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

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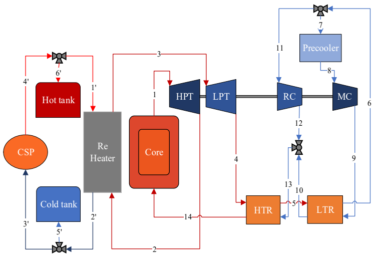
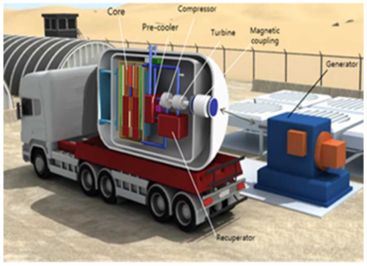
Introduction

- ▣ 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.
- ▣ KAIST-MMR is a reactor developed by the KAIST research team to solve the limitation of transportability of the existing SMR (Small Modular Reactor) by using a light sCO_2 power cycle.
- ▣ 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 is used for the hybrid system.



△ **Recompression with reheating cycle layout**



△ **Concept diagram of the KAIST MMR**

- ▣ 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.
- ▣ 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.

Cycle optimization for new hybrid system

1. Re-select the heat source ratio

- ▣ In the previous study, the ratio of the heat source of MMR and CSP of the hybrid system is = 1.33:1.
- ▣ The hybrid system is designed by decreasing the heat source of CSP while the heat source of MMR is fixed.

▽ **The new heat source ratio**

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

2. Cycle optimization

- ▣ The KAIST-CCD code, MATLAB-based in-house code, is used to optimize the hybrid system.
- ▣ The fixed values and optimization variables used for the optimization of the hybrid system are summarized in the table.

▽**Fixed value and optimization variables for the Cycle design**

<table>
<tr><td colspan="6">Fixed value</td></tr>
<tr><td>Max P (Mpa)</td><td>20</td><td colspan="3">MMR heat (MW_{th})</td><td>36.2</td></tr>
<tr><td>Min T (°C)</td><td>35</td><td colspan="3">Max T (°C)</td><td>550</td></tr>
<tr><td>Turbine eff. (%)</td><td>85</td><td colspan="3">Compressor eff. (%)</td><td>80</td></tr>
<tr><td>HTR, LTR effectiveness</td><td>0.95</td><td colspan="3">Component pressure drop (kPa)</td><td>100-150</td></tr>
<tr><td>MMR : CSP</td><td colspan="2">3:1</td><td colspan="2">5:1</td><td>7:1</td></tr>
<tr><td>Re-heat (MW_{th})</td><td colspan="2">9.05</td><td colspan="2">6.033</td><td>4.525</td></tr>
<tr><td colspan="6">Optimization variables</td></tr>
<tr><td colspan="2">Pressure ratio</td><td colspan="2">Flow split ratio</td><td colspan="2">HPT Pressure ratio</td></tr>
</table>

- ▣ The optimization results of the hybrid systems are as follows.

▽ **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

Result : Component conceptual design

- ▣ 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 heat exchanger is designed with KAIST-HXD code, a MATLAB-based in-house code.
- ▣ 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.

▽ **Heat exchanger design results (3:1)**

<table>
<tr><th colspan="5">MMR : CSP = 3:1</th></tr>
<tr><th>Parameters</th><th>HTR</th><th>LTR</th><th>PC</th><th>RH</th></tr>
<tr><td>Heat load [MW]</td><td>101.31</td><td>41.04</td><td>28.41</td><td>11.98</td></tr>
<tr><td>ΔP_{hot} [kPa]</td><td>150</td><td>150</td><td>100</td><td>10</td></tr>
<tr><td>ΔP_{cold} [kPa]</td><td>100</td><td>100</td><td>55</td><td>150</td></tr>
<tr><td>Active length [m]</td><td>0.90</td><td>2.17</td><td>0.87</td><td>0.70</td></tr>
<tr><td>Active volume [m^3]</td><td>3.71</td><td>8.59</td><td>1.55</td><td>1.37</td></tr>
</table>

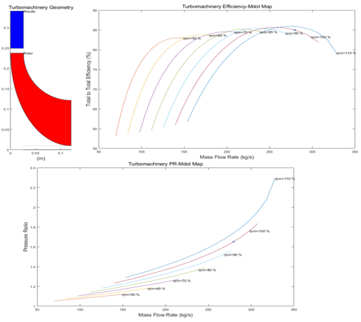
▽ **Heat exchanger design results (5:1)**

<table>
<tr><th colspan="5">MMR : CSP = 5:1</th></tr>
<tr><th>Parameters</th><th>HTR</th><th>LTR</th><th>PC</th><th>RH</th></tr>
<tr><td>Heat load [MW]</td><td>89.06</td><td>36.75</td><td>25.64</td><td>27.27</td></tr>
<tr><td>ΔP_{hot} [kPa]</td><td>150</td><td>150</td><td>100</td><td>5</td></tr>
<tr><td>ΔP_{cold} [kPa]</td><td>100</td><td>100</td><td>60</td><td>150</td></tr>
<tr><td>Active length [m]</td><td>0.89</td><td>2.25</td><td>0.87</td><td>0.57</td></tr>
<tr><td>Active volume [m^3]</td><td>3.32</td><td>8.10</td><td>1.39</td><td>0.84</td></tr>
</table>

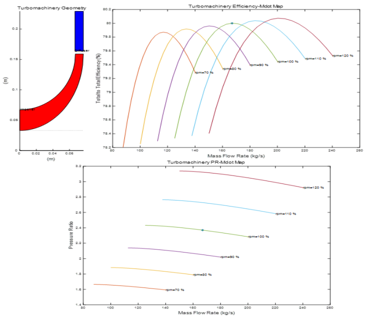
▽ **Heat exchanger design results (7:1)**

<table>
<tr><th colspan="5">MMR : CSP = 7:1</th></tr>
<tr><th>Parameters</th><th>HTR</th><th>LTR</th><th>PC</th><th>RH</th></tr>
<tr><td>Heat load [MW]</td><td>83.93</td><td>17.76</td><td>24.28</td><td>5.175</td></tr>
<tr><td>ΔP_{hot} [kPa]</td><td>150</td><td>150</td><td>100</td><td>5</td></tr>
<tr><td>ΔP_{cold} [kPa]</td><td>100</td><td>100</td><td>70</td><td>150</td></tr>
<tr><td>Active length [m]</td><td>0.89</td><td>2.29</td><td>0.92</td><td>0.49</td></tr>
<tr><td>Active volume [m^3]</td><td>3.07</td><td>7.84</td><td>1.21</td><td>0.62</td></tr>
</table>

- ▣ 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 turbomachinery is 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.



△ **Turbine geometry and performance map**



△ **Compressor geometry and performance map**

▽ **Turbomachinery design results (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

▽ **Turbomachinery design results (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

▽ **Turbomachinery design results (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

Conclusions

- ▣ The heat source ratio of the newly selected hybrid system is Nuclear: Solar = 3:1, 5:1, and 7:1, and each system is optimized and components are conceptually designed.
- ▣ As a further study, the off-design performance of the hybrid system will be estimated using the cycle design results and the component conceptual design.
- ▣ 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.