Thermodynamic assessment of gas removal systems for single-flash geothermal power plants

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ABSTRACT

Geothermal fluids contain non-condensable gases (NCGs) at various amounts. NCGs flow to a conventional geothermal power plant (GPP) with steam phase and should be withdrawn from the condenser by a gas removal system to prevent increase in condenser pressure and consequently decrease in power generation. Therefore, to remove NCGs from the system is critical especially at high NCG fractions. In this study, the net power output and specific steam consumption of a single-flash GPP is evaluated depending on the separator pressure, NCG fraction and wet bulb temperature of the environment, and three different conventional gas removal options which are two-stage steam jet ejector system, two-stage hybrid system and two-stage compressor system. A simulation code is written in EES to model the plant for each option. The 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. Under given conditions, thermodynamic analysis resulted that NCG fraction is the most significant factor on GPP performance and the compressor system is the most efficient and robust option where the influence of the NCG fraction is limited.

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1. Introduction

Flash-steam geothermal power plants (GPPs) are the most commonly used power generation systems with a total share of 63% within the installed capacity in the World, mainly because most geothermal reservoirs are formed by liquid dominated hydrothermal systems. Of this, 59% is single-flash plants [1,2].

The steam used in GPPs, is not pure but contains non-condensable gases (NCGs) (CO_2, H_2S, NH_3, N_2, CH_4, etc.), which have significant impact on power generation performance of a GPP. Depending on the resource, the fraction of the NCGs can vary from less than 0.2 wt% to greater than 25 wt% of steam [3–5].

Literature reveals quite a number of studies on the influence of NCGs on GPP performance [3,6–16]. The authors reported that the presence of NCGs in geothermal steam, results with a dramatic decrease in the net power output compared to clean steam because of two factors. First, gas removal system which evacuates the NCGs from the condenser requires more steam and/or electric power. Second, increasing gas levels increases condenser pressure thus reduces turbine power output per unit of steam feeding the turbine [4].

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 [9,11].

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).

Changes in the resource are usually accompanied by changes in the NCG flow. Typically power plants must modify the gas removal system to accommodate the changes. Because the gas removal system uses a large amount of auxiliary power, the modifications are also directed toward improving the efficiency of the gas removal system. Therefore, to improve the power plant efficiency reducing the consumption of gas removal systems have been great concern and many theoretical and experimental studies are carried out on the improvement of existing gas removal systems and development of alternatives.

Steam jet ejectors are widely used in low NCG applications with low efficiency [10,15,17,18]. As an alternative hybrid systems such

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Nomenclature

C_p	constant pressure specific heat (kJ/kg K)
C_v	constant volume specific heat (kJ/kg K)
f	non-condensable gas fraction (wt%)
h	enthalpy (kJ/kg)
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 (m³/s)
ΔP	pressure drop (Pa)
γ	Cp_{CO_2}/Cv_{CO_2} (−)

Subscripts

aux	auxiliary

comp	compressor
cond	condenser
CO_2	carbon dioxide
d	discharge
fans	fans
gen	generator
grs	gas removal system
HPC	high pressure compressor
i	indice for steam jet ejectors
LPC	low pressure compressor
LRVP	liquid ring vacuum pump
motor, pump	motor pump
net	net
pump	pump
s	suction
sep	separator
sje	steam jet ejector
t	turbine
wb	wet bulb

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as combined steam jet ejectors and centrifugal compressors [19,20] or combined steam jet ejectors and LRVPs [10,15,18,21,22], atmospheric exhaust turbines [11], biphase eductors [15] and reboilers [3,5,7,15,23–32] have been proposed and developed.

The performance of a geothermal power cycle is influenced by geothermal fluid properties such as temperature, pressure, NCG fraction, separator/condenser pressure [18,22] and wet bulb temperature of environment [18]. In a specific field, temperature and pressure do not change much in the short-medium term, whereas NCG fraction may vary significantly [33].

This study examines the performance of a single-flash GPP for three 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) [34] for two-stage steam jet ejector system, two-stage hybrid system (steam jet ejector and LRVP) and two-stage compressor system.

