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Modeling of Hybrid Micro Modular Reactor with GAMMA+ Code

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1. Introduction

Nowadays, the electricity demand is increasing, and to fulfill the increasing demand, a reliable source of energy is crucial to the societies all over the world. Previously, energy sources such as fossil-fuel power generation were widely used. However, the conventional energy sources caused worldwide rapid climate changes due to their massive greenhouse gas emissions. Thus, finding a new source of energy that can both satisfy the increasing demand as well as minimize the greenhouse gas emissions has gained attention.

Renewable energies, such as wind turbine, and solar power, have been suggested as future sources of energy, because they emit no greenhouse gas and do not require any fuel. On the other hand, their intermittent nature hinders them from generating electricity steadily. To alleviate the issue, nuclear power, especially small modular reactor (SMR) with supercritical carbon dioxide (S-CO_2) power cycle, is proposed as a baseload energy source. According to Dostal, S-CO_2 Brayton cycle is compact yet has competitive thermal efficiency [1]. S-CO_2 has low compressibility near its critical point (7.38 MPa, 31°C), which causes the reduction of compressor work substantially compared to the existing gas Brayton cycle. As a result, the thermal efficiency of S-CO_2 Brayton cycle becomes higher than those of Brayton cycles using different gases, such as helium and nitrogen [2].

In this study, modeling of Hybrid Micro Modular Reactor (H-MMR) with GAMMA+ Code is discussed. H-MMR is a 24 MW_{th} solar-nuclear hybrid system with S-CO_2 reheat-recompression cycle as shown in Figure 1. The cycle is optimized with KAIST-CCD code and the components are designed with KAIST-HXD and KAIST-TMD codes.

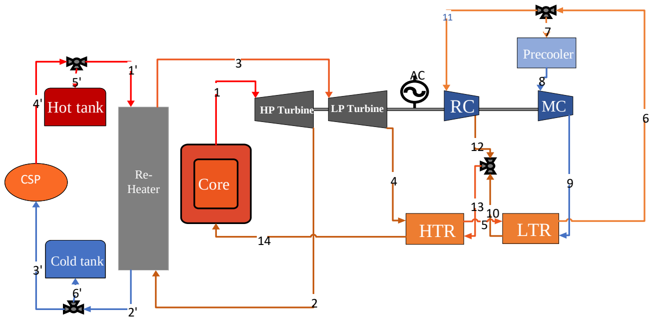

Figure 1. Layout of H-MMR Cycle

2. Method and Results

2.1 Cycle Optimization

In the target system, a heat pipe cooled reactor and concentrated solar power (CSP) with thermal energy storage (TES) system are used as heat sources. From the reactor side, 18 MW_{th} heat is transferred to the power conversion system through the intermediate heat exchanger. Similarly, 6 MW_{th} heat from the CSP side is transferred through the re-heater.

To optimize the power cycle, a MATLAB based in-house code KAIST-CCD (Closed Cycle Design) is used. The code inputs some parameters including the maximum temperature and pressure, the minimum temperature, heat exchanger pressure drops, and the turbomachinery efficiencies. With the input, the code calculates the cycle efficiency and mass flow rate based on the turbine pressure ratio and flow split ratio. Table 1 shows the result from the KAIST-CCD code for the target system.

Table 1. KAIST-CCD Result

Design parameter	Value
Cycle Thermal efficiency(%)	42.94
Cycle work (MW_e)	10.3
MMR heat (MW_{th})	18
CSP(Reheat) heat (MW_{th})	6
Total heat (MW_{th})	24
HPT pressure ratio	1.36
LPT pressure ratio	1.66
Flow Split ratio	0.66
Minimum Pressure (MPa)	8.26
Mass flow rate(kg/s)	133.1172
Maximum Temperature(°C)	600

Cycle Point	1	2	3	4	5
T [C]	600.00	562.70	599.21	538.98	191.06
P [MPa]	19.65	14.50	14.35	8.66	8.51
Cycle Point	5	6	7	9	10
T [C]	71.71	71.71	35.00	66.80	182.53
P [MPa]	8.36	8.36	8.26	20.00	19.90
Cycle Point	11	12	13	14	
T [C]	71.71	154.70	172.76	490.99	
P [MPa]	8.36	19.90	19.90	19.80	

2.2 Component Design

The reheat-recompression S-CO_2 cycle has three Printed Circuit Heat Exchangers (PCHE), two turbines and two compressors. To design PCHE type heat exchangers and turbomachinery, MATLAB based in-house codes, KAIST-HXD (Heat eXchanger Design) and KAIST-TMD (TurboMachinery Design), were used, respectively.

KAIST-HXD code inputs the parameters such as geometry, mass flow rate, temperature and pressure, then calculates appropriate channel numbers and total heat exchanger volume. Similarly, KAIST-TMD code inputs turbomachinery parameters such as type, and mass flow rate, then calculates impeller size and turbomachinery off-design performance map. Table 2 shows the results from both KAIST-HXD and KAIST-TMD.

