The concept design of the nuclear-renewable hybrid system: Component designs for different Nuclear-Renewable heat ratio

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1. Introduction

A distributed power generation system is attracting worldwide attention for its merits that it can meet electricity demand by itself and reduce electricity transmission costs. A CO_2 reduction and refueling cost reduction can be achieved simultaneously relying on renewable energy. However, due to the natural intermittency of renewable energy such as solar or wind power, it is inefficient to meet the electricity demand of micro-grids with only renewable energy.

To compensate for these shortcomings, the KAIST research team conducted a conceptual design of a hybrid system incorporating MMR (Micro Modular Reactor) as a base energy source to CSP (Concentrated Solar Power) and TES (Thermal Energy Storage) in the previous study [1]. KAIST-MMR is a reactor developed by the KAIST research team to solve the limitation of transportability of the existing SMR (Small Modular Reactor). KAIST-MMR improved transportability by using a light supercritical CO_2 (sCO_2) power cycle instead of a bulky steam Rankine power cycle.

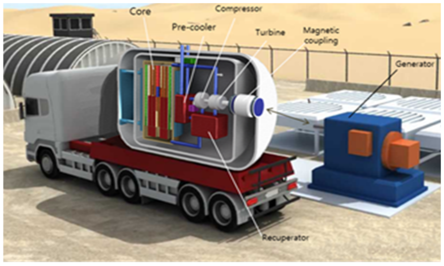

Fig 1. KAIST MMR concept diagram [2]

However, as revealed in the previous study results, it was difficult to meet the electricity demand with only the hybrid system. Due to the seasonal intermittency of renewable energy, the previous study concluded that reducing the ratio of the CSP heat source in the hybrid system could stably meet the electricity demand [1]. Therefore, in this study, the conceptual design of the hybrid system was conducted while decreasing the ratio of the CSP heat source compared to nuclear.

2. Cycle optimization

In the previous study, the ratio of the heat source of MMR and CSP of the hybrid system was = 1.33:1. In this study, the new hybrid system was conceptually designed by decreasing the heat source of CSP further while the heat source of MMR is fixed. The system layout and heat source ratio of the new hybrid system is shown in the figure and table below.

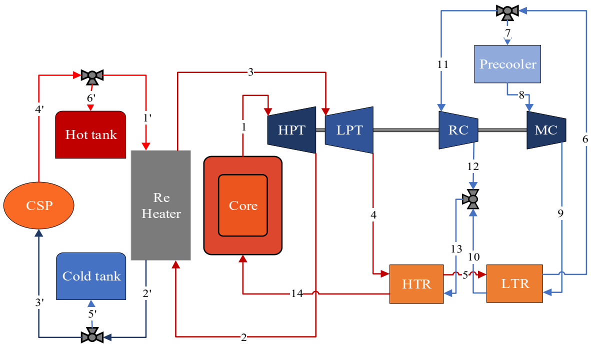

Fig 2. Recompression with reheating cycle layout of the hybrid system

Table 1. The heat source ratio of the new hybrid system

MMR : CSP	3:1	5:1	7:1
MMR (MW_{th})	36.2	36.2	36.2
CSP (MW_{th})	9.05	6.033	4.525

To design the hybrid system for the heat source ratio MMR : CSP = 3:1, 5:1, and 7:1, the system for each heat source ratio was optimized first. The KAIST-CCD code was used to optimize the hybrid system. The KAIST-CCD code is a MATLAB-based in-house code and was developed by the KAIST research team. One can refer to the reference [3] for more detailed description of the code.

The fixed values and optimization variables used for the optimization of the hybrid system are summarized in the table below.

Table 2. Fixed value and optimization variables for the Cycle design

<table>
<tr><th colspan="12">Fixed value</th></tr>
<tr><td colspan="3">Max P (Mpa)</td><td colspan="3">20</td><td colspan="3">MMR heat (MW_{th})</td><td colspan="3">36.2</td></tr>
<tr><td colspan="3">Min T (°C)</td><td colspan="3">35</td><td colspan="3">Max T (°C)</td><td colspan="3">550</td></tr>
<tr><td colspan="3">Turbine eff. (%)</td><td colspan="3">85</td><td colspan="3">Compressor eff. (%)</td><td colspan="3">80</td></tr>
<tr><td colspan="3">HTR, LTR effectiveness</td><td colspan="3">0.95</td><td colspan="3">Component pressure drop (kPa)</td><td colspan="3">100-150</td></tr>
<tr><td colspan="3">MMR : CSP</td><td colspan="3">3:1</td><td colspan="3">5:1</td><td colspan="3">7:1</td></tr>
<tr><td colspan="3">Re-heat (MW_{th})</td><td colspan="3">9.05</td><td colspan="3">6.033</td><td colspan="3">4.525</td></tr>
<tr><th colspan="12">Optimization variables</th></tr>
<tr><td colspan="4">Pressure ratio</td><td colspan="4">Flow split ratio</td><td colspan="4">HPT Pressure ratio</td></tr>
</table>

