Conceptual System Design of a Supercritical CO_2 cooled Micro Modular Reactor

Seong Gu Kim[a], Bongseong Oh[a], Seung Joon Baik[a], Hwanyeal Yu[a], Yonghee Kim[a], Jeong Ik Lee[a]
[a]*Dept. Nuclear & Quantum Eng., KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea*
**Corresponding author : jeongiklee@kaist.ac.kr*

1. Introduction

The pre-developed small modular reactor (SMR) concepts showed quite compact size than the large nuclear power plants. However, those concepts have not reached fully modularization Therefore, the authors suggest a concept to replace existing steam Rankine cycle, with the supercritical CO_2 (S-CO_2) Brayton cycle for complete modularization of the whole nuclear system.

The S-CO_2 Brayton cycle has many advantages for SMR's power conversion system. The S-CO_2 cycle can achieve small component size and simple cycle layout as shown in Fig. 1 [1]. Therefore, a concept of one module containing the S-CO_2 cooled fast reactor core and power conversion system is realizable. Thanks to the compact heat exchanger technology such as Printed Circuit Heat Exchanger (PCHE), the supercritical fluid with mediocre heat transfer performance can be utilized to a thermal cycle. This concept of fully modularized reactor is named as KAIST Micro Modular Reactor (MMR). It can achieve large economic by production in series, and transported in the land way or sea way.

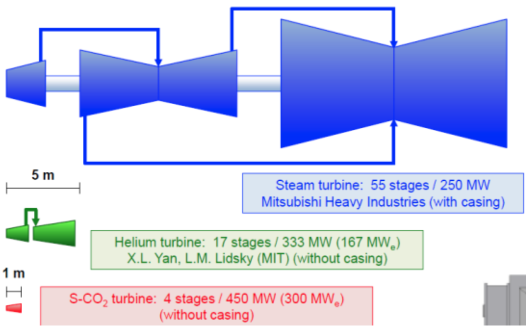

Fig. 1. Size of S-CO_2 turbine in comparison to the steam and helium turbine [1].

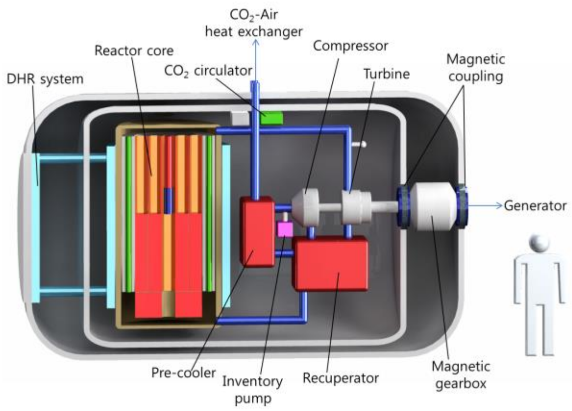

Fig. 2. Schematic figure of KAIST MMR.

2. Reactor Core Design

The reactor core for MMR is designed by neutronic analysis with MCNP code, Serpent [2]. Each fuel assembly consists of 127 fuel pins. The diameter of the pin is 1.5cm and P/D ratio is 1.13. Fig. 3 shows a configuration of the core. The drum type control rod is used as primary control rod since the core size can be more compact than the insert type control rod. Table 1 shows the design parameters of KAIST MMR [3].

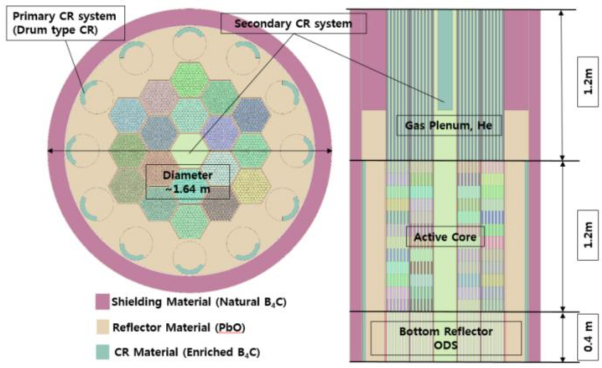

Fig. 3. Radial and axial configuration of the reactor core.

Table 1. Design parameters of KAIST MMR.