The 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.

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 Fig. 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.

The study is focused on gas removal systems of single-flash GPPs. The most commonly used gas removal system is steam jet ejector, which removes the NCGs from the condenser and compresses 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 throughout it can deliver. For greater compression, two or more ejectors can be arranged in series [4,18,35].

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 [18,35].

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 [4].

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 [18].

The influence of gas removal options on GPP performance is evaluated depending on separator pressure, NCG fraction and wet bulb temperature. Increase in separator pressure results with a decrease in steam flowrate thus yielding a lower power output per unit of steam feeding the turbine. Cooling water demand increases with increasing NCG fraction mainly due to the increase in cooling water need at inter and after-condensers. Increase in wet bulb temperature also increases cooling water flowrate because of maintaining the cooling load of the condenser. Thus, cost of cooling water system and auxiliary power consumption of fans and pumps also increases. Consequently to generate the same
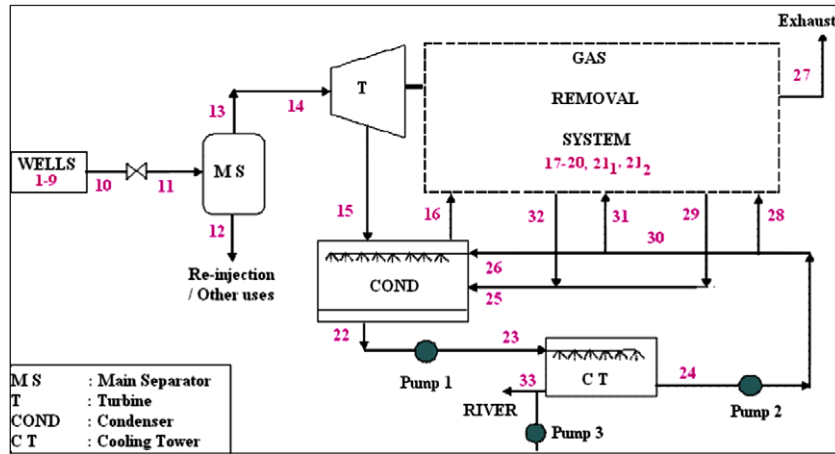
Fig. 1. Schematic diagram of a typical single-flash GPP.

amount of net power output, steam flowrate to the plant should be increased [5,18,22].

3. Methodology

The plant is first modelled for three conventional gas removal options using EES software then thermodynamic analysis has been carried out to evaluate the net power output and specific steam consumption of the plant under a range of separator pressure (100–1000 kPa), NCG fraction (0–20%) and wet bulb temperature (5–25 °C).

The general assumptions and constant parameters are listed in Table 1 and simplified flow diagram of the modelling process is shown in Fig. 2.

Table 1
Constant parameters and general assumptions.

Constant parameters	
Wellhead pressure [36] (kPa)	1331
Separator pressure [36] (kPa)	360
Wellhead flowrate [36] (tonnes/h)	870.1
Atmospheric pressure [38] (kPa)	95
Yearly average outdoor temperature [38] (°C)	16
Wet bulb temperature (°C)	13
Relative humidity [38] (%)	65
NCG fraction in steam [36] (%)	13
CO_2 fraction in NCG [16] (%)	96–99
Condenser pressure [16] (kPa)	10
T_{24} (Fig. 1) [16] (°C)	29
General assumptions	
η_{comp} (%)	75
η_{gen} (%)	90
$T_{23}-T_{hot,air}$ (Fig. 1) [18,22] (°C)	6
$T_{22}-T_{23}$ (Fig. 1) [18] (°C)	3
$P_{13}-P_{14}$ (Fig. 1) (kPa)	10
η_{pump}, η_{fan} [18] (%)	70
$\eta_{motor,pump}$, $\eta_{motor,fan}$ [18] (%)	85
ΔP_{pump}, ΔP_{fan} [18] (kPa)	100
P_{19} [4] (kPa)	105
T_{CO_2} [18] (°C)	T_{wb}
P_{16} [4] (kPa)	$0.90P_{cond}$

Geothermal fluid at the wellhead is saturated vapour–liquid mixture.
The presence of NCGs is treated as only CO_2 since it constitutes 96–99% of the NCGs.
CO_2 is an ideal gas and not to dissolve in the water.
Baumann rule [37] applies to 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)).

