System Design of a Supercritical CO\textsubscript{2} cooled Micro Modular Reactor

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Abstract – Small modular reactor (SMR) systems that have advantages of little initial capital cost and small restriction on construction site are being developed by many research organizations around the world. Existing SMR concepts have the same objective: to achieve compact size and a long life core. Most of small modular reactors have much smaller size than the large nuclear power plant. However, existing SMR concepts are not fully modularized. This paper suggests a complete modular reactor with an innovative concept for reactor cooling by using a supercritical carbon dioxide. The authors propose the supercritical CO\textsubscript{2} Brayton cycle (S-CO\textsubscript{2} cycle) as a power conversion system to achieve small volume of power conversion unit (PCU) and to contain the reactor core and PCU in one vessel. A conceptual design of the proposed small modular reactor was developed, which is named as KAIST Micro Modular Reactor (MMR). The supercritical CO\textsubscript{2} Brayton cycle for the S-CO\textsubscript{2} cooled reactor core was optimized and the size of turbomachinery and heat exchanger were estimated preliminary. The nuclear fuel composed with UN was proposed and the core lifetime was obtained from a burnup versus reactivity calculation. Furthermore, a system layout with fully passive safety systems for both normal operation and emergency operation was proposed.

I. INTRODUCTION

Interest of the world in a large nuclear power plant moved to the interest in nuclear power system that is small and can be modularized. Current small modular reactors have smaller size than the large nuclear power plants, however they are not fully modularized yet. In this study, existing power conversion system, which is a steam Rankine cycle is replaced with the supercritical CO\textsubscript{2} (S-CO\textsubscript{2}) Brayton cycle for modularization of the whole nuclear system including the power conversion system.

The S-CO\textsubscript{2} Brayton cycle has many advantages for power cycle application to small modular reactors. It can achieve high cycle efficiency in relative low operating temperature range among the closed gas Brayton cycles. Also, it has small component size and simple cycle layout [1]. Therefore, the concept of complete module containing the reactor core and the power conversion system is realizable with S-CO\textsubscript{2} cycle. With a compact heat exchanger technology such as Printed Circuit Heat Exchanger (PCHE), the working fluids such as supercritical fluid or gas can be used. The size of heat exchangers can be made in compact size than the components of steam Rankine cycle.

The demand for small modular reactor is increasing where the countries requiring distributed power generation, developing countries that are difficult to purchase a large nuclear power plant,
countries with limited water resource. Since the micro modular reactor is produced in a modular way and transported to the installation site, construction period is not delayed and can achieve large economic benefit by production in series.

In this study, the conceptual system design for KAIST Micro Modular Reactor (MMR) and supercritical CO
$\text{\textsubscript{2}}$ cooled long-life reactor core were developed. The supercritical CO
$\text{\textsubscript{2}}$ Brayton cycle for the developed gas-cooled fast reactor core was designed and the size of turbomachinery and heat exchanger are presented. Furthermore, a passive safety system for both normal operation and emergency operation was proposed.

II. OPERATIONAL LAYOUT

KAIST MMR is a gas cooled fast reactor, using supercritical CO
$\text{\textsubscript{2}}$ as a working fluid of reactor core and power cycle without intermediate heat exchanger. Concept picture of MMR is shown in Fig. 1.

As shown in Fig. 2, in a state of normal operation, coolant from the reactor core flows into the turbine. Otherwise, in a state of emergency operation, control rods are inserted to the core and the coolant flows out of the reactor vessel and cooled by decay heat removal heat exchanger located in the internal containment as shown in Fig. 2.(b). The safety systems of MMR are being considered for: (i)non-LOCA : Power conversion unit is utilized as a cooling system by operating turbine and compressor in a turbocharger mode. (ii)LOCA: A separate heat exchanger located in the containment will act as a decay heat removal system.

III. REACTOR CORE DESIGN

The reactor core for MMR is designed by performing neutronic analysis with Monte Carlo code, McCARD. The core consists of 18 fuel assemblies, 18 primary control assemblies, and 24 shielding assemblies [2]. Fig. 3 shows a configuration of the core.

The reactor power is set to be 36.2MW in thermal power. The equivalent active core radius is around 46.6cm and active height is 120cm. The top pressure of coolant is 20MPa and average speed of coolant in the reactor core is 6.92m/sec. At the inlet of the core, coolant temperature is 655.35K and it flows out from the core with temperature of 823.15K. Total amount of mass of the reactor core is about 21-24tons, but it depends on material of the reflector. The design life time of the core is 20 years. Fig. 4 shows configuration of the nuclear fuel, the reflector and the shield assemblies.

The shape of assemblies is hexagonal type, and it contains 127 fuel pins in each assembly. Cladding material of the fuel is Oxide Dispersion-strengthened Steel (ODS). In this study, authors proposed uranium enriched-mononitride ($\text{U}^{15}$N) as fuel material since the UN fuel has a high melting temperature and high thermal conductivity. The neutronic feasibility of this core is examined. Moreover, the safety parameters of the core such as control rod worth, Doppler reactivity coefficients, coolant void reactivity (CVR) coefficient have been examined in another paper from the same research group [2].
IV. CYCLE DESIGN

An in-house cycle design code KAIST-CCD developed by KAIST research team was used to design S-CO$_2$ Brayton cycle. As shown in Fig. 5 and Fig. 6, a nuclear system with S-CO$_2$ simple recuperated Brayton cycle and S-CO$_2$ recompressing Brayton cycle configurations were considered for designing a power conversion system of MMR. Based on these cycle configurations, size estimation of components such as turbomachinery and heat exchanger were performed. In this code, the properties of CO$_2$ fluid were referred from the NIST REFPROP database [3].

