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Preliminary Design of S-CO_2 Brayton Cycle for KAIST Micro Modular Reactor

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1. Introduction

Small modular reactor (SMR) systems that have advantages of low initial capital cost and site flexibility are being actively developed by many organizations. Existing SMR concepts in the world have the same objective: to achieve small size and long core life. This paper suggests a complete modular reactor with an innovative concept of reactor cooling by using a supercritical carbon dioxide directly. Authors propose the supercritical CO_2 Brayton cycle (S-CO_2 cycle) as a power conversion system to achieve small volume of power conversion unit (PCU) and to contain the core and PCU in one vessel for the full modularization. This study suggests a conceptual design of small modular reactor including PCU which is named as KAIST Micro Modular Reactor (MMR).

2. Supercritical CO_2 Cooled Micro Modular Reactor

2.1 Operational Layout of KAIST MMR

KAIST MMR is a gas cooled fast reactor, using supercritical CO_2 as a working fluid of core cooling and power cycle. Schematic diagram of KAIST MMR is shown in Fig.1. In case of normal operation, coolant out of the reactor flows into the turbine inlet. Otherwise, during an abnormal operation, coolant flows out of the reactor vessel and cooled by decay heat removal system.

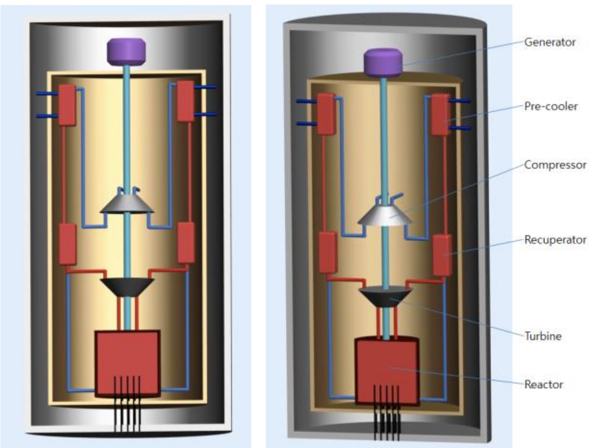

Fig.1. Schematic figure of KAIST MMR.

2.2 Supercritical CO_2 Brayton Cycle

The supercritical carbon dioxide Brayton (S-CO_2) cycle is considered as an attractive power cycle for a small sized nuclear system because relatively high efficiency under moderate turbine inlet temperature (450~750℃). Comparing to the power generation cycle working with steam or helium, S-CO_2 cycle occupies much less volume due to smaller component size. With the combination of compact heat exchangers such as PCHE (Printed Circuit Heat Exchanger) technology, fluid with mediocre heat transfer capacity can be used for working fluid.

2.3 Cycle configuration for MMR

In this study, an in-house cycle design code developed by KAIST research team was used to design S-CO_2 Brayton cycles. As shown in Fig. 2, a 15MWe gas-cooled reactor with S-CO_2 recuperated Brayton cycle and S-CO_2 recompressing Brayton cycle configuration were considered for designing a power conversion system for MMR. Based on these cycle configurations, size estimation of components such as turbomachinery and heat exchanger were performed.

Target performance and size of KAIST MMR is listed in Table I. The electric power output target is set to 15MW and top pressure and turbine inlet temperature is selected to be 20MPa, 550℃. The physical size of KAIST MMR is selected to be less than a transportable limit of container.

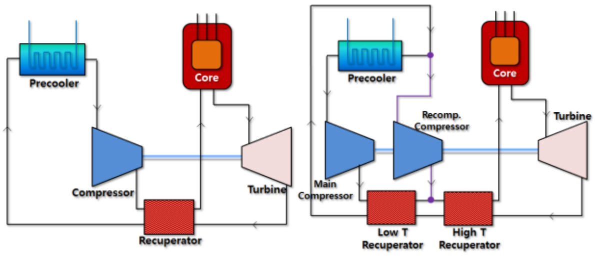

Fig.2. Schematics of (a)S-CO_2 recuperated Brayton cycle and (b)S-CO_2 recompressing Brayton cycle for KAIST MMR.

Table I . Target specification of KAIST MMR.

