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An Evaluation of Single Flash Power Plants with ORC Bottoming Units at High NCG Content

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ABSTRACT

The use of ORC bottoming units in series with steam turbines bring forth some advantages compared to single flash units with conventional cooling circuits. One of the most evident advantages is that an ORC unit does not require power for the extraction of non-condensable gases since the condensing process takes place at a pressure higher than atmospheric pressure. However, the ORC unit has lower thermal efficiency compared to conventional single flash units, and therefore the power produced with this integration is lower in terms of overall produced net power. Although this is the case, the use of an ORC as a bottoming unit might help produce more overall net power in cases where the NCG content is high enough to make the gas extraction process demanding in terms of power consumption. In this study, we will try to identify roughly at which percentage of NCG content in steam, the use of an ORC as a bottoming unit will be advantageous against the conventional single flash cycle in terms of net power production.

1. INTRODUCTION

We will model a conventional single flash plant and a single flash with a bottoming unit and compare their net power production with increasing non-condensable gas content. The total steam flow rate and the inlet pressure supplied to both systems will be kept the same in order to provide a fair comparison.

2. SINGLE FLASH POWER PLANT DESIGN

Single flash geothermal power plants are the most widely used geothermal plants in the world, mainly due to their simplicity and low investment cost. They operate solely by steam, obtained by flashing the geothermal fluid in a cyclonic separator. Geothermal fluid in use is usually liquid phase in the reservoir and two-phase when it reaches the separator due to flashing starting inside the wellbore.

The power plant we will base our study on operates with similar aforementioned conditions. It produces 37,163 kW gross power with 269.2 t/h saturated steam at 5.77 bara. A simple schematic of the process can be seen in Figure 1.

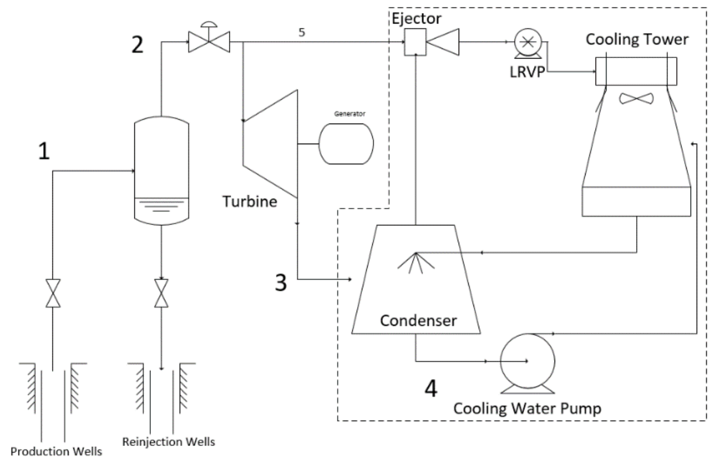

Figure 1: A Schematic of a Single Flash Geothermal Power Plant

Two phase fluid flows to the separator from the well on the left. Phase separation takes place in the separator at an optimum pressure, which will keep the temperature of the brine above the silica saturation temperature in order to avoid scaling. Steam goes to the steam turbine; brine goes directly to the reinjection well.

Steam spins the turbine, produces electricity through the generator, which is connected to the turbine shaft. Some portion of the steam condenses in the turbine, the amount of which is dependent on how large the enthalpy drop across the turbine is. Steam and the condensate flows to the condenser, which is at vacuum condition. All steam condenses in the condenser and is pumped to the cooling tower via the cooling water pumps to be cooled and sent back to the condenser again. The non-condensable gases in the condenser, which constitute of 1% of the total flow, are sucked by a hybrid gas extraction system made of steam ejectors and liquid ring vacuum pumps and released to the atmosphere. So the auxiliary consumption units mainly are the cooling water pump, cooling tower fans and the liquid ring vacuum pump. There is also a small portion of cooling to be done for turbine and generator, in addition to other minor consumptions due to auxiliaries such as cooling water pumps, oil pumps, compressors etc.