IV. A. Cycle optimization

Target performance and size of KAIST MMR is listed in Table I. The electric power output target is 10-12MWe. Top pressure of cycle and turbine inlet temperature are selected to 20MPa, 550°C, respectively. This top pressure condition was found by performing cycle optimization study. Bottom temperature of cycle is selected to be 60°C, which is considering the air-cooling capability at the pre-cooler side. External size and weight of total system is selected to be less than the transportable limit.

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 be 84.9% and 92.2%, respectively. The optimum component efficiency was found by using radial turbomachinery design code, KAIST-TMD [4]. Net cycle efficiency versus pressure ratio for simple recuperated cycle and recompressing recuperated cycle is shown in Fig. 6. The net cycle efficiency is considering the generator and gear reduction losses, which are assumed to be 2% for both. The maximum net cycle efficiencies were found at the pressure ratio of 2.621 and 1.867 in the simple cycle and the recompressing cycle, respectively.
Turbine inlet temperature 550.0℃
Compressor inlet temperature 60.0℃
Total Weight <100ton
Total Height <8m
Cylindrical diameter 3-4m
Pre-cooler coldside coolant Air

Table II. Design results of turbomachinery and heat exchanger.

<table>
<thead>
<tr>
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<th>Simple recuperated</th>
<th>Recompressing recuperated</th>
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<tbody>
<tr>
<td>Rotating speed</td>
<td>21,000 rpm</td>
<td>9,800 rpm</td>
</tr>
<tr>
<td>Compressor specific speed</td>
<td>0.644 (main)</td>
<td>0.642 (main)</td>
</tr>
<tr>
<td>Turbine specific speed</td>
<td>0.493</td>
<td>0.501</td>
</tr>
<tr>
<td>Compressor diameter</td>
<td>0.318m</td>
<td>0.438m (main)</td>
</tr>
<tr>
<td>Turbine diameter</td>
<td>0.402m</td>
<td>0.527m</td>
</tr>
<tr>
<td>Pre-cooler volume</td>
<td>1.5178m³</td>
<td>2.8174 m³</td>
</tr>
<tr>
<td>Recuperator volume</td>
<td>2.8321m³</td>
<td>HTR: 7.3549 m³</td>
</tr>
<tr>
<td>Heat exchanger volume</td>
<td>4.3499m³</td>
<td>LTR: 6.6444 m³</td>
</tr>
<tr>
<td>Pre-cooler mass flow rate</td>
<td>Air 200 kg/sec</td>
<td>Air 360 kg/sec</td>
</tr>
<tr>
<td>Recuperator design point</td>
<td>Hot side inlet : 432.7℃, 7.58MPa</td>
<td>Cold side inlet : 149.9℃, 20.0MPa</td>
</tr>
<tr>
<td>Temperature difference</td>
<td>22-58℃</td>
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Table III. Result of simple recuperated Brayton cycle.

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<tr>
<td>Thermal power</td>
<td>36.2 MWe</td>
<td>175.34 W</td>
</tr>
<tr>
<td>Mass flow rates</td>
<td>11.99 MWe</td>
<td>2.66 kg/s</td>
</tr>
<tr>
<td>Net electric power</td>
<td>33.11%</td>
<td>20.0 MPa</td>
</tr>
<tr>
<td>Thermal efficiency</td>
<td></td>
<td></td>
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<tr>
<td>Compressor outlet pressure</td>
<td>22.65 MW</td>
<td>Compressor inlet pressure</td>
</tr>
<tr>
<td>Compressor work</td>
<td>10.17 MW</td>
<td>Pre-cooler volume</td>
</tr>
<tr>
<td>Rotating speed</td>
<td>21,000rpm</td>
<td>Recuperator volume</td>
</tr>
</tbody>
</table>

V. ASSESSMENT OF CONCEPT LAYOUT

Based on the design results of the reactor core, turbomachinery and heat exchangers, concept layout of MMR was suggested. For the radiation shielding of gamma rays and fast neutron, double wall of internal and external containments are proposed. The concept layout is shown in Fig. 7. Turbine and generator are connected with magnetic coupling without penetration on the containment. Thus, turbine torque is transferred through the internal containment to generator. A leakage problem of seal around the rotating shaft can be resolved.

To estimate the size of the whole system, rough dimensions of each component were estimated. This information is summarized in Table IV. The mass of reactor core is about 24tons. Including the vessel and structural materials, the mass of reactor core will be...
increased to about 40-50 tons. The mass of heat exchangers is about 20 tons. Therefore, mass of power conversion system including the turbomachinery with casing, generator and pipes is approximately 30-35 tons. Estimated external dimension of MMR is 8.0m in height and 3.8m in diameter. Total weight of module is about 100 tons, so the module can be transported by a module trailer or a ship.

VI. SUMMARY AND FUTURE WORKS

Design of power conversion cycle for MMR was performed. Also, the passive safety system and core design were proposed. The cycle configuration of simple recuperated S-CO$_2$ Brayton cycle was chosen for power conversion system due to the small volume and light weight, which accords with concept of MMR: transportable, modular reactor. Cycle optimization and sizing of turbomachinery and design of heat exchangers were done by using in-house codes developed by the KAIST research team. The size of components in the S-CO$_2$ cycle is much smaller than the existing closed Brayton cycles or the steam Rankine cycle. Therefore, power conversion system can be contained with a reactor core in one containment module. Also, the authors examined transportable possibility of MMR. External dimensions and mass of the total module were estimated. MMR module can be transported by land or seaway.

Concept design and results from this study will be used for developing an economic small modular reactor. Based on the proposed design of reactor core, power conversion system and safety system, more detailed design will be performed in further studies.

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REFERENCES