Item	Value
Core Thermal Power	36.2 MWth
Life time	20 years
Number of Fuel Assemblies	18
Active core equivalent radius / height	46.58 cm / 120 cm
Whole core equivalent radius / height	82 cm / 280 cm
Coolant pressure / velocity	20 MPa / 6.9 m/s
Coolant inlet and outlet Temp.	655.4 K / 823.2 K
Total weight of core	39.6 ton
Averaged discharged burnup	51.6 GWd/MTHM
Power density	88.23 W/cc
Fuel enrichment	15.5 $^{w}/_{o}$ $U^{15}N$ fuel

2. Design of S-CO_2 Power Conversion Cycle

The direct cycle configuration was chosen for the MMR to achieve simple layout and light-weight module. An in-house cycle design code KAIST-CCD was used to design S-CO_2 Brayton cycles. The simple recuperated S-CO_2 Brayton cycle, and recompressing recuperated S-CO_2 Brayton cycle were considered for the power conversion cycles for MMR. These cycle layouts and operating conditions are shown in Fig. 4. The target performance and module size of MMR are listed in Table 3. The top pressure of the cycle was determined by performing a cycle optimization study. The compressor inlet temperature was determined to be

60℃ for the air cooling capability of pre-cooler cold side. The CO_2-Air heat exchanger connected to the pre-cooler cold side was proposed to achieve dry air-cooling capability [4].

To find an optimum top pressure at the fixed compressor inlet pressure (7.5MPa), the net cycle efficiency versus pressure ratio was found by using cycle design code, KAIST-CCD. The component efficiencies of compressor and turbine were assumed to be 85% and 92%, respectively [5]. The estimated size and efficiency of tubomachineries were obtained by KAIST-TMS radial. This in-house code utilizes Balje's n_s-d_s diagram to determine the impeller diameter and isentropic efficiency. The NIST REFPROP database for thermodynamic properties is coupled to this design code. The maximum net cycle efficiencies appeared at the pressure ratio of 2.62 and 1.81 in the simple recuperated cycle, and the recompressing cycle, respectively.

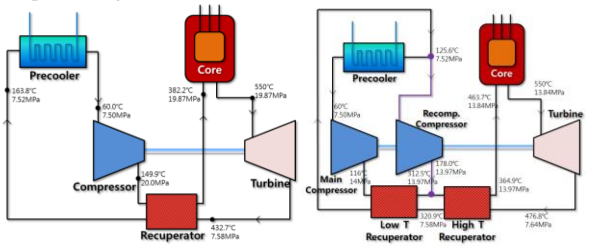

Fig. 4. Schematic figure of simple recuperated, and recompressing S-CO_2 Brayton cycle.

Table 2. Target performance and size.

Electric power output	10-12 MWe
Turbine inlet temperature	550.0℃
Compressor inlet temperature	60.0℃
Total Weight	Mass < 250ton
Total Height	Height < 7m
Cylindrical diameter	Diameter < 4m
Pre-cooler cold side coolant	CO_2, 45℃
Outside heat exchanger coolant	Air, 25℃

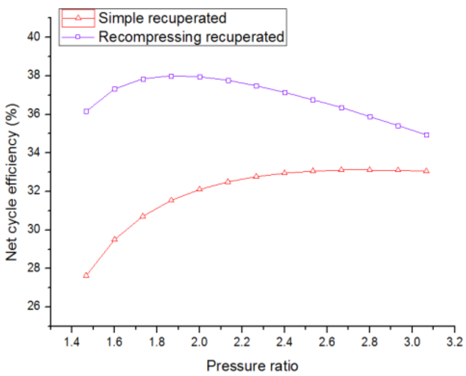

Fig. 5. Net cycle efficiencies of simple recuperated cycle and recompressing recuperated cycle with respect to pressure ratio.

Based on the optimized cycle condition, the radial type single-stage compressors and turbine coupled to single shaft was employed. The performance and size of heat exchangers were computed by using the KAIST-HXD, which is an in-house code utilizing the heat transfer coefficient and friction factor correlations for Printed Circuit Heat Exchanger. The set of correlations was developed by performing 3-D CFD analyses [7]. This correlation was compared to the several previous experimental studies of PCHE and compact heat exchangers [6].

As shown in Table 2, the recompressing cycle has a complex layout and large mass of heat exchangers. Due to the large mass flow rate (410 kg/s) of the recompressing cycle, the size of cycle components is larger than that of the simple recuperated cycle. Therefore, the authors propose the simple recuperated cycle as an appropriate power conversion cycle because lightweight module and compact cycle are important for transportable KAIST MMR. Therefore, the designed power conversion system generates 12MWe. The rotating shaft of S-CO_2 turbine and generator is connected to the magnetic coupling and gearbox as shown in Fig. 2 [7].

Table 3. Design results of turbomachineries and heat exchangers for simple recuperated and recompressing cycles.