The fixed values were chosen to be the same with the previous study [1]. Optimization variables include cycle pressure ratio, flow split ratio to the main compressor, and HPT (High-Pressure Turbine) pressure ratio, which relates to how much pressure ratio is divided between the two turbines. The optimization results of the hybrid system for each heat source ratio are as follows.

Table 3. Optimization results of the hybrid system

MMR : CSP	3:1	5:1	7:1
Cycle Thermal efficiency (%)	41.17	41.0	40.86
Cycle work (MW_e)	19.87	17.8	16.9
MMR heat (MW_{th})	36.2	36.2	36.2
Re-heat (MW_{th})	12.07	7.24	5.17
Total heat (MW_{th})	48.27	43.44	41.37
HPT pressure ratio	1.34	1.21	1.15
LPT pressure ratio	1.65	1.82	1.91
Flow Split ratio	0.66	0.66	0.66
Minimum Pressure (MPa)	8.41	8.44	8.46
Mass flow rate (kg/s)	279.5	263.0	241.9

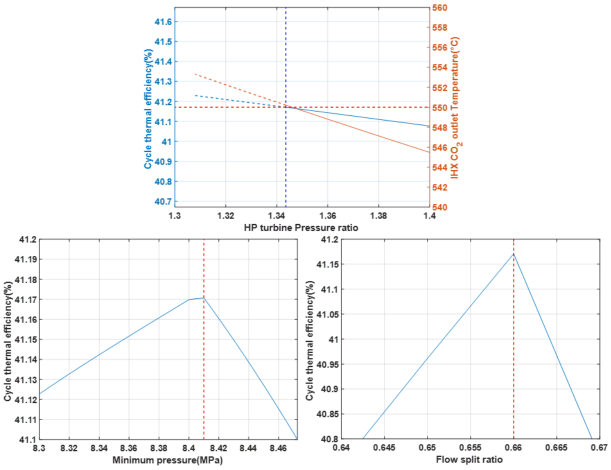

Fig 3. Optimization results of the hybrid system (3:1)

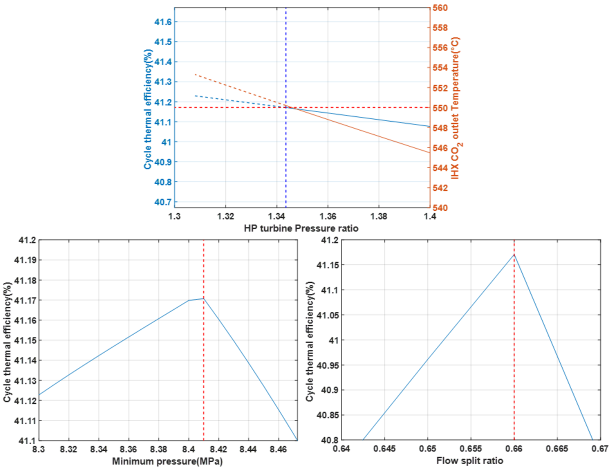

Fig 4. Optimization results of the hybrid system (5:1)

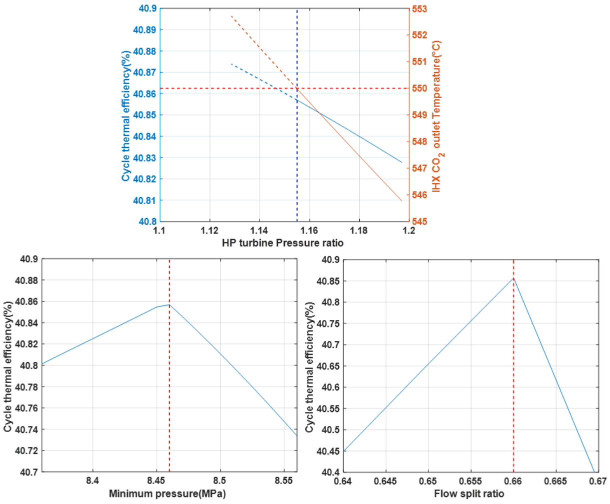

Fig 5. Optimization results of the hybrid system (7:1)

3. Component conceptual design

In this section, the heat exchanger and turbomachinery of the hybrid system are conceptually designed using the optimization results.

