The concept design of the new cycle layout of the nuclear-solar hybrid system

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1. Introduction

The electricity generation is changing from a central power generation to a decentralized distributed power generation in that electricity transmission cost and CO_2 emissions can be reduced. A micro-grid using distributed power generation should be able to meet the electricity demand of the target region by themselves and usually have a scale of several kW to 50MW. The distributed power generation mainly relies on conventional energy sources such as coal, oil and natural gas. However, for micro-grids in an island or remote regions, an energy source requiring infrequent refueling should be preferred due to the high fuel transmission costs.

Noting this point, the KAIST research team developed the concept of a nuclear-solar hybrid system that combines nuclear power, TES (Thermal Energy Storage), and CSP (Concentrated Solar Power), altogether [1]. Nuclear power and CSP are suitable as heat sources for the micro-grid because they hardly require fuel recharge, and TES can be used to adjust the system output in response to the variable electricity demand of the region. In addition, nuclear-solar hybrid systems have the advantage of being able to compensate for each other's shortcomings. Under load fluctuations to meet the electricity demand of the grid, a capacity factor of nuclear power can be kept high while at the same time reducing the intermittent and large site area of the CSP.

KAIST-MMR developed by KAIST research team was used for the nuclear power of the hybrid system. A conventional SMR (Small Modular Reactor) was limited in mobility by using a bulky steam Rankine power cycle. To solve this problem, KAIST-MMR used the supercritical CO_2 (sCO_2) power cycle, which is relatively small in volume and has high efficiency at a moderate heat source temperature [2]. KAIST-MMR is composed of a single module that combines the power system and the reactor core. It is suitable for hybrid systems because it can be transported by truck or ship.

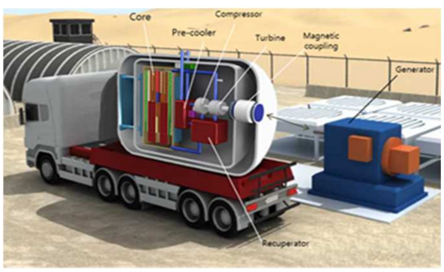

Fig 1. Concept diagram of the KAIST MMR [2]

Since MMR is a CO_2-cooled reactor and the working fluid of the CSP and TES is a molten salt, recompression with reheating cycle layout in which the heat sources of MMR and CSP are separated as shown below is used in the hybrid system.

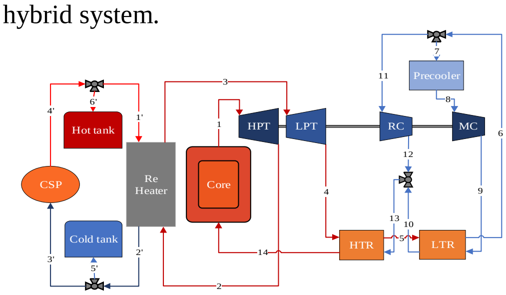

Fig 2. Recompression with reheating cycle layout of the previous hybrid system

The power generation concept of the hybrid system is a way to respond to changes in the electricity demand of the target region by adjusting the output of TES and CSP while maintaining nuclear power output at constant as much as possible.

However, in the case of the cycle layout, as the outputs of TES and CSP change, the thermal properties of the reactor inlet and outlet change, and eventually the output of nuclear power has to be changed as well. In addition, as shown in the below table, the temperature difference between the TES inlet and outlet of the hybrid system is significantly smaller than that of the TES used in the operating CSP.

Table 1. The temperature difference between the hot and cold TES of the various operating CSP

	Hybrid system	Gemasolar plant [3]	Dunhuang plant [4]
$T_{TES,Hot}$ (°C)	585	565	565
$T_{TES,Cold}$ (°C)	530	290	290
ΔT_{TES} (°C)	55	275	275

To resolve these issues, the following new cycle layout is proposed using a molten salt cooled reactor that has the same output as MMR.