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

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

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

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

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

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

3.1. Steam jet ejectors

Two-stage steam jet ejector system is shown in Fig. 3. Steam consumption of steam jet ejectors increases with increasing NCG fraction. Therefore, it is important to define the motive steam flowrate which feeds the steam jet ejectors (Eq. (5)) [4].

$$\dot{m}_{21,i} = \frac{TAE_i}{AS_i} \quad (kg/s) \tag{5}$$

The mass flowrate of the turbine inlet is calculated by

$$\dot{m}_{14} = \dot{m}_{13} - \sum_{i=1}^{2} \dot{m}_{21,i} \quad (kg/s) \tag{6}$$

The corresponding power potential of steam consumed can be calculated as

$$\dot{W}_{sje} = \sum_{i=1}^{2} \dot{m}_{21,i} \cdot (h_{14} - h_{15}) \quad (kW) \tag{7}$$

Gas removal system power is:

$$\dot{W}_{grs} = \dot{W}_{sje} \quad (kW) \tag{8}$$

3.2. Hybrid system (steam jet ejector + LRVP)

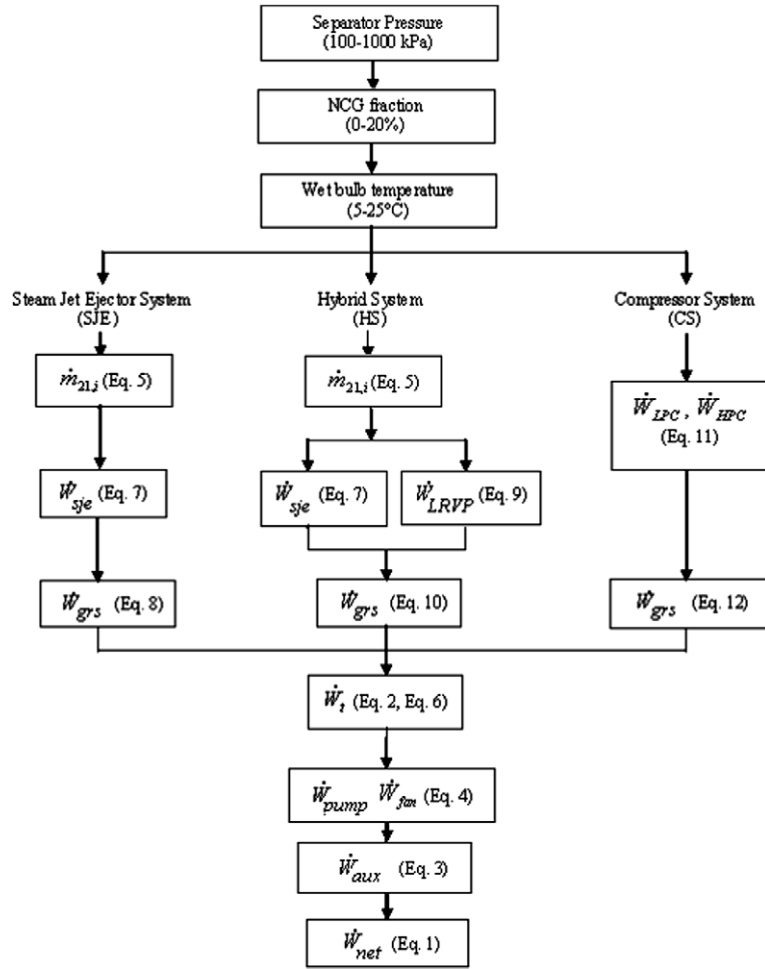The flow diagram of the hybrid system is shown in Fig. 4.