The heat exchanger was designed with KAIST-HXD code, a MATLAB-based in-house code [4]. KAIST-HXD code is a printed circuit heat exchanger (PCHE) design code for the application to a sCO_2 system using the 1-D FDM method. The heat transfer correlation and the pressure drop correlation are selected from the references [4-7]. The heat exchanger of the hybrid system is composed of HTR (High-Temperature Recuperator), LTR (Low-Temperature Recuperator), PC (Pre-Cooler), RH (Re-heater). The conceptual design results of the heat exchangers in the hybrid system for different heat source ratios are as follows.

Table 4. Heat exchanger design results (3:1)

MMR : CSP = 3:1				
Parameters	HTR	LTR	PC	RH
Type	PCHE (Zigzag)	PCHE (Zigzag)	PCHE (Zigzag)	PCHE (Straight)
Heat load [MW]	101.31	41.04	28.41	11.98
Hot Avg. Re #	19944	23129	38322	642
Cold Avg. Re #	23873	17004	2054	23143
ΔP_{hot} [kPa]	150	150	100	10
ΔP_{cold} [kPa]	100	100	55	150
Active length [m]	0.90	2.17	0.87	0.70
Active volume [m^3]	3.71	8.59	1.55	1.37

Table 5. Heat exchanger design results (5:1)

MMR : CSP = 5:1				
Parameters	HTR	LTR	PC	RH

Type	PCHE (Zigzag)	PCHE (Zigzag)	PCHE (Zigzag)	PCHE (Straight)
Heat load [MW]	89.06	36.75	25.64	27.27
Hot Avg. Re #	20215	23059	38339	616
Cold Avg. Re #	24099	16778	2069	27272
ΔP_{hot} [kPa]	150	150	100	5
ΔP_{cold} [kPa]	100	100	60	150
Active length [m]	0.89	2.25	0.87	0.57
Active volume [m^3]	3.32	8.10	1.39	0.84

Table 6. Heat exchanger design results (5:1)

MMR : CSP = 7:1				
Parameters	HTR	LTR	PC	RH
Type	PCHE (Zigzag)	PCHE (Zigzag)	PCHE (Zigzag)	PCHE (Straight)
Heat load [MW]	83.93	17.76	24.28	5.175
Hot Avg. Re #	20951	22626	44293	579
Cold Avg. Re #	24936	17762	2386	30268
ΔP_{hot} [kPa]	150	150	100	5
ΔP_{cold} [kPa]	100	100	70	150
Active length [m]	0.89	2.29	0.92	0.49
Active volume [m^3]	3.07	7.84	1.21	0.62

The turbomachinery was designed using the KAIST-TMD code, a MATLAB-based in-house code. The code can estimate the geometry and on- and off-design performances of the turbomachinery by applying the 1D-mean-line method with loss models. A detailed explanation of the code is provided in the references [8, 9]. The turbomachinery of the hybrid system is composed of HPT (High-Pressure Turbine), LPT (Low-Pressure Turbine), MC (Main Compressor), and RC (Re-Compressor). The design results of the components in the hybrid system for different heat source ratios are as follows.