Target	
Electric power output	15.0 MW_e
Turbine inlet temperature	550.0℃
Compressor inlet temperature	45.0℃
Volume	42~76m^3
Total Height	<6m
Cylindrical diameter	3~4m
Pre-cooler coldside coolant	Air

To find an optimum top pressure for fixed bottom pressure of the S-CO_2 cycle, thermal efficiency for various pressure ratios was investigated. Efficiency of compressor and turbine was assumed to 70% and 85%, respectively. As shown in Fig.3, the maximum thermal efficiency of a simple recuperated cycle and a recompressing cycle occur at 2.621 and 1.809 pressure ratio, respectively.

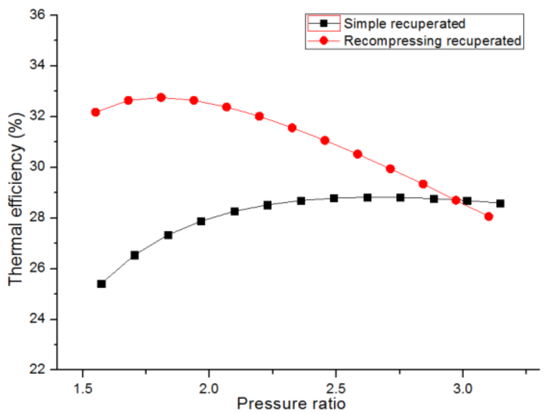

Fig.3. Variations of thermal efficiency with respect to pressure ratio.

2.4 Components sizing for MMR

After the cycle basic parameters are set for S-CO_2 cycle, preliminary design of turbomachinery and heat exchanger was done by using in-house codes KAIST-TMD and KAIST-HXD, respectively. From the result of cycle design at optimum pressure, radial type single-stage turbine and compressor coupled with one shaft were designed for each case of simple recuperated cycle and recompressing cycle. And the size of PCHE was estimated based on the cycle design.

Table II. Estimated results of turbomachinery and heat exchanger.

	Simple recuperated (20MPa)	**Recompressing recurperated (14MPa)**
Rotating speed	16,000 rpm	8,100 rpm
Compressor specific speed	0.644	0.641 (main) 0.315 (recomp.)
Turbine specific speed	0.493	0.481
Compressor diameter	0.318m	0.484m(main) 0.609m (recomp.)
Turbine diameter	0.402m	0.625m
Pre-cooler volume	3.4611m^3	6.6394 m^3
Recuperator volume	2.8321m^3	HTR: 7.3549 m^3 LTR: 6.6444 m^3
Heat exchanger volume	6.2932m^3	20.6387 m^3
Pre-cooler mass flow rate	Air 410 kg/sec	Air 630 kg/sec

2.5 Cycle design results

As shown in the Table II, recompressing cycle occupies too much volume and has a complicated layout. Therefore, authors considered that the simple recuperated cycle is more suitable for the power cycle of MMR. Therefore, simple recuperated S-CO_2 Brayton cycle and components were designed to generate 15.0MW electricity. Design results are shown in Table III.

Table III. Results of simple Brayton cycle for MMR.

Thermal power	54.2 MWth	**Mass flow rate**	261.55 kg/s
Net electric power	15.0 MWe	**Pressure ratio**	2.621
Thermal efficiency	28.82 %	**Compressor outlet pressure**	20.0 MPa
Turbine work	31.12 MW	**Compressor inlet pressure**	7.50 MPa
Compressor work	15.50 MW	**Pre-cooler volume**	3.4611 m^3
Rotating speed	16,000 rpm	**Recuperator volume**	2.8321 m^3

3. Conclusions

As a part of ongoing research of conceptual design of KAIST MMR, preliminary design of power generation cycle was performed in this study. Since the targets of MMR are full modularization of a reactor system with S-CO_2 coolant, authors selected a simple recuperated S-CO_2 Brayton cycle as a power conversion system for KAIST MMR. The size of components of the S-CO_2 cycle is much smaller than existing helium Brayton cycle and steam Rankine cycle, and whole power conversion system can be contained with core and safety system in one containment vessel. From the investigation of the power conversion cycle, recompressing recuperated cycle showed higher efficiency than the simple recuperated cycle. However the volume of heat exchanger for recompressing cycle is too large so more space will be occupied by heat exchanger in the recompressing cycle than the simple recuperated cycle. Thus, authors consider that the simple recuperated cycle is more suitable for MMR. More research for the KAIST MMR will be followed in the future and detailed information of reactor core and safety system will be developed down the road. More refined cycle layout and design of turbomachinery and heat exchanger will be performed in the future study.

ACKNOWLEDGEMENT

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