	Inlet	Outlet
Pressure, bara	5.77	0.08
Temperature, ºC	158.3	41.6
Flow Rate, t/h	269.2	269.2
Steam Quality	1	0.87
Shaft Power, kW	37,921	
Isentropic Efficiency:	%79.6	

Table 1: Process Conditions of the Steam Turbine

The power produced at these conditions and the auxiliary power consumption are summarized as follows;

	Power, kW
Turbine Shaft Power	37,921
Generator	37,163
Hot Water Pump	968.2
Cooling Tower Fans	298.4
LRVP	475.2
Plant Net Output	35,412

Table 2: Power Generation and Auxiliary Consumption of the Single Flash Unit

Net generated power is 35,412 kW assuming a generator efficiency of %98. The isentropic efficiency of the turbine is calculated as %79.6 from Baumann rule by assuming a dry efficiency of 85%.

Please note that the total amount of steam used by the turbine is actually 267.5 t/h. An amount of around 1.7 t/h is used by the ejector and the vacuum pump for the removal of non-condensable gases from the condenser.

3. BINARY CYCLE POWER PLANTS

If the enthalpy of the resource at hand is low, the flashing process will not produce enough steam at adequate pressure to operate a steam turbine efficiently. In this case, the required amount of vapor to operate an ORC turbine can be obtained by transferring the heat of the geothermal resource to a secondary fluid, which has a lower boiling point than water. Binary power plants work on this principle. The choice of the fluid, which usually is a hydrocarbon, depends on the compliance of the thermodynamic properties of the fluid to the specific case at hand, as well as its availability and environmental compatibility.

Binary cycle power plants are very important in the sense that they make it possible for us to utilize low-medium temperature brines, which constitute most of the geothermal resources in the world. This is their main purpose in geothermal industry. Their use as bottoming units have lately come into play and they have been implemented for the first time in Indonesia in Sarulla field.

4. INTEGRATING THE BOTTOMING UNIT TO THE SINGLE FLASH PLANT

For this study we will try to design a bottoming ORC unit for the single flash plant we mentioned before by replacing the section with the dashed line in Figure 1 by an ORC. It is important to first assess the back-pressure of the turbine. Once we remove the condenser, it leaves us with the atmospheric pressure. To compensate for the losses in the heat exchanger we can add an additional 0.25 bar margin and estimate a backpressure of 1.25 bara as is the case for some actual bottoming units. Steam turbine calculation results with 1.25 bara backpressure is as follows. As can be seen, one advantage of increasing the backpressure is the increase in turbine efficiency due to the higher steam quality at the exit.

	Inlet	Outlet
Pressure, bara	5.77	1.25
Temperature, ºC	158.3	105.8
Flow Rate, t/h	269.2	269.2
Steam Quality	1	0.94
Shaft Power, kW	16,406	
Isentropic Efficiency:	%82.5	

Table 3: Process Conditions of the Steam Turbine after increase in backpressure

4.2 Design of the ORC Bottoming Unit

We used the combination of Microsoft Excel and CoolProp for our calculations. CoolProp is a free digital library that provides the thermodynamic properties of more than 100 substances including the most popular hydrocarbons used in geothermal binary cycles such as n-pentane, n-butane and cyclopentane. We cannot help but mention here that it is quite generous of the developers of CoolProp to share such a useful library for free and make it available even for commercial projects.

Coming to the design of the ORC, first we need to decide on some fixed inputs in order to proceed with the optimization of the cycle. The fixed inputs are the boiling and the cooling temperature of the motive fluid. The boiling temperature is dependent on the condensing temperature of the steam. Usually a 10°C temperature difference between the two cycles would be safe. Since the condensing temperature of steam will be 105.8°C (see table 2), the boiling temperature of the motive fluid is chosen as 95.8°C.

Once the motive fluid vapor expands in the turbine, it will be sent to the air coolers to be condensed and sent back to the cycle. Considering an average ambient temperature of 25°C, and a pinch point temperature difference of 7°C, we chose the cooling temperature of the motive fluid to be 32°C.