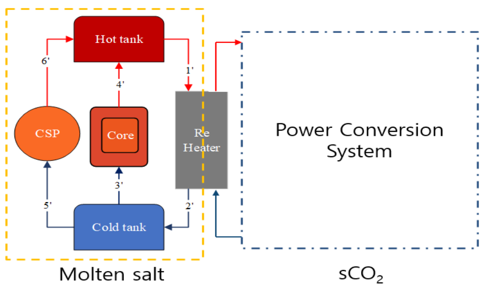

Fig 3. New cycle layout of the hybrid system

The new cycle layout maintains the temperature of the hot and cold tanks, thereby reducing the temperature change at the inlet and outlet of the reactor relatively, so the nuclear power output can be kept constant. In addition, it has the advantage of increasing the temperature difference of TES and can improve the flexibility of the system output through one integrated heat source.

Therefore, in this study, the new cycle layout is optimized and the cycle component design is performed. In the future, the off-design performance of the new hybrid system will be calculated to evaluate the feasibility of the system compared to the previous one.

2. Methods and Results

2.1 Target region

The same heat output and target region were set to fairly compare the previous hybrid system and the new system [1]. Therefore, the electricity demand of the target region was selected using South Korea's electricity demand data from the Korea Power eXchange (KPX) as follows.

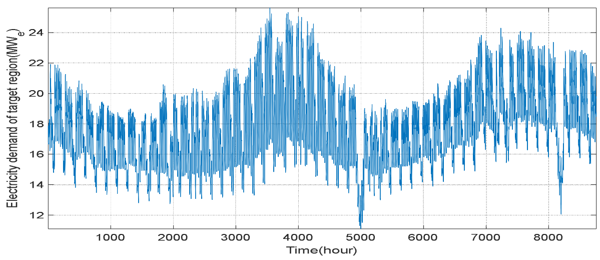

Fig 4. The electricity demand in the target area for one year [1]

The electricity demand in the target region was calculated by scaling the annual electricity demand of Korea using the characteristics of Korea's electricity demand data. For the detailed process, refer to the previous study [1]. In addition, the DNI used the same thing as the previous hybrid system.

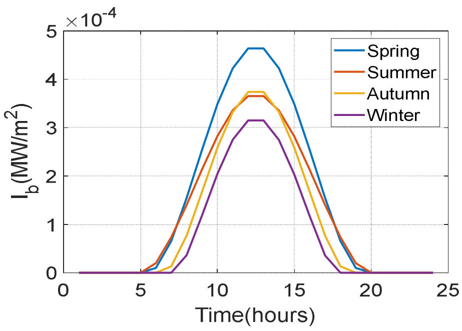

Fig 5. The seasonal average DNI of the target area [1]

2.2 Cycle layout selection

According to Ahn's work, the recompression cycle has the highest cycle efficiency at 400-600 °C among the various layout [5]. Therefore, the cycle layout of the new hybrid system is the recompression cycle as shown in the figure below.

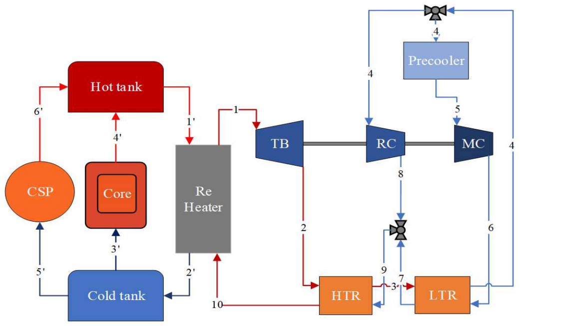

Fig 6. The new cycle layout for the hybrid system

For a fair comparison with the existing system, the CO_2 outlet temperature of the re-heater was fixed at 550°C. Unlike the existing system, the CSP, nuclear core inlet and cold tank temperature are the same, and the CSP, nuclear core outlet and hot tank temperature are the same in order to reduce the variation of MMR inlet and outlet thermal properties as possible during part-load operation.

In addition, the cycle turbomachinery efficiency and minimum temperature and maximum pressure were set the same as in the previous hybrid system except for the re-heater CO_2 outlet temperature as shown in the below table.

Table 2. Cycle design fixed value and optimization variables

Cycle design fixed value			
Max P	20Mpa	MMR heat	36.2MWth
Min T	35°C	Reheat	27.15MWth
MMR outlet T	550°C	Turbine eff.	85%
Re-heater outlet T New / Previous	**550°C/ 570°C**	Compressor eff.	80%
HTR, LTR effectiveness	0.95	Component pressure drop (Kpa)	100-150
Optimization variables			
Pressure ratio		Flow split ratio	

KAIST-CCD code developed by the KAIST research team was used to optimize the new hybrid system. This code is a MATLAB-based in-house code, and detailed explanations are shown in the references [6].