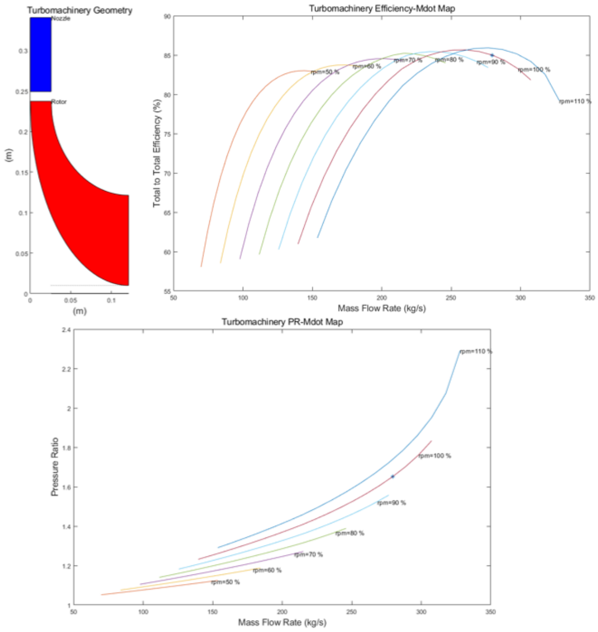

Fig 6. Turbine geometry and performance map

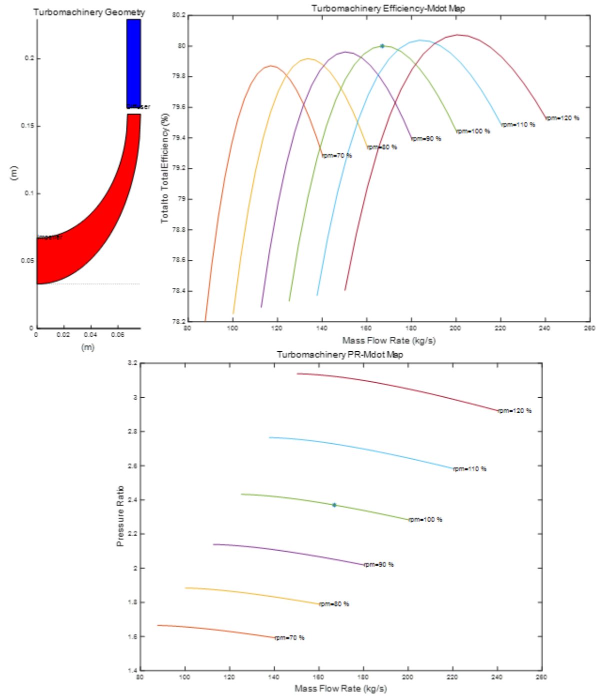

Fig 7. Compressor geometry and performance map

Table 7. Turbomachinery design results (3:1)

MMR : CSP = 3:1				
	HPT	LPT	MC	RC
Work (MW)	10.9	18.0	4.0	5.0
Pressure ratio	1.34	1.65	2.38	2.34
Efficiency (%)	85%	85	80	80
T_{in} (°C)	550	550	35	67.7
P_{in} (MPa)	19.75	14.55	8.41	8.51
P_{out} (MPa)	14.7	8.81	20.0	19.9

mass flow rate (kg/s)	279	279	279	279

Table 8. Turbomachinery design results (5:1)

MMR : CSP = 5:1				
	HPT	LPT	MC	RC
Work (MW)	6.5	19.43	3.6	4.47
Pressure ratio	1.21	1.82	2.37	2.32
Efficiency (%)	85%	85%	80	80
T_{in} (°C)	550	550	35	66.7
P_{in} (MPa)	19.75	16.15	8.44	8.56
P_{out} (MPa)	16.3	8.84	20.0	19.9
mass flow rate (kg/s)	253	253	253	253

Table 9. Turbomachinery design results (7:1)

MMR : CSP = 7:1				
	HPT	LPT	MC	RC
Work (MW)	4.68	19.93	3.4	4.27
Pressure ratio	1.15	1.91	2.36	2.32
Efficiency (%)	85%	85%	80	80
T_{in} (°C)	550	550	35	67.1
P_{in} (MPa)	19.75	16.95	8.46	8.54
P_{out} (MPa)	17.1	8.86	20.0	19.9
mass flow rate (kg/s)	242	242	242	242

4. Summary and Further Works

As a result of previous studies, due to the seasonal intermittency of CSP, there is a limit to meeting the electricity demand in the target region with a hybrid system. Therefore, in this study, a concept design was conducted first by decreasing the ratio of CSP heat energy while nuclear energy is fixed in the hybrid system.

The heat source ratio of the newly selected hybrid system is Nuclear: Solar Heat = 3:1, 5:1, and 7:1, and each system was optimized and components were conceptual designed.

In the future, the off-design performance of the hybrid system will be estimated using the cycle design results and the component conceptual design. Using the calculated off-design performance of the hybrid system, the feasibility of how the hybrid system for each heat source ratio can meet the electricity demand according to the heat source ratio will be evaluated. Additionally, an economic evaluation model will be developed to calculate the optimal heat source ratio of the hybrid system that can meet the electricity demand in the target area.

ACKNOWLEDGEMENTS

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