	Simple recuperated (20MPa)	*Recompressing recuperated (14MPa)*
Rotating speed	20,200 rpm	9,800 rpm
Mass flow rate	175.3 kg/s	345.4 kg/s
Compressor specific speed	0.643	0.642 (main) 0.319 (recomp.)
Turbine specific speed	0.510	0.502
Compressor diameter	0.274m	0.438m (main) 0.528m (recomp.)
Turbine diameter	0.323m	0.527m
Pre-cooler volume	**0.309m^3**	**1.761 m^3**
Pre-cooler length	0.670m	0.810m
Recuperator volume	**0.596m^3**	**HTR: 1.623 m^3** **LTR: 1.193 m^3**
Recuperator length	0.722m	HTR: 0.810m LTR: 0.690m
Mass of heat exchangers	**3.8 ton**	**19.3 ton**
Pre-cooler cold side mass flow rate	97 kg/sec	410 kg/sec
Dimentions of PCHE	Diameter : 1.9mm Fin angle : 32.5°	Plate thickness : 1.63mm

Table 4. Design result of simple recuperated S-CO_2 Brayton cycle.

Thermal power	36.2 MWth	***Mass flow rates***	175.34 kg/s
Net electric power	11.99 MWe	***Pressure ratio***	2.62
Thermal efficiency	33.12%	***Compressor outlet pressure***	20.0 MPa
Turbine work	22.65 MW	***Compressor inlet pressure***	7.50 MPa
Compressor work	10.17 MW	***Size of pre-cooler***	0.3095 m^3 1.2 ton
Rotating speed	20,200rpm	***Size of recuperator***	0.5958 m^3 2.6 ton

Design point of recuperator	*Hot side inlet* : 432.7℃, 7.58MPa *Cold side inlet* : 149.9℃, 20.0Mpa *Temperature difference* : 22-58℃

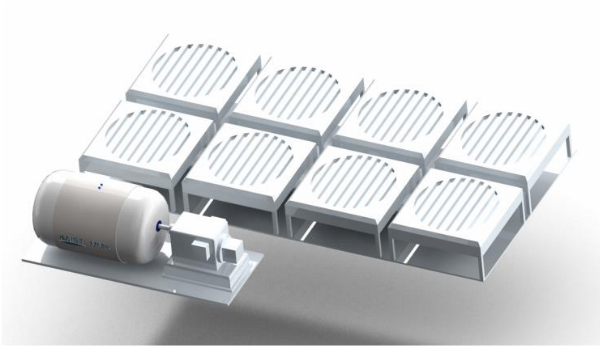

Fig. 6. Schematic of KAIST-MMR with CO_2 to air heat exchanger and synchronous generator (60Hz).

VI. ASSESSMENT OF CONCEPTUAL LAYOUT

Based on the design results of the reactor core, power conversion system, and decay heat removal system, the conceptual figure of MMR was made. Including the vessel and structural materials, the mass of reactor core will be increased up to 50 tons. The thickness of double containments was obtained from the pressure vessel thickness formula [8]. The mass of coolant were estimated based on the containment size and CO_2 filled volume at each system pressure. External dimensions of KAIST-MMR are 6.8m in length and 4.0m in diameter. Total weight of MMR module is estimated to be 183 ton as summarized in Table 5. Thus, this module can be transported via ground transportation by module trailer, which has a transportable limit up to 260 ton.

Table 5. Volume and weight of reactor, cycle components, and whole module.

	Dimensions	*Volume*	*Weight*
Core	2.8m (H) 1.5m (Dia.)	4.9m^3	50 ton
Pre-cooler	-	0.309m^3	1.2 ton
Recuperator	-	0.596m^3	2.6 ton
Containment material (Outside)	8.3m (L) 3.5m (Dia.) 7cm (T)	7.73m^3	60.7 ton
Containment material (Inside)	7.0m (L) 3.1m (Dia.) 7cm (T)	5.83m^3	45.8 ton
Coolant	Outer containment 12.5m^3 (1MPa)		0.2 ton
	Inner containment 26.4m^3 (5MPa)		2.1 ton
	Coolant 5m^3 (20MPa)		0.6 ton
Turbomachinery & Magnetic gear	-		~10 ton
DHR system	-		~10 ton
Total module	-		183 ton

VII. CONCLUSION AND FUTURE WORKS

An innovative concept of single module with S-CO_2 cooled fast reactor coupled to S-CO_2 Brayton cycle is proposed. Based on the design results and dimensions of the reactor core and cycle components, the authors propose a conceptual layout of KAIST MMR. Based on this concept of reactor core, power conversion system, and decay heat removal system, the seasonal operation and transient analysis will be performed in the further works. Also, the transient analysis for load following, and safety analysis will be followed.

ACKNOWLEDGEMENT

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