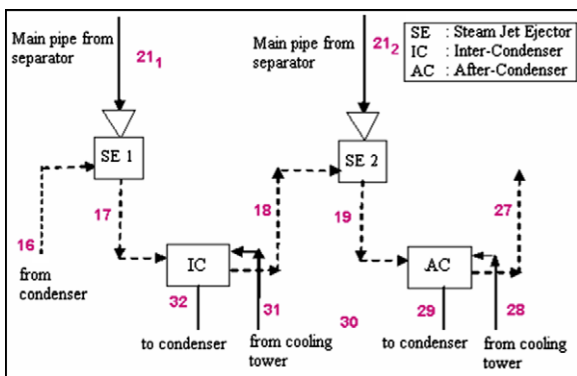Fig. 2. Simplified flow diagram of the modelling process.

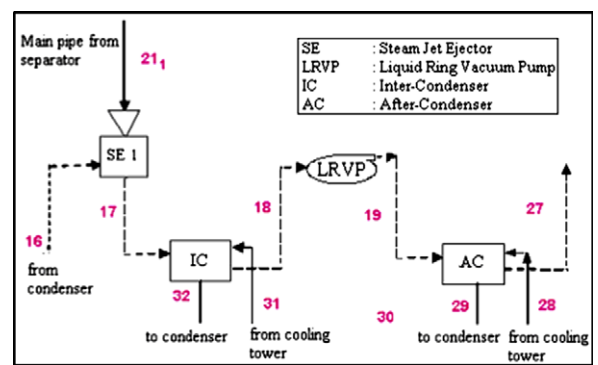Fig. 3. Flow diagram of two-stage steam jet ejector system.

Fig. 4. Flow diagram of hybrid system (steam jet ejector + liquid ring vacuum pump).

The LRVP power is calculated by [4,22]

$$\dot{W}_{LRVP} = \left[\frac{\gamma}{\gamma - 1}\right] \frac{\dot{m}_{CO_2} \cdot Ru \cdot T_{CO_2}}{\eta_{LRVP} \cdot M_{CO_2}} \left[\left(\frac{P_d}{P_s}\right)^{\left(1 - \frac{1}{\gamma}\right)} - 1\right] \quad (kW) \qquad (9)$$

Gas removal system power is:

$$\dot{W}_{grs} = \dot{W}_{sje} + \dot{W}_{LRVP} \quad (kW) \qquad (10)$$

3.3. Centrifugal compressors

A two-stage compressor system flow diagram is shown in Fig. 5. Power consumption of the compressors is calculated as

$$\dot{W}_{LPC} = \dot{m}_{17} \cdot (h_{17} - h_{16}) \quad (kW)$$

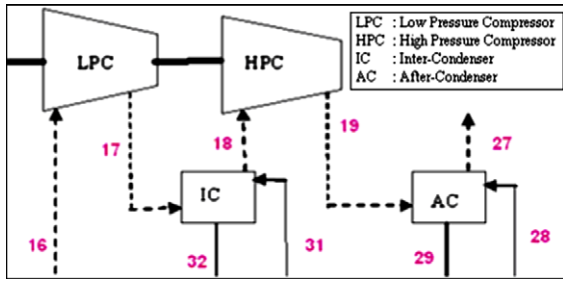$$\dot{W}_{HPC} = \dot{m}_{19} \cdot (h_{19} - h_{18}) \quad (kW) \qquad (11)$$

Fig. 5. Flow diagram of two-stage compressor system.

Gas removal system power is:

$$\dot{W}_{grs} = \dot{W}_{LPC} + \dot{W}_{HPC} \quad (kW) \tag{12}$$

4. Results and discussion

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.

