OPTIMIZING HYBRID NONCONDENSABLE GAS REMOVAL SYSTEMS FOR FLASH STEAM GEOTHERMAL POWER PLANTS

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ABSTRACT

The energy required to operate the Noncondensable Gas (NCG) Removal System for the condenser of a flash steam geothermal power plant constitutes a significant parasitic load affecting the overall power production and efficiency of the generating unit. Hybrid vacuum systems, incorporating steam jet air ejectors and liquid ring vacuum pumps, have proven to be reliable and efficient in this service. However, for optimum efficiency, the designer of the hybrid vacuum system must evaluate the thermal efficiency, the thermal limitations and the capitalized energy costs of the NCG Removal System design for each specific application as well as the installed cost and effect on associated systems design.

Both environmental and commercial factors must be considered along with the properties of the geothermal resource in the optimization of NCG Removal System design. Environmental factors such as design basis ambient temperature and absolute barometric pressure physically limit the operating range of the liquid ring vacuum pump. Capitalized costs of geothermal steam, cooling water and electrical power requirements for the NCG Removal System must be considered in the division of the gas compression work between the steam jet air ejector stage and the vacuum pump stage. Steam usage of the NCG Removal System also directly affects cooling tower sizing and cooling water system design.

This paper defines the required design basis parameters and illustrates how these parameters are used to optimize the NCG Removal System design for a typical flash steam geothermal power plant.

1. INTRODUCTION

Flash cycle geothermal steam typically includes a component of naturally occurring noncondensable gases that may amount to 1-12% or more by weight. The noncondensable gases are usually comprised primarily of carbon dioxide, with a significant component of hydrogen sulfide, and smaller components of other gases. In addition, because the condenser operates under vacuum, a significant amount of air is released from the cooling water (in barometric condenser applications) and some atmospheric air will leak into the condenser system. The NCG Removal System is designed to compress these gases from condenser operating pressure to atmospheric pressure for release to atmosphere. Figure 1 illustrates how the NCG Removal System fits in the typical flash cycle power plant.

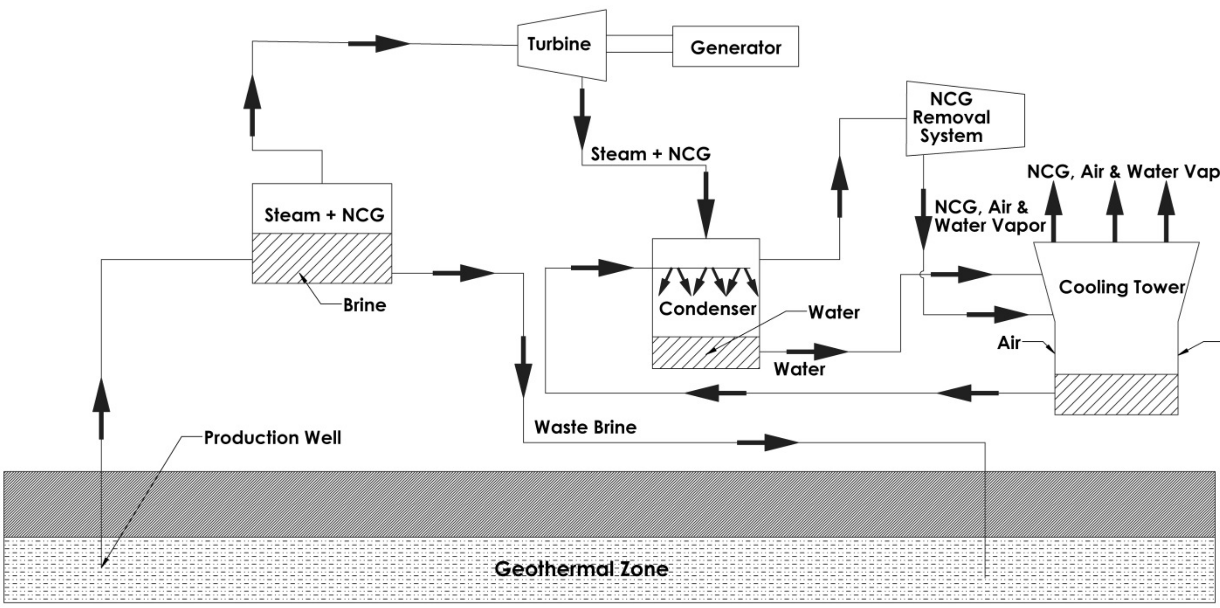

Figure 1: Typical Flash Cycle Geothermal Power Plant.