4.1.1 Heat Transfer Calculations

In order to proceed with the ORC design, we need to know how much heat we can harness from the steam. Condensing all of the steam will give us a total heat input as follows;

$$(\dot{h}_{vapor} - \dot{h}_{liquid}) * \dot{m} = 161{,}221\ kW \tag{1}$$

where h_{vapor} and h_{liquid} are the enthalpies of vapor and liquid at 105.8°C calculated by CoolProp and m is the mass flow rate of 269.2 t/h. This value of mass flow rate includes the motive steam used for the gas extraction system of the single flash case.

We will additionally cool the condensate down to 60ºC. The heat to be gained with this conductive cooling is calculated as;

$$(\dot{h}_{@106} - \dot{h}_{@60}) * \dot{m} = 10{,}028\ kW \tag{2}$$

where enthalpy values correspond to liquid enthalpies at mentioned temperatures as subscripts and m is the mass flow rate of 260 t/h, inclusive of the interstage drains of the steam turbine. Thus, we have a total heat duty of 171,250 kW, which we can use to boil our motive fluid.

We ran trial and error scenarios using n-pentane and n-butane as motive fluids and obtained better results with n-butane, probably due to its lower boiling temperature, which is more suitable for this case since we are dealing with a low condensing temperature.

Next, we need to calculate the flow rate of the motive fluid. Since we know the heat input, the flow rate of n-butane can be calculated as;

$$\dot{m} = \frac{171{,}250}{h_{vapor@95} - h_{liquid@35}} = 1392.3\ t/h \tag{3}$$

Where $h_{vapor@95}$ is the enthalpy of the motive fluid vapor at 95.8°C and $h_{liquid@35}$ is the enthalpy of the motive fluid liquid at 32°C. Now we can calculate the heat duty requirements of preheating and vaporizing of the motive fluid. Preheating of n-Butane from 32°C to 95.8°C is calculated as;

$$(\dot{h}_{@95} - \dot{h}_{@32}) * m = 67{,}719\ kW \tag{4}$$

And the heat duty of the vaporizing process is;

$$(\dot{h}_{V95} - \dot{h}_{L95}) * m = 103{,}531\ kW \tag{5}$$

Where $h_{@95}$ and $h_{@32}$ are liquid n-butane enthalpy values at 95.8°C and 32°C consecutively. And h_{V95} is vapor enthalpy of n-butane at 95.8°C while h_{L95} is the liquid enthalpy at the same temperature.

We can see a summary of the heat transfer process in figure 2 below.

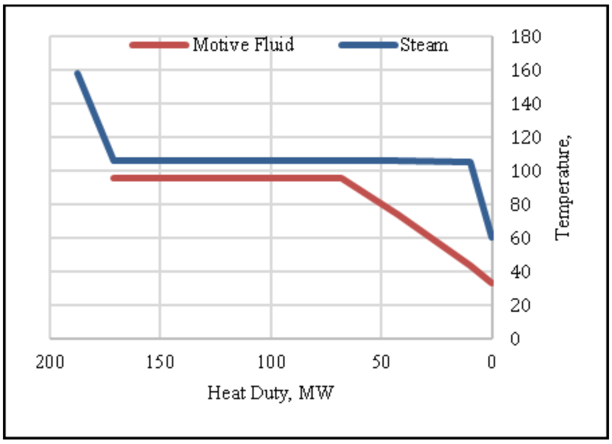

Figure 2 ORC T-H Diagram

<u>4.1.2 ORC Turbine Power Production</u>

In order to calculate the power to be produced by the ORC turbine, we need to know the enthalpy at turbine outlet since the power produced by the turbine is simply;

$$W = (\dot{h}_{inlet} - \dot{h}_{outlet}) * \dot{m} \tag{6}$$

Outlet enthalpy of the turbine is dependent on the temperature and pressure at the outlet. We know that our back pressure is equal to the saturation pressure of n-butane at cooling temperature which is 32°C. Therefore, the only missing variable is outlet temperature. At this point we will use the isentropic efficiency of the turbine to come up with the outlet temperature.