4.1. Impact of separator pressure

The effect of separator pressure and NCG fraction on the net power output at 10 kPa condenser pressure and 13 °C wet bulb temperature for a 100–1000 kPa range of separator pressure is plotted in Fig. 6. Increasing separator pressure increases the net power output until a peak value which corresponds to optimum separator pressure. Further increase in separator pressure shows a dramatic decrease in net power generation caused by the de-
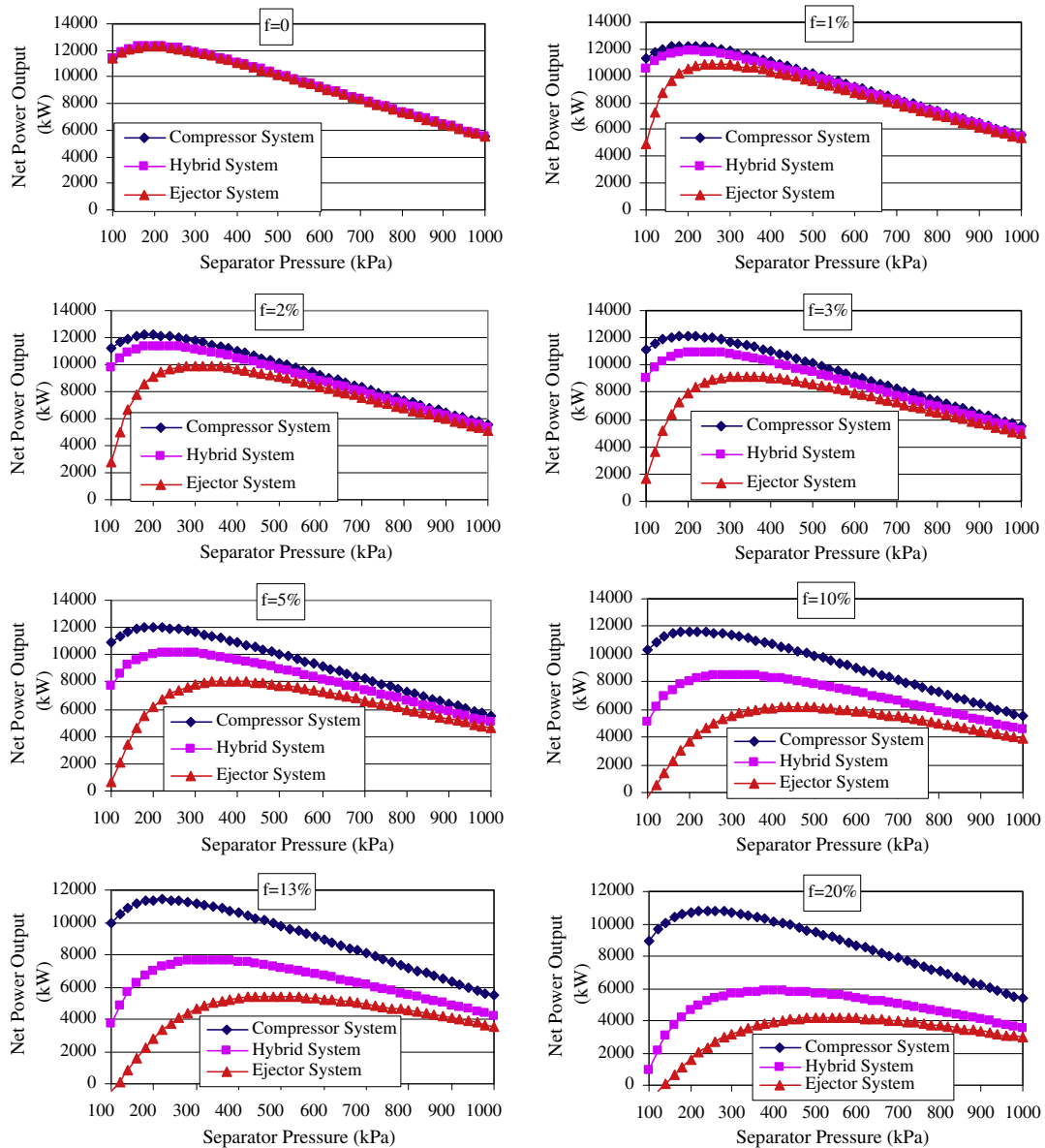

Fig. 6. Net power output for various NCG fractions and separator pressures at 10 kPa condenser pressure and 13 °C wet bulb temperature.

Table 2
Comparison of optimum and operational separator pressures of KGPP for compressor system (13% NCG fraction, 10 kPa condenser pressure).

