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Load Following Capability of KAIST-MMR for Marine Application

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1. Introduction

Recently, a supercritical carbon dioxide (sCO_2) cycle is attracting attention as the next generation power conversion system to replace a steam Rankine cycle in various energy industries including nuclear power. The biggest advantage is that it is a very compact system due to high average fluid density. This benefit is maximized when configuring a direct cycle in combination with a fast neutron nuclear reactor.

The KAIST research team previously developed the concept of Micro Modular Reactor (KAIST-MMR), which is an sCO_2 fast reactor with 12 MW_e power output [1]. Fig. 1 shows the concept of KAIST-MMR. It is a very compact power generation system designed to be transportable and installed to generate electricity in extreme environments. However, due to spatial constraints, air-cooled heat exchangers and generators must be installed externally. Applying this concept to the ocean, which is a coolant-rich environment, allows the creation of a power generation module with all the equipment inside, including the generator and pre-coolers.

In this study, the authors propose the multi-purpose fully integrated nuclear power module for marine applications by extending the existing KAIST-MMR concept. In marine environments, it can be an engine for the propulsion by itself, an offshore floating or submerged power generation system, or a distributed power source to supply electricity to islands or electric propulsion vessels. For this concept, a novel cycle layout is first proposed, in which all components including the generator, precooler, control and safety system can be configured inside a limited space. Next, transient analysis has been performed using the system analysis code to evaluate the load following performance.

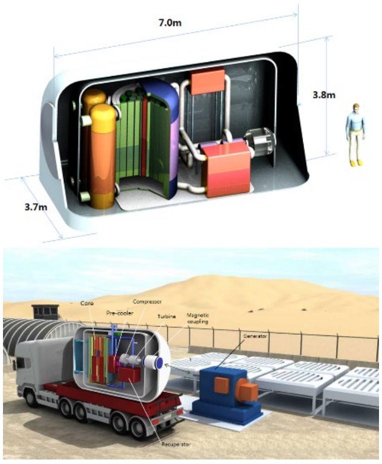

Fig. 1. Concept of KAIST-MMR.

2. Methods and Results

2.1 System configuration

The system design has been carried out by changing the layout of the power conversion system while referring to KAIST-MMR for the reactor part. Thermodynamic parameters are similarly referenced except for the compressor inlet temperature, which is changed from 60°C to 35°C in consideration of seawater cooling conditions. The basic cycle layout is based on the simple recuperated cycle that allows the most compact system to be built.

In order to become an independent electricity generation module, a compact and high-speed generator is required. The Advanced Locomotive Propulsion System (ALPS) high speed generator is referenced in this study [2]. It is designed to deliver 2.5 to 3.0 MW while directly coupled to a gas turbine with a power turbine shaft speed of 12,000 to 15,400 rpm. It is 1.45 m long and weighs 1,160 kg.

Fig. 2 shows the cycle layout. Considering the technical specification of the generator, the simple recuperated cycle of 10 MW_e class is selected by separating the power turbine into four parts. It consists of one turbine-alternator-compressor (TAC) and four power turbines, each designed to produce 2.5 MW of power to match well with the generator. The thermodynamic parameters of each station are determined from cycle optimization, and the conceptual design of heat exchangers and each turbomachinery are performed with in-house component design codes. The design procedure and results for each component is not covered because it is not the main scope of this study. Consequently, it is confirmed that all devices, including main components, the generator, control valves, and the safety system, can be placed in a cylindrical space with a diameter of 5 m and a length of 7 m.

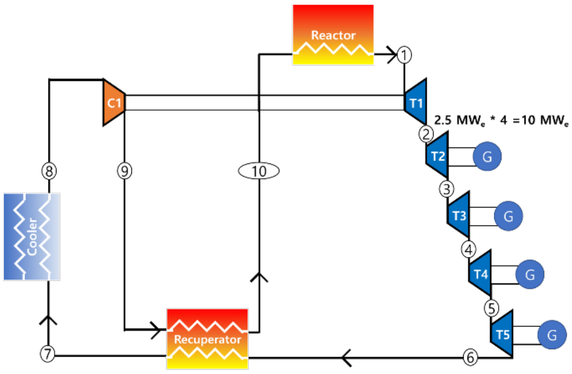

Fig. 2. Cycle layout of the proposed system.

