts

0	: Refers to the environmental state
a	: Dry air
ac	: After-condenser
air, A	: Air inlet
air, B	: Air outlet
aux	: Auxiliary
comp	: Compressor
con	: Condenser
ct	: Cooling tower
cw	: Cooling water
dem	: Demister
gen	: Generator
grs	: Gas removal system
$i$	: Indice for steam jet ejectors
ic	: Inter-condenser
in	: Input/ inlet
is	: Isentropic
l	: liquid stream
out	: Output/ outlet
s	: Steam stream
sep	: Separator
sje	: Steam jet ejector
tur	: Turbine