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An Assessment on the Electricity and Potable Water Production of a Combined Cycle with High Temperature Gas Cooled Reactor

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1. Introduction

An assessment on the co-generation of electricity and the desalination of sea water for a High Temperature Gas Cooled Reactor (HTGR) system was carried out. A custom made analysis program was developed and used to simulate a combined cycle with desalination layout. The assessment shows that the combined cycle is well suited to produce electricity with high efficiency and that the steam bleeds can be used to produce potable water by desalination. The steam bleed can potentially be used as a load-follow control mechanism.

2. Assessment Methods

2.1 Combined Cycle Layout and Major Components

The overall layout of the simple combined cycle model is schematically depicted in Figure 1.

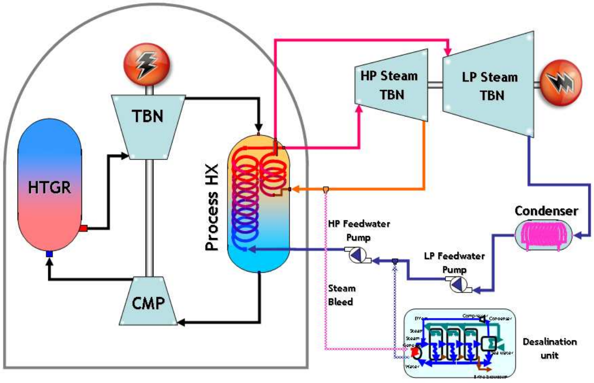
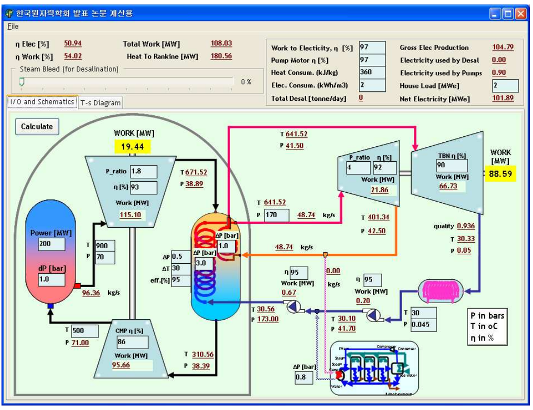


Figure 1. Schematic Diagram of the Simplified Combined Cycle

The primary side consists of an HTGR connected directly to a simple closed Brayton Cycle and a process heat exchanger. The secondary of the process heat exchanger is the boiler for the Rankine cycle. The coolant for the primary side is helium. The Rankine cycle consists of a high pressure turbine, a low pressure turbine which is fed with the re-heated steam, a condenser, a low pressure feedwater pump, and a high pressure feedwater pump connected to the secondary side of the process heat exchanger. A portion of steam is bled at the exit of the high pressure steam turbine to heat the motive steam for the desalination unit.

2.2 Analysis Tool

A custom program was developed to analyse the combined cycle layout under investigation. The program was written in Delphi using object-oriented program techniques. A snapshot of the program is shown in Figure 2.


한국원자력학회 발표 논문 계산용

η Elec [%] 50.94
η Work [%] 54.02
Total Work [MW] 108.03
Heat To Rankine [MW] 180.56
Steam Bleed (for Desalination) 0 %

Work to Electicity, η [%] 97
Pump Motor η [%] 97
Heat Consum. (kJ/kg) 360
Elec. Consum. (kWh/m3) 2
Total Desal [tonne/day] 0

Gross Elec Production 104.79
Electricity used by Desal 0.00
Electricity used by Pumps 0.90
House Load [MWe] 2
Net Electricity [MWe] 101.89

Figure 2. A snapshot of the Custom Analysis Program

The program consists of following models and correlations

- Fluid thermal hydraulic property calculation object.
  This object calculates the TH properties for helium, water, CO_2 or N_2. It can calculate TH properties for given 2 properties such as (P, T), (P, h) or (P, s).
- Compressor/turbine/pump state calculation routines
  These routines calculate the TH conditions at the inlet or outlet of compressor, pump or turbine for a given isentropic efficiency.
- Flow rate calculation routines
  These routines calculate flow rates at all points of the layout. The flow rates are calculated based on continuity of flows. There is a provision to vary the steam bleed at the exit of the high pressure steam turbine for controlling the desalination rates. These routines are hard-wired to the layout under investigation.
- Desalination model
  This is a black box model where the heat and electricity requirement inputs are used for calculating the desalination rate by simple arithmetic.