2. TYPICAL HYBRID VACUUM SYSTEM

Figure 2 illustrates a hybrid NCG Removal System using a steam jet air ejector (SJAE) for the initial stage of compression, with an intercondenser used to minimize the condensable vapor load to the liquid ring vacuum pump (LRVP) performing the final stage of compression. The system requires steam for the ejector(s), cooling water for the intercondenser and vacuum pump and electrical power for the vacuum pump. The cooling water is usually furnished from the main cooling tower and is usually drained to the condenser to be returned to the cooling tower.

The actual configuration of the hybrid NCG removal system often consists of multiple parallel partial capacity trains which may be used with a common intercondenser. Configuration of the system is specified by the user based on confidence in NCG load and requirement for redundancy.

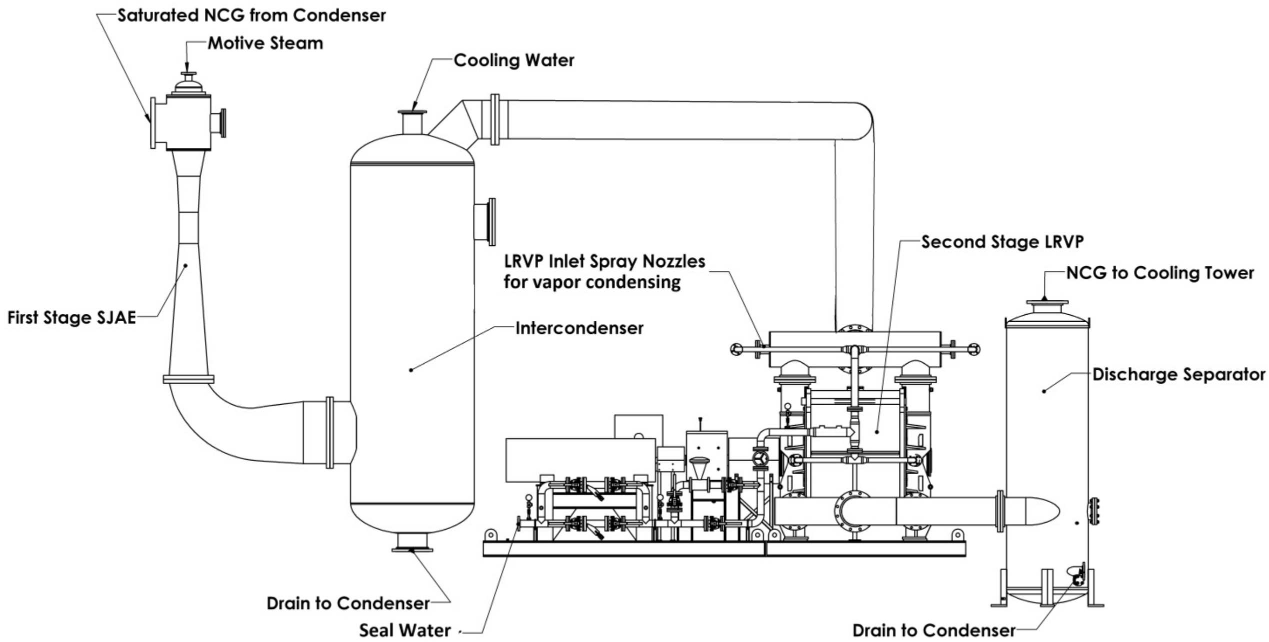

Figure 2: Typical Hybrid NCG Removal System.

3. HYBRID NCG REMOVAL SYSTEM DESIGN

The design capacity of the NCG Removal System is the sum of the expected noncondensable gases in the steam reaching the condenser, the air released by the condenser cooling water (barometric design), the expected air in-leakage and the water vapor required to saturate the noncondensable gases at the condenser operating pressure and vapor temperature. Additional noncondensable gases, from steam jet motive steam, intercondenser cooling water air release (barometric design), and gland steam condensers are usually introduced into the process and must be considered.