2.2 MARS code modeling

To evaluate the load following performance of the proposed system, the modified MARS code previously developed to analyze the sCO_2 cycle is selected as the system analysis code [3]. Fig. 3 shows the nodalization diagram for MARS code simulation. Each component has been modeled based on conceptual design results. As a result of the steady-state analysis, it is confirmed that the temperature, pressure, and mass flow rate at each location show relative errors within 1% of the design values.

For the control system, compressor inlet temperature control, turbine bypass control, and inventory control are adopted. The reactor power is passively controlled by the fuel temperature coefficient (FTC) and the coolant density coefficient (CDC). Compressor inlet temperature is maintained with cooling water flow control. There are four turbine bypass valves to control each power turbine, and the inventory tank is connected to power conversion system with one injection and one discharge valve. Inventory control is important for system stability and compensation for thermal efficiency at low power operation, and mass of the working fluid at each power has to be determined. An inventory profile derived from a number of simulations is shown in Fig. 4. All control valves are designed as automatic valves based on PID control, and each control coefficient is optimized by the Ziegler-Nichols method [4].

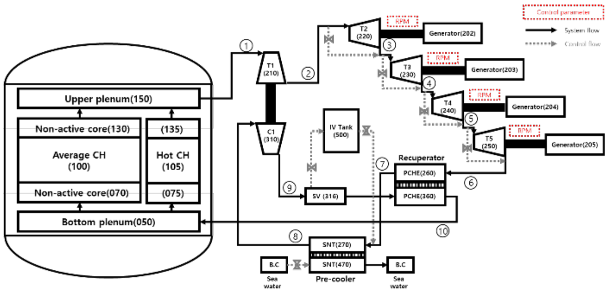

Fig. 3. Input nodalization for MARS code simulation.

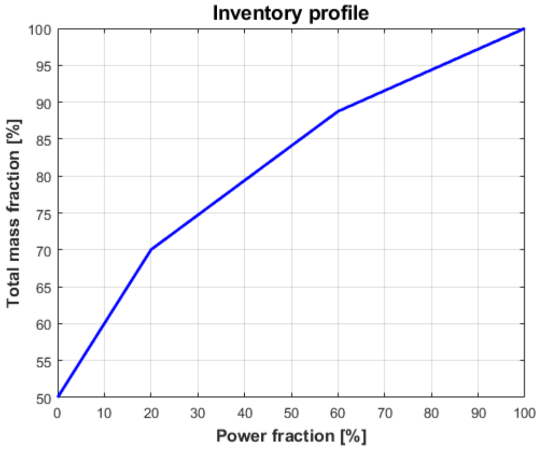

Fig. 4. Inventory profile depending on total power.

2.3 load following simulation

In order to be utilized as a multi-purpose electric power generation system, it is necessary to demonstrate excellent load following performance. It is required to respond reliably to fast load variation in a wide operating range. A transient simulation has been performed for a load variation scenario with a rate of 10%/min from 100% rated power to 5% electric power.

Fig. 5 shows the temperature and pressure changes of the sCO_2 working fluid at each location. Since it causes change of the coolant density inside the reactor, the reactor power is passively controlled by FTC and CDC. Fig. 6 shows the change in total reactivity by FTC and CDC. As shown in Fig. 7, it can be observed that the reactor is stable in passive load-following operation under the given scenario. In addition, by turbine bypass control and inventory control, the power conversion system responds to power increase or decrease operation without causing instability. Fig. 8 shows that the rotational speeds of the power turbines are well controlled. In conclusion, from load variation simulation using the modified MARS code, it is confirmed that the proposed system shows good load following performance.

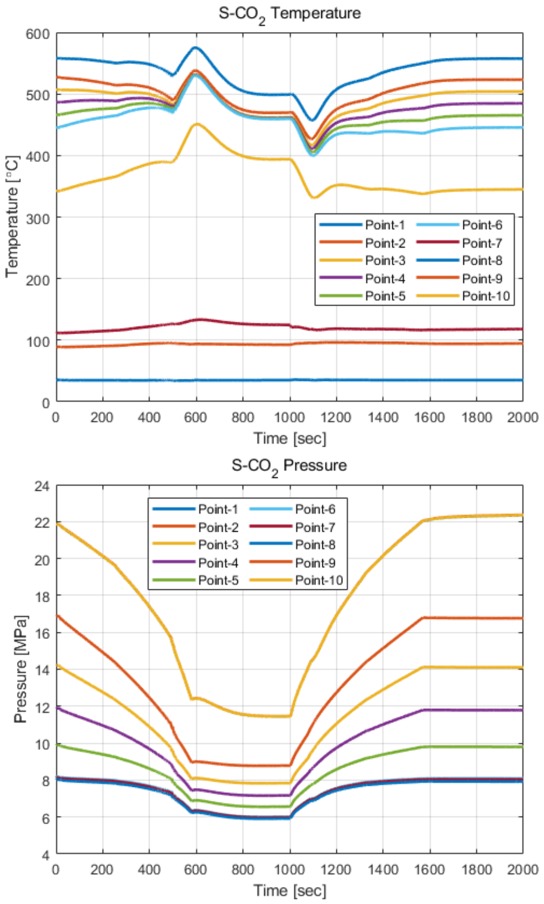

Fig. 5. Temperature and pressure at each location.