2.3 Plant Parameters and Major Assumptions

The assessment was carried out for a 200 MW thermal HTGR connected to a combined cycle layout with controlled steam bleed for desalination. The outlet temperature of the reactor is selected to be 900 ^{o}C which is expected to be achievable in an industrial scale within several years. The isentropic efficiencies of the turbo-machines deemed reasonable from various sources were selected. In the assessment, the heat loss to the environment is assumed to be negligible. But a 5% loss is assumed in the heat transfer from the primary to the secondary. The desalination heat and electricity requirements are based on those of the MED process. Major parameters are listed in Table 1.

Table 1. Major Parameters

Parameter	unit	value
Reactor power	MWt	200
Reactor outlet pressure	bar	70
Reactor pressure drop	bar	1
Rx inlet, outlet temperatures	℃	500, 900
Process HX pimary pressure drop	bar	0.5
Process HX secondary pressure drop	bar	3
Process HX re-heat pressure drop	bar	1
ΔTmax primary to secondary	℃	30
Brayton TBN P ratio		1.3~2.9
Brayton TBN isentropic efficiency	%	93
Brayton CMP isentropic efficiency	%	86
Rankine HP TBN inlet temperature	℃	492~761
Rankine HP TBN inlet pressure	bar	170
Rankine HP TBN P ratio		4
Rankine HP TBN isentropic efficiency	%	92
Rankine LP TBN isentropic efficiency	%	90
Rankine Pump isentropic efficiency	%	95
T ambient	℃	30
P condenser		0.045
Desalination heat consumption	kJ/kg	360
Desalination electricity consumption	kWh/tonne	2
Electricity conversion efficiency	%	97

3. Assessment Results

Figure 3 shows the effects of the helium turbine pressure ratio on the turbine work output for the case where there is no steam bleed for desalination.

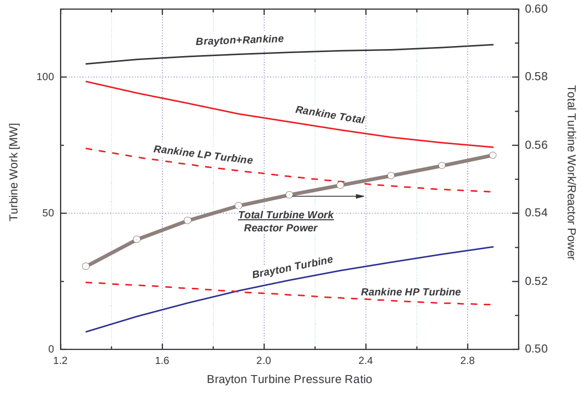


Figure 3. Effect of Brayton Turbine Pressure Ratio (without desalination)

Figure 3 shows that as the pressure ratio of the Brayton turbine is increased, the work from the Brayton turbine increases while that of the Rankine turbines decrease. The total work however increases and the total efficiency in the turbine work ranges from 53~56%.

Figure 4 shows the assessment case where the steam bleed for desalination is varied.

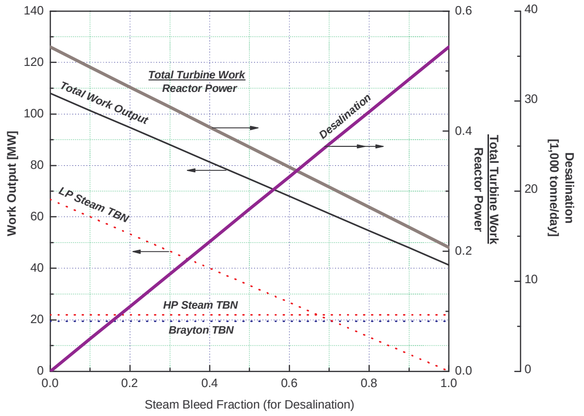


Figure 4. Effect of Steam Extraction for Desalination

As the steam bleed is linearly decreased, the work output also decreases linearly while the desalination rate increases linearly. This is as expected and this can be used as a means of load-following operation whereby the steam is bled more during such off-peak periods as the night-times to produce more potable water and less electricity.

Results indicate that for the case of no potable water production, the electricity generation efficiency of over 50% can be expected. For the case of the maximum potable water production (~35,000 tonne/day for 200 MW HTGR), electricity generation efficiency of 15~20% can be expected.

4. Conclusions

The capability of the 200 MW HTGR with a combined cycle layout for an application in the cogeneration of electricity and desalination was assessed using a custom made program. The results show that electricity generation efficiency of over 50 % can be achieved with the high temperature of the HTGR. By maximizing the steam bleed, up to 35,000 tonne/day of potable water can be produced with electricity generation efficiency in the 15~20% range. The 35,000 tonne/day potable water is deemed sufficient for the population of 200,000~350,000. The current layout has the advantages of 1) high electricity generation efficiency, 2) a provision of load follow mechanism by controlling the steam bleed for desalination, and 3) application of the proven and popular Rankine cycle which can ease the engineering burdens expected with the installation of a large capacity helium Brayton cycle.