As a result of the optimization, it was confirmed that the highest efficiency was 40.2% at Pressure Ratio (PR) = 2.26 and Flow split ratio (FSR) =0.65. Compared to the previous cycle layout results (Cycle thermal efficiency = 41.63%), the optimum cycle efficiency was lowered, which was caused by the difference between the absent of the reheating and the maximum temperature of the re-heater.

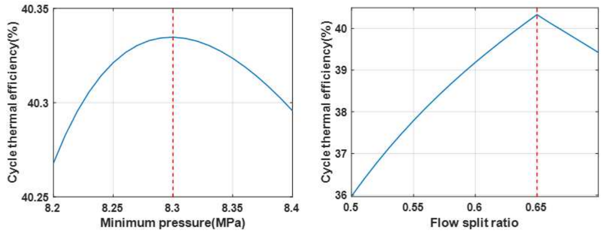

Fig 7. Optimization results of the hybrid system

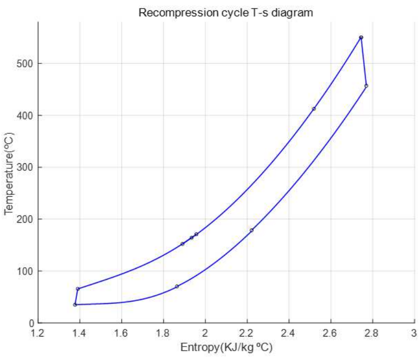

Fig 8. T-s diagram of the hybrid system

2.3 Turbomachinery design

The turbomachinery of the hybrid system consists of a turbine, the main compressor, and a re-compressor. It is assumed that the turbomachinery of the hybrid system uses an integral gear approach. An integral gear compressor expander is composed of one large bull-gear in the center with surrounding pinion as shown in the figure below and is being developed by applying it to the sCO_2 system in the US DOE project [7].

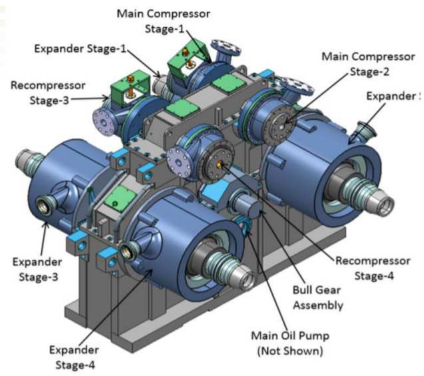

Fig 8. The example of the integrally geared expander compressor [6]

Therefore, the turbomachinery of the new hybrid system uses an integrally geared approach and assumes that even if the turbomachinery is designed at different rpm, it is connected to one shaft by being bitten by the central bull-gear shaft.

To design a turbomachinery of the hybrid system, KAIST-TMD code based on MATLAB developed by KAIST research team was used. The code uses the 1D mean-line method and can estimate the geometry, on-design, and off-design performance of turbomachinery. The detailed description of the code is shown in the following reference [8]. The geometry and performance map of the turbine, main-compressor, and re-compressor were calculated using the KAIST-TMD code, and the results are shown below.