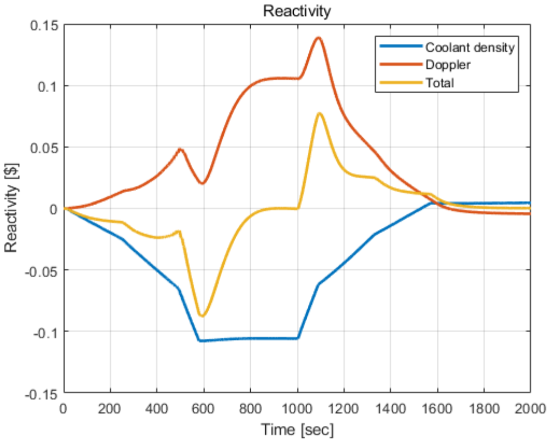

Fig. 6. Reactivity over the time.

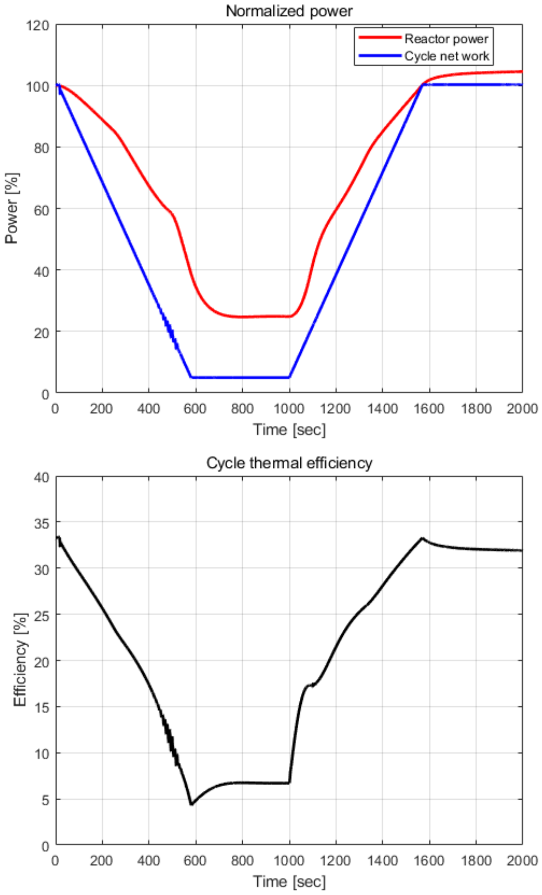

Fig. 7. Normalized power and cycle thermal efficiency.

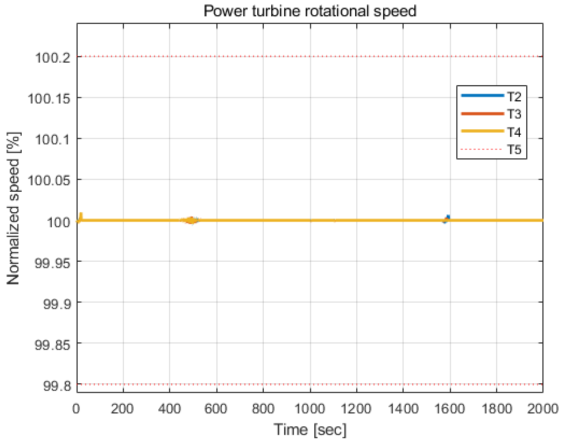

Fig. 8. Normalized rotational speed of power turbines.

3. Summary and Conclusions

In this study, a novel cycle layout is proposed to apply the sCO_2 cooled fast reactor as a multi-purpose integrated electricity generation system in a marine environment. Simple recuperated cycle is designed based on four power turbines to be equipped with high-speed generators. From transient analysis using the modified MARS code, it is demonstrated that the newly proposed system can respond stably to fast load changes in a wide operating range.

ACKNOWLEDGEMENT

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