Following is the minimum information required for design of the Hybrid NCG Removal System:

1. First stage suction pressure (condenser design operating pressure – pressure drop in vapor piping to first stage ejector)
2. Vapor temperature at first stage suction
3. Design basis noncondensable gas mass flow rate
4. Design basis noncondensable gas composition or average molecular weight
5. Design basis air release from cooling water and air leakage
6. Mass flow of water vapor to saturate noncondensables and air at condenser operating pressure and vapor discharge temperature
7. Design basis motive steam pressure available for steam jet(s)
8. NCG content (%) of motive steam
9. Design basis cooling water supply temperature and pressure
10. Discharge pressure of the system (average absolute atmospheric pressure + any pressure required for discharge vapor piping or processing)

4. KEYS TO THERMODYNAMIC OPTIMIZATION

4.1 Perform as much of the compression work as possible with the most efficient device.

A typical 50 mW (net) geothermal power plant typically requires approximately 97 kg/s of flash steam to the turbine. Therefore, approximately 0.002 kg/s of steam is required to produce 1 kW of electricity.

With 2% NCG in the steam, the NCG load is approximately 1.94 kg/s. Assuming a condenser operating pressure of

0.100 bara, the noncondensable gas must be compressed to atmospheric pressure (or more), and the required compression ratio is approximately 10:1. Because the NCG is saturated with condensable water vapor, an efficient hybrid system would have a lower compression ratio for the first stage, leaving a higher compression ratio for the second stage.

A comparison of the estimated total steam requirements for a two stage steam jet air ejector system (with compression work divided equally between stages) versus a hybrid system using a liquid ring vacuum pump (beginning with a 2.5:1 compression in the first steam jet stage and 4:1 compression in the second stage) reveals that use of the vacuum pump as the second stage significantly reduces the overall steam requirement as shown in Table A.

NCG Removal System	Two Stage SJAE	Hybrid SJAE/LRVP
NCG Load	1.94 kg/s	1.94 kg/s
Motive Steam Requirement	6.94 kg/s	2.31 kg/s
Electric Power Requirement	0 kW	576 kW
Steam Required to Generate Electric Power	0.00 kg/s	1.11 kg/s
Total Steam Required	6.94 kg/s	3.42 kg/s

Table A: Comparison of Total Steam Requirements for Two Stage Steam Jet versus base Hybrid NCG System

4.2 Minimize the water vapor carryover to the liquid ring vacuum pump.

The 1.94 kg/s of dry NCG in the example above would occupy a partial volume of 4.93 m^3/s, but this gas would be saturated with water vapor at the intercondenser exit temperature. Table B illustrates that the effect of lowering the intercondenser vapor temperature reduces the vacuum pump size and power requirement as well as the vacuum pump operating temperature.

Intercondenser Vapor Outlet Temperature	35°C	30°C
Partial Volume of Vapor	1.57 m3/s	1.07 m3/s
Total Volume to Vacuum Pump	6.90 m3/s	6.37 m3/s
Power Requirement for Vacuum Pump	712 kW	576 kW
Condensing Heat Load to Vacuum Pump	230 kJ/s	148 kJ/s
Vacuum Pump Operating Temperature	37°C	34.5°C

Table B: Comparison of the Effect of Intercondenser Vapor Temperature on Vacuum Pump Selection Parameters

4.3 Condense vapor in the vacuum pump inlet manifold.

In most applications, the vapor volume to be handled by the liquid ring vacuum pump can be further reduced by spraying a portion of the vacuum pump seal water supply directly into the vacuum pump inlet manifold. For the 30°C vapor example above, with a seal water supply temperature of 23°C, diverting approximately 65% of the seal water requirement to the spray nozzles reduces the vapor volume to approximately 6.0 m^3/s. Conical port liquid ring vacuum pumps are designed to accept this much liquid in the inlet ports without affecting capacity or power consumption.

4.4 Choose the most efficient vacuum pump.

For a given volumetric capacity requirement, a larger vacuum pump operating at a slower speed requires less power than a smaller pump operating at a higher speed and usually operates at a lower temperature.