Isentropic efficiencies of ORC turbines may range from 85% to 90%. We aimed for 86% isentropic efficiency for this case. Isentropic efficiency can be formulated as follows;

$$\eta_t = \frac{W_{actual}}{(h_{inlet} - h_{outlet\_iso}) * \dot{m}} \tag{7}$$

Where h_{outlet_iso} is the enthalpy at the outlet of the turbine if the turbine was working with 100% isentropic efficiency.

Outlet temperature of the ORC turbine is iterated until the efficiency of the turbine corresponds to 86%. So the final conditions of the ORC turbine is as shown in table 4.

<u>4.1.3 Auxiliary Power Consumption Calculations</u>

Now we need to condense the waste vapor at turbine outlet. The total heat duty required to condense all n-butane is calculated as;

$$(\dot{h}_{t\_Out} - \dot{h}_{@32}) * \dot{m} \; = \; 150{,}758\,kW \tag{9}$$

	Inlet	Outlet
T, °C:	95.8	49.9
P, bara:	14.09	2.99
h, kj/kg:	716.6	630.6
s, kj/kg.K:	2.49	2.42
Power : 21,506 kW		Isentropic Efficiency: 86%

Table 4 Process Conditions of the ORC Turbine

Air cooled condensers are usually used in binary cycles to condense the motive fluid vapor and cool it down. We will assess the fan power required to dissipate the heat duty calculated in equation 8 from empirical correlations. We know from experience that to discharge around 150,000 kW of thermal power, approximately 1,300 kW of fan power is needed. These numbers are average values taken from some actual ORC units. So, assuming a linear relationship for the same temperature range, our fan consumption to discharge 150,758 kW of thermal power is expected to be around 1,311 kW.

Power consumption of the motive fluid pump is calculated as follows;

$$P = (\dot{m} * \rho * g * h / \eta)/3.6E6 = 1{,}014\ kW \tag{10}$$

Where $\dot{m}$ is flow rate in m^3/h, ρ is the density of the motive fluid in kg/m^3, g is gravity in m/s^2, h is hydraulic head in meters and η is the efficiency of the pump which is taken as 65%.

5. COMPARISON

In this section, we will compare the power production of both options with the numbers we have come up so far.

5.1 Comparison of Power Production and Efficiency

The table below summarizes the results of the two options. We used the following formula to calculate the efficiency values given;

$$\eta_{act}(\%) = \frac{W}{\dot{m} * h} * 100 \tag{11}$$

Where W is the net produced electrical power, $\dot{m}$ is the total steam flow and h is the enthalpy of the fluid at turbine inlet. In this case, the enthalpy and the mass flow is the same in both cases. In conclusion the two options are quite close in terms of power production. We would expect the combined cycle to have a lower net production output due to the lower efficiency of binary cycles compared to single flash cycles. However, this is not the case. The efficiency values of both options are very close, mainly due to the increase in the steam turbine efficiency in the combined cycle. The increase in the steam quality at the turbine outlet compensates for the low efficiency of the binary cycle.

	Single Flash with CT	Single Flash with ORC bottoming
Generator Power, kW	37,163	37,154
Net Power, kW	35,412	34,830
Efficiency:`	%17.1	%16.9

Table 5 Comparison of two options in terms of power production and efficiency

In an ORC unit the condensing of steam takes place at a pressure that is higher than atmospheric and therefore the non-condensable gases can be released to the atmosphere without the requirement of any extra equipment. This encourages us to study the issue further since in cases of high NCG content, ORC bottoming units might actually have an advantage over the cooling water circuit when it comes to net power production.

5.2 Comparison with increasing CO_2 Content

We simulated both cycles with increasing carbon dioxide content up to %4.5. Figures below show the net specific mass consumption and the net power production of both options at different gas contents.