Table 2. Results from KAIST-HXD and TMD

Parameters	HTR	LTR	Pre-cooler
Diameter [mm]	2	2	2
Channel Number	197000 148000	200000 92000	32466 49722
Heat load [MW]	53.68	20.35	13.693
Hot Avg. Re #	18195.94	24010.49	84582.74
Cold Avg. Re #	22644.83	20231.44	4270.01
ΔP_{hot} [kPa]	150	150	100
ΔP_{cold} [kPa]	100	100	100
Active Length [m]	0.91997	1.8223	0.62319
Volume [m^3]	1.9043	3.1926	0.30731

	High Pressure Turbine	Low Pressure Turbine	Recompressor	Main Compressor
Work [MW]	5.70	9.2	2.55	2.00
Pressure ratio [-]	1.36	1.66	2.38	2.42
Efficiency [%]	85%	85%	80%	80%
T_{in} [°C]	600	600	71.7	35
P_{in} [Mpa]	19.65	14.35	8.36	8.26
P_{out} [Mpa]	14.5	8.66	19.9	20
mass flow rate [kg/s]	133.12	133.12	45.26	87.86
RPM	18000	18000	18000	14400
Mass flow rate, rpm range	0.5-1.1	0.5-1.1	0.7-1.2	0.7-1.2

2.3 Modeling of H-MMR with GAMMA+ Code

GAMMA+ code is a system analysis code developed by Korea Atomic Energy Research Institute to simulate gas-cooled reactors. Originally, GAMMA+ code calculated CO_2 fluid properties with ideal gas correlations. Since, CO_2 behaves as a non-ideal gas near the critical point (7.38 MPa & 30.98 °C), the fluid properties calculated by the original GAMMA+ code deviated from the exact value. Therefore, the NIST-REFPROP, which provides the exact CO_2 properties, is implemented in GAMMA+ code. Additionally, a turbomachinery module for off-design condition is implemented. The modified GAMMA+ code was validated with two different experimental facilities: SCO_2PE and SCIEL [3,4].

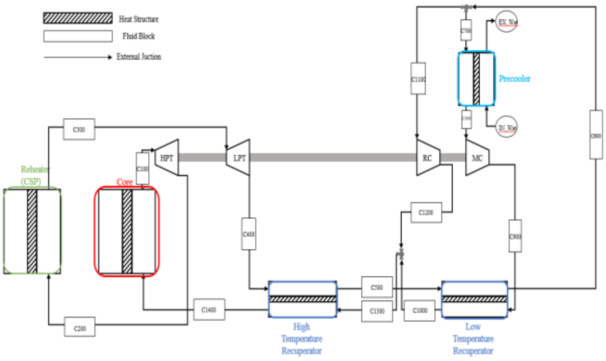

Figure 2. H-MMR GAMMA+ Nodalization

With the results from the previous sections, H-MMR was modeled with GAMMA+. Currently, only steady-state condition is modeled. The GAMMA+ nodalization and steady-state result of H-MMR are shown in Figure2, and Table 3, respectively. The maximum error between the values from KAIST-CCD and those from GAMMA+ code is far less than 1%. Thus, the steady-state result from GAMMA+ code can be used for the transient analysis in the further work.

Table 3. Steady-State Result from GAMMA+

Design Parameter	GAMMA+	Err [%]
Efficiency [%]	42.854	0.200
Cycle Work [MW_e]	10.285	0.146
HPT Pressure Ratio	1.359	0.101
LPT Pressure Ratio	1.657	0.176
Flow Split Ratio	0.661	0.218
Mass Flow Rate [kg/s]	133.054	0.047

Cycle Point	T [°C]		P [MPa]	
	GAMMA+	Err [%]	GAMMA+	Err [%]
1	598.64	0.227	19.637	0.064
2	561.34	0.242	14.454	0.318
3	597.90	0.218	14.345	0.035
4	537.74	0.230	8.657	0.037
5	190.23	0.434	8.508	0.023
6	71.85	0.195	8.359	0.017
7	71.84	0.181	8.357	0.034
8	35.00	0.006	8.256	0.049
9	66.85	0.075	19.962	0.192
10	181.05	0.811	19.880	0.100
11	71.84	0.177	8.357	0.040
12	154.83	0.085	19.880	0.100
13	171.90	0.500	19.881	0.097
14	489.56	0.291	19.787	0.064

3. Summary and Further Works

Hybrid Micro Modular Reactor, a CSP-nuclear power hybrid system with reheat-recompression $S\text{-}CO_2$ cycle, is modeled with GAMMA+ code for transient simulation in the future. The system was designed with KAIST-CCD, HXD, and TMD codes. Based on the design parameters, GAMMA+ code was used, and the steady-state input was prepared and the results show satisfactory performance of the code when compared to the design values. Henceforth, the reactor side and the CSP side of the system will be modeled to simulate full transient of the H-MMR.

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