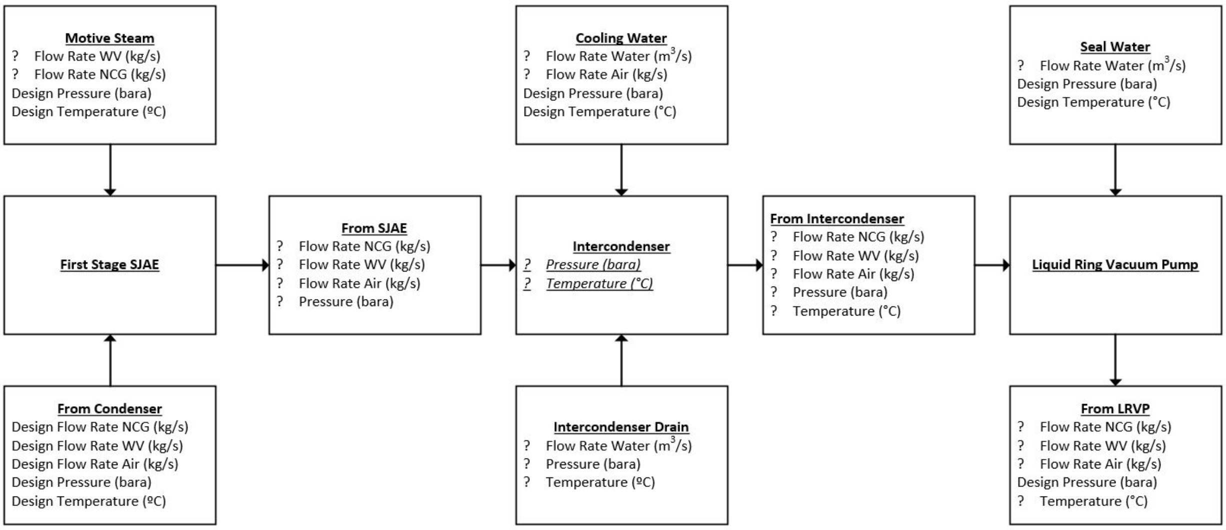

Figure 3: Mass and Heat Balance for Hybrid Vacuum System.

5. THE THERMAL OPTIMIZATION PROCESS

The thermodynamic optimization process involves iteratively solving a mass flow and heat balance, beginning with an estimated intercondenser operating pressure and vapor temperature, as shown in Figure 3.

Figure 4 illustrates the relationship of interstage (intercondenser) pressure to the equivalent steam usage of the hypothetical system configured with two 50% capacity vacuum pumps or three 33% capacity vacuum pumps.