	Optimum separator pressure (220 kPa)	Operational separator pressure (360 kPa)	Decrease (%)
Turbine power output (kW)	14,019	13,009	7.2
Auxiliary power (kW)	2612	2167	17.0
Net power output (kW)	11,407	10,842	4.95

crease in steam flowrate. For the same NCG fraction, optimum separator pressure varies for each gas removal option.

Generally, GPPs operate at off-design conditions. Although Fig. 6 gives an optimum separator pressure of 220 kPa at 13% NCG fraction for compressors, average operational separator pressure of KGPP is as high as 360 kPa. The deviation from the optimum case is presented in Table 2. The decrease in net power output is approximately 1 MW because of the elevated operational separator pressure. Even though auxiliary power consumption is decreased by 17%, the net power loss is approximately 5%.

4.2. Impact of NCG fraction

In Fig. 6, each gas removal system exhibits the same behaviour for zero NCG fraction. Increasing NCG fraction decreases the net power output for each option regardless from separator pressure but at different amounts. Steam jet ejectors give a quick response to NCG fraction change and show a dramatic depletion with increasing NCG fraction. Table 3 gives examples of optimum separator pressure and corresponding net power output for two different NCG fraction. NCG fraction (13%) corresponds to average value for KGPP. Table indicates that increasing NCG fraction is accompanied by an increase in optimum separator pressure.

For the same separator pressures, plant which is employed with compressors generates highest net power output at each NCG fraction.

Fig. 7 gives a better insight of the operational condition of KGPP illustrating net power output depending on NCG fraction for each gas removal option. Increment in NCG fraction (1%) causes a net power output loss of 0.6% for compressor, 3.3% for hybrid system and 4.7% for steam jet ejectors.

4.3. Impact of wet bulb temperature

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 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. The change in net power output depending on wet bulb tem-
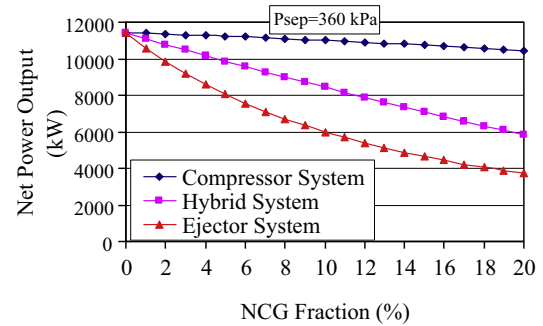

Fig. 7. Net power output of gas removal systems depending on NCG fraction at operational separator pressure of KGPP (10 kPa condenser pressure, 13 °C wet bulb temperature).

perature and NCG fraction at 360 kPa separator and 10 kPa condenser pressures is exhibited in Fig. 8. Figure indicates that the net power output decreases with increasing wet bulb temperature for each option. In fact, increasing wet bulb temperature causes an increase in motive steam flowrate thus the auxiliary power consumption. Decrease in net power output depending on wet bulb temperature is quite sensitive to gas removal options as quantified in Table 4.

4.4. 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 Fig. 9. Steam jet ejector consumes the highest and compressor consumes the lowest steam flowrate as it is expected. The slope of specific steam consumption is steep for steam jet ejectors however a gradual increase is observed for compressors. While steam jet ejector system consumes 15% more steam than compressor system at 2% NCG fraction, the consumption is as high as 112% at 13% NCG fraction.

5. Conclusions

In this study, the impact of gas removal systems on the performance of single-flash GPPs is investigated. Main conclusions can be drawn from the thermodynamic assessment of the given plant.

5.1. Separator pressure

- Optimum separator pressure which corresponds to the maximum net power output, is the highest for steam jet ejector system and lowest for compressor system at the same NCG fraction and wet bulb temperature. Optimum separator pressure is

Table 3
Comparison of net power output and optimum separator pressures depending on NCG fraction.