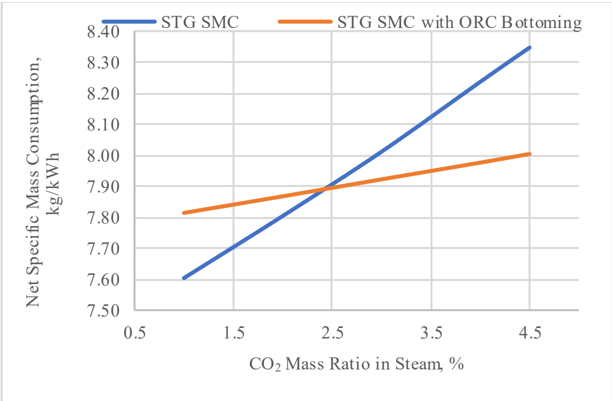

Figure 3 Net Specific Mass Consumptions vs. CO_2 Mass Ratio in Steam

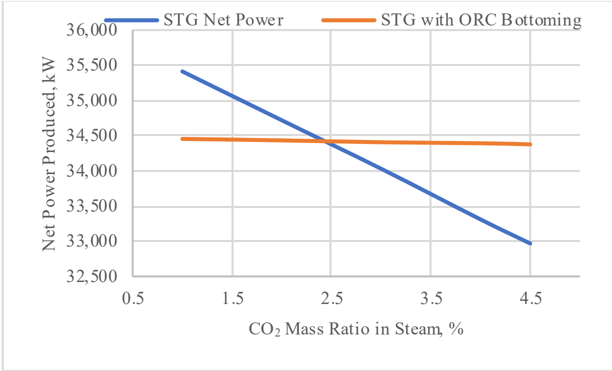

Figure 4 Produced Net Power vs. CO_2 Mass Ratio in Steam

As can be seen in the figures above, the combined cycle gains a clear advantage with increasing high non-condensable gas content. At around 2.5% CO_2 content in steam, the combined cycle actually starts to become more efficient compared to the conventional single flash cycle.

Up to now all calculations were run with a turbine inlet pressure of 5.77 bara. We ran the same calculations with a fixed steam turbine inlet pressure of 7.5 bara. Below is the net mass specific consumption figure at turbine inlet pressure of 7.5 bara. All other values are kept the same.

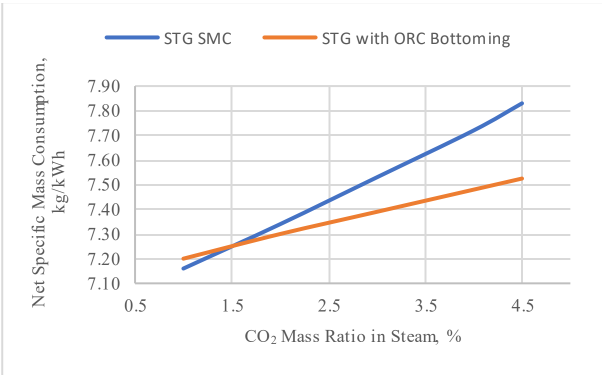

Figure 5 Net Specific Mass Consumption at Higher Steam Pressure

In this case the combined cycle becomes more efficient starting with 1.5% CO_2 content in steam. However, the derivative of the single flash cycle decreases and gets closer to the combined cycle, suggesting that the difference in efficiency between the two cycles decrease with increasing turbine inlet pressure.

SUMMARY AND CONCLUSION

We adapted an ORC bottoming unit to a steam turbine and compared the results with a conventional single flash cycle. At low non-condensable gas content in steam, we could not find a significant advantage of using a combined cycle in terms of net power production. However, with increasing non-condensable gas content, the combined cycle started to become more efficient compared to the conventional single flash cycle. We saw that the necessary NCG content in steam, for the combined cycle to be more efficient, decreases with increasing steam turbine inlet pressure. At 5.77 bara steam pressure the combined cycle outran the single flash at 2.5% NCG content, while in 7.5 bara steam pressure this value decreased to 1.5%.

Further elaborations shall be made taking into account the capital expenses of both options in order to have an idea of the feasibility of the ORC bottoming option at high NCG contents.

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