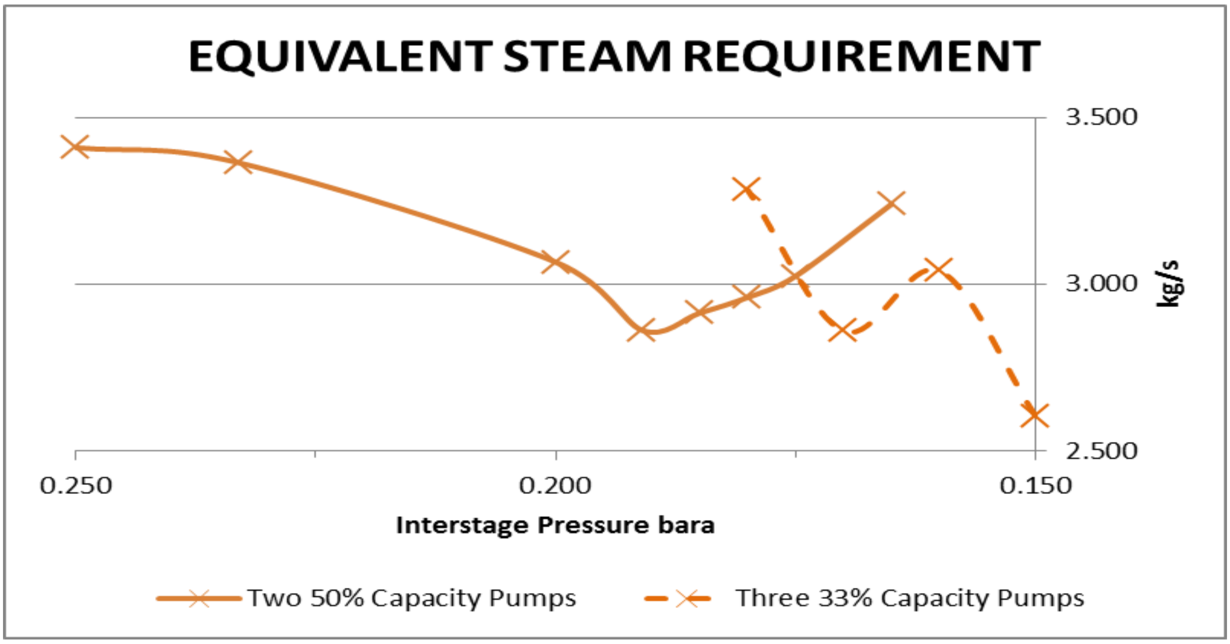

Figure 4: Thermal Optimization of Hybrid System Design

6. LIMITATIONS OF THERMAL OPTIMIZATION

Given that the first key to optimization involves assigning as much of the compression work as possible to the liquid ring vacuum pump, the limitations of the liquid ring vacuum pump must be considered. Most importantly, the liquid ring of the vacuum pump must remain liquid at the vacuum pump suction pressure, so the operating temperature of the pump must not approach the vapor temperature corresponding to absolute suction pressure. Otherwise, cavitation limits the capacity of the vacuum pump and eventually causes physical damage to the vacuum pump rotor. The mass flow and temperature of seal water supplied to the vacuum pump must be sufficient to absorb the heat of compression and heat of condensation of the vapor entering the vacuum pump with some margin to handle off-design or transient operating conditions.

In this example, the vacuum pump approaches the thermal operating limits with an interstage pressure of less than 0.150 bara.

7. ECONOMIC OPTIMIZATION OF THE NCG SYSTEM

Overall optimization of the NCG System requires consideration of the capital and operating costs of the NCG system as well as the effect on the capital and operating costs of associated systems. As the limits of thermodynamic efficiency are approached:

- The capital cost of the NCG system (generally) increases
- The direct steam usage of the NCG system decreases
- The cooling water usage of the NCG system decreases
- The cooling tower heat load attributable to the NCG system decreases
- The auxiliary electric power consumption increases

If the capitalized costs of steam usage, cooling water usage, cooling tower heat load and auxiliary power consumption are provided to the NCG System designer, these costs may be used to balance capital cost versus operating cost of the NCG System design.

7.1 Example of Economic Optimization

Capitalized costs for steam and other utilities vary widely from project to project. Using the original example of a system with 0.250 bara interstage pressure as a baseline, the comparative costs of alternate system configurations (identified by interstage pressure) are shown as differential evaluated costs in Figure 5. The example economic optimization uses the following values:

Steam: NZ$5,400,00 per kg/s
Electric Power: NZ$10,000 per kW
Cooling Water: NZ$7,200 per kg/s