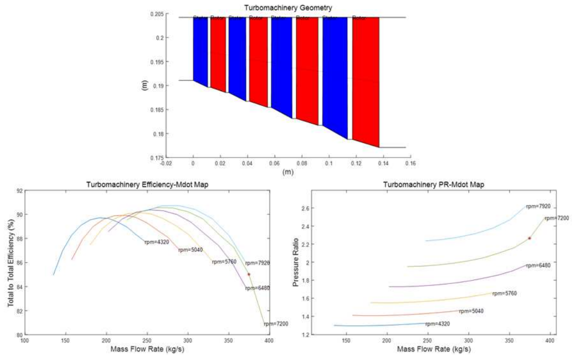

Fig 9. Geometry and performance map of the turbine

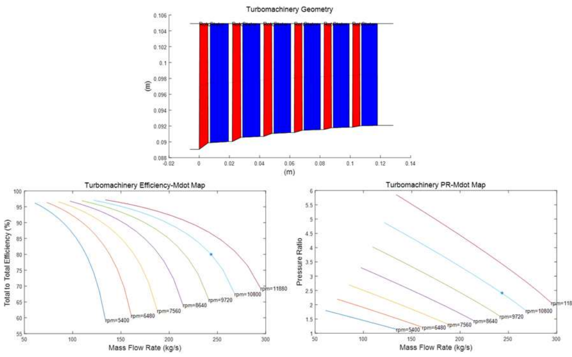

Fig 10. Geometry and performance map of main compressor

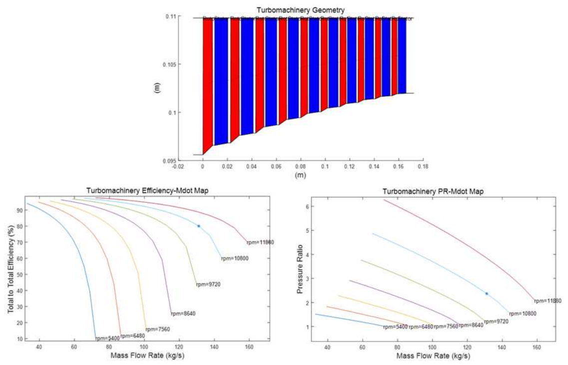

Fig 11. Geometry and performance map of the re-compressor

Table 3. Design result of the turbomachinery

	Turbine	Main comp.	Re-comp.
RPM	7200	10800	10800
Stage	4	6	10
Work (MW)	38.3	5.5	7.3
Pressure ratio	2.26	2.4	2.37
Efficiency (%)	85	80	80
T_{in} (°C)	550	35	70.3
P_{in}(Mpa)	19.7	8.3	8.4
P_{out}(Mpa)	8.7	20.0	19.9
Mass flow rate(kg/s)	374.4	243.4	131.1

2.4 Heat exchanger

KAIST-HXD code developed by KAIST researchers based on MATLAB was used to design the heat exchanger of the hybrid system. This code is a PCHE design code applicable to the sCO_2 system. The detailed description of the code is shown in the following reference [9].

Before designing the re-heater, it is necessary to select molten salt, which is the storage medium of TES and the working fluid of CSP and nuclear reactor. Among the various molten salts, solar salt, which has a composition of 40% KNO_3 and 60% $NaNO_3$, is widely used and commercialized, and cost-effective [10]. Therefore, solar salt was selected as a working fluid for the nuclear reactor and CSP, and a storage medium for TES.

The heat exchangers of the hybrid system include Re-heater, High-Temperature Recuperator (HTR), Low-Temperature Recuperator (LTR), and Pre-cooler, and the design results of the heat exchangers are as follows. As a result of the design, it was confirmed that the difference between the TES inlet (565℃) and outlet temperature (422℃) was 143℃.

Table 4. Design result of the heat exchangers

Parameters	HTR	LTR	Pre-cooler	Re-heater
Type	PCHE (Zigzag)	PCHE (Zigzag)	PCHE (Zigzag)	PCHE (Straight)
Heat load [MW]	120.0	52.9	38.3	63.3
Hot Avg. Re #	35000	46000	74400	1000
Cold Avg. Re #	54000	23000	3930	16000
ΔP_{hot} [kPa]	150	150	100	80
ΔP_{cold} [kPa]	100	100	100	100
Active Length [m]	2.15	3.74	0.97	4.63
Active Volume [m^3]	6.34	11.92	1.13	17.26

3. Conclusions

In this study, the cycle layout of the new hybrid system was optimized and the cycle components were designed. As a result of optimization, it shows a cycle thermal efficiency of 40.2%, which is about 1.4% lower than that of the previous hybrid system. The reason is the difference between the absence of reheating and the maximum cycle temperature.

The design of the cycle component was calculated using the KAIST-TMD and HXD codes developed by the KAIST research team, and the geometry, performance map of each turbomachinery and heat exchangers performance were estimated. As a result of the re-heater design, it was confirmed that the difference in TES temperature was increased by about 90℃ compared to the previous hybrid system, which suggests that the volume can be significantly reduced compared to the same TES heat capacity.

As a future study, the off-design performance of the new hybrid system will be calculated using the cycle optimization results and cycle components performance calculated in this paper. Finally, for the new hybrid system, the feasibility and potential of meeting the electricity demand in the target region will be evaluated compared to the previous hybrid system.

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