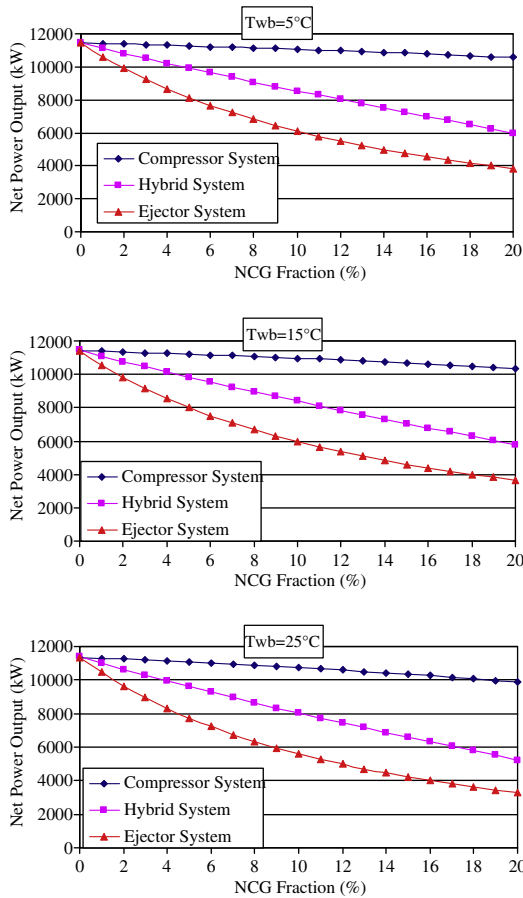| Gas removal system	NCG fraction (%)				Decrease in net power output (%)
	2		13		
	Optimum separator pressure (kPa)	Net power output (kW)	Optimum separator pressure (kPa)	Net power output (kW)	
Compressor system	180	12,178	220	11,407	6.3
Hybrid system	220	11,380	320	7649	32.8
Steam jet ejector system	300	9932	500	5411	45.5

Fig. 8. Effect of NCG fraction and wet bulb temperature on net power output (360 kPa separator pressure, 10 kPa condenser pressure).

Table 4
Net power output change with wet bulb temperature (13% NCG fraction, 360 kPa separator pressure, 10 kPa condenser pressure).

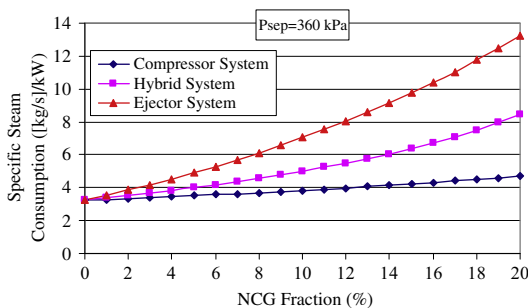| Gas removal system	Net power output (kW) Wet bulb temperature		Decrease in net power output (%)
	5 °C	25 °C	
Compressor system	10,934	10,508	3.9
Hybrid system	7761	7166	7.7
Steam jet ejector system	5240	4712	10.1

Fig. 9. Specific steam consumption depending on NCG fraction.

highly sensitive to NCG fraction but insensitive to wet bulb temperature change. Net power output of the plant decreases with increasing separator pressure with a decrease in steam flowrate feeding the turbine. This makes the situation more dramatic for steam jet ejectors in a feasibility study. To increase the power output, steam flowrate should be increased by drilling more wells which leads the higher cost of field development.
- GPPs should be urged to operate around design conditions to generate optimum net power.

5.2. NCG fraction

- NCG fraction is the most influencing factor on GPP performance.
- 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 exhibit as the worst case. Hybrid system is responded late to the change in NCG fraction because the LRVP is more efficient since its performance lies between compressors and steam jet ejectors.

5.3. Wet bulb temperature

- Increasing wet bulb temperature causes a decrement on net power output and an increase in auxiliary power consumption with an increase in motive steam flowrate.

5.4. Specific steam consumption

- For constant separator pressure and wet bulb temperature, specific steam consumption is highest for steam jet ejectors. The consumption becomes severe at higher NCG fractions.

Thermodynamic assessment allows evaluating the performance of gas removal options and their behaviour under different plant and environmental conditions, which is helpful for determining the operating conditions, system design and selection of the plant components. For a final decision, thermodynamic assessment should be accompanied by an economical analysis.

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