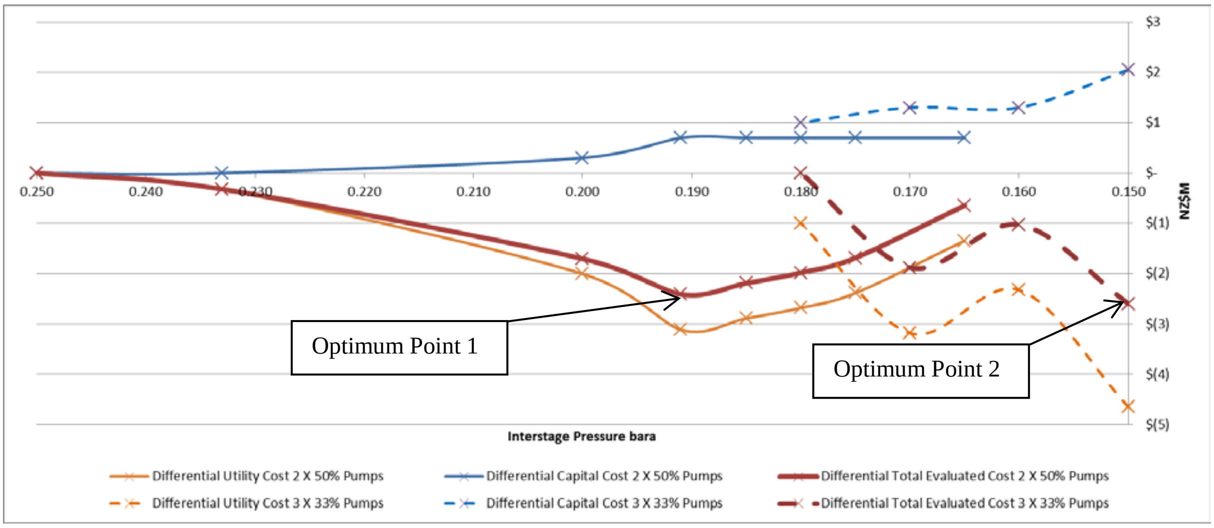

Figure 5: Economic Optimization of Alternative NCG System Configurations

7.2 Selection of Optimum NCG System Design

Figure 5 illustrates that the example evaluation indicates two nearly equal optimum system selections, Optimum 1 with an interstage pressure of approximately 0.191 bara and Optimum 2 with an interstage pressure of 0.150 bara. Because Optimum 2 operates near the thermal limitation of the vacuum pump, Optimum 1 is the more conservative system selection.

Expanding Table A to include the economically optimized selection shows that the steam savings of the optimized system is approximately 0.56 kg/s compared to the base hybrid system and 4.08 kg/s compared to the two stage steam jet air ejector system.

NCG Removal System	Two Stage SJAE	Base Hybrid System	Optimized Hybrid System
NCG Load	1.94 kg/s	1.94 kg/s	1.94 kg/s
Motive Steam Requirement	6.94 kg/s	2.31 kg/s	1.64 kg/s
Electric Power Requirement	0 kW	576 kW	628 kW
Steam Required to Generate Electric Power	0 kg/s	1.11 kg/s	1.22 kg/s
Total Steam Required for NCG System	6.94 kg/s	3.42 kg/s	2.86 kg/s
Estimated Total Differential Evaluated Cost NZ$	+$18.9M	Base	-$2.4M

Table C: Comparison of Evaluated Energy and Capital Costs for Two Stage Steam Jet versus base Hybrid NCG System and Optimized Hybrid System

7.3 Other Cost Factors

A more rigorous evaluation would apply the site specific capitalized cost of variations in:

- Differential NCG System installation cost (space, foundations, piping, controls, etc.)
- Incremental Drilling cost
- Incremental Reinjection cost
- Incremental Cooling Tower cost
- Maintenance costs

8. SUMMARY AND CONCLUSIONS

A. Optimization of the Hybrid NCG System design yields steam savings significant enough to affect the overall efficiency of the power plant, so NCG system performance should be considered early in the overall power plant design process.

B. Specification of a hybrid vacuum system without capitalized cost factors does not assure optimum hybrid system design.

C. Generally, the most thermally efficient system has the lowest overall evaluated cost.

D. Optimum hybrid system design is project specific and requires evaluation of project specific technical and commercial considerations.

NOTES

Note 1: The example geothermal power plant design used in this optimization does not represent a specific power plant, but rather is derived from over twenty power plant designs with conditions averaged and normalized to a design capacity of 50 mW net electric generation capacity.

Note 2: The example geothermal power plant design is based 50 MW net generating capacity, using 97 kg/s of geothermal steam with 2% by weight of NCG with an average molecular weight of 43.5. Condenser operating pressure is assumed to be 0.100 bara. Motive steam pressure for steam jets is based on 5 bara. Cooling water is assumed to be available at 23°C. Discharge pressure of the system is assumed to be 1.013 bara. While the method of optimization remains the same, any change to any of the operating parameters will affect the optimum design.

Note 3: Motive steam consumption indicated in this example is mathematically corrected for capacity and compression ratio from similar designs.

Note 4: Optimizations are based on the performance of liquid ring vacuum pump models offered by Vooner FloGard Corporation. Use of other models of vacuum pumps will affect the optimization.

Note 5: Capitalized costs of steam, cooling water and auxiliary electrical power are averaged from three geothermal NCG removal bid specifications issued in 2013 and 2014.

Note 6: Estimated capital costs of NCG removal systems are based on a typical scope of supply including two 50% capacity steam jet air ejectors, one 100% capacity intercondenser and two 50% or three 33% capacity liquid ring vacuum pump systems with normal accessories in 316 stainless steel construction. No shipping or installation costs are considered.