Transient Analyses of the S-CO_2 Cycle Coupled to PWR for Nuclear Marine Propulsion

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1. Introduction

Recently, nuclear-powered ships have attracted attention due to strengthening of international regulations on greenhouse gas emissions while ships are becoming larger and faster. In order for a nuclear system to be used in marine propulsion, it is important to achieve small in size and should be able to respond to rapid load demand changes. In this paper, a super-critical carbon dioxide (S-CO_2) cycle is proposed as a power conversion system for pressurized water reactors (PWR) for marine propulsion. In order to apply nuclear systems for the marine propulsion, it should exhibit superior load following capability under severe load changes as shown in Table I. Therefore, a new nuclear propulsion system which couples the S-CO_2 power conversion system to a pressurized water reactor is designed in conceptual level and transient analyses under severe load changes are conducted to demonstrate the feasibility of the proposed system concept for the marine application.

Table I: General information of nuclear merchant ships

Parameter		NS Savannah	NS Otto Hahn	NS Mutsu
Displacement (tons)		21,800	25,790	25,790
Reactor thermal power		74 MW	38 MW	38 MW
Cruising speed		21 knots (39 km/h)	17 knots (31 km/h)	17 knots (31 km/h)
Load change requirement	Increase	20-80% in 10s (6%/s)	10-100% in 90s (1%/s)	18-90% in 30s (2.4%/s)
	Decrease	100-20% in 3s (26.7%/s)	100-10% in 1s (90%/s)	100-18% in 1s (82%/s)

2. Description of System

2.1 Primary System (Reference reactor)

Since the design of primary coolant system and reactor core is beyond the scope of this paper, it is referred to the existing reactor system. Thermal characteristics are referred to SMART reactor developed by KAERI (Korea Atomic Energy Research Institute), which is an integral-type PWR with the thermal power of 330 MW considering current trend of mega-sized container ship power [1]. Reactor feedback coefficients are referred to the Autonomous Transportable On-demand Reactor Module (ATOM), which is a water-cooled autonomous small modular reactor (SMR) under development by a university consortium led by KAIST with the thermal power of 450 MW [2]. A notable feature that ATOM differs from the SMART is that ATOM is designed as a soluble-boron-free (SBF) reactor. Therefore, the primary system could be much simpler and it targets the passively autonomous load-follow operation with strongly negative moderator temperature coefficient (MTC). The major parameters of the primary system are summarized in Table II.

Table II: Major parameters of the primary system

Reactor type	Integral PWR
Core thermal power [MW_{th}]	330
System Pressure [MPa]	15
Core inlet temperature [°C]	296
Core outlet temperature [°C]	323
$\dot{m}_{coolant}$ in core [kg/sec]	2090

2.2 Secondary System (S-CO_2 system)

The S-CO_2 system was conceptually designed under the assumed conditions of the primary system described above. Due to the relatively low turbine inlet temperature (TIT) under the PWR primary system temperature conditions, recompression cycle was chosen which is generally known as the most efficient cycle among the basic cycle layouts [3]. Cycle optimization and design of main components including turbomachinery and heat exchangers were conducted. Since the system design procedure is not the main topic in this paper, only the results are summarized in Table III.

Table III: Cycle design results

Maximum pressure [MPa]	15
Maximum temperature [°C]	315
Minimum temperature [°C]	32
IHX pressure drop [kPa]	100
$\Delta P_{HTR,hot}$ [kPa]	100
$\Delta P_{HTR,clod}$ [kPa]	50
$\Delta P_{LTR,hot}$ [kPa]	100
$\Delta P_{LTR,cold}$ [kPa]	50
HTR effectiveness [%]	95
LTR effectiveness [%]	90
Turbine efficiency [%]	92
Main compressor efficiency [%]	85
Recompressing compressor efficiency [%]	88
Turbine expansion ratio	1.799

Flow split ratio [%]	55.857
Turbine work [MW_e]	153.58
Main compressor work [MW_e]	18.79
Recompressing compressor work [MW_e]	37.2
Cycle net work [MW_e]	97.6
Cycle thermal efficiency [%]	29.58

A control system is designed to respond to fast load changes. The main control component responding to severe load changes is a turbine bypass valve which is designed to automatically operate based on the proportional-integral-differential (PID) controller [4]. Fig. 1 shows the control scheme of the $S\text{-}CO_2$ power conversion system. In this paper, the target control variables are shaft rotational speed, flow split ratio, cycle minimum temperature, cycle minimum pressure, and cycle maximum pressure.

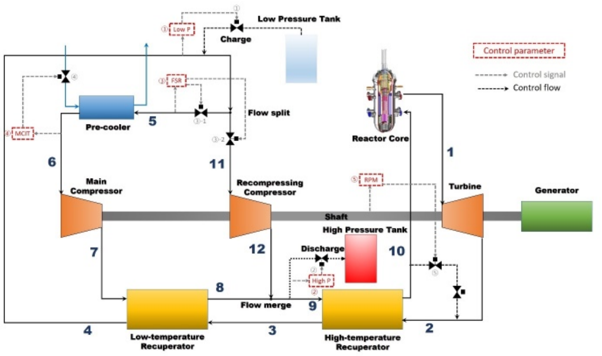

Fig. 1. Control scheme of $S\text{-}CO_2$ power conversion system

3. Transient Analysis Tool

To analyze rapid power transients of the proposed system, the system code has to conduct realistic performance analysis of a power conversion system, as well as the safety analysis of the reactor core. In this paper, MARS code is used for system transient analyses [5]. However, since the original MARS code focuses on analyzing water-cooled reactor core transients, it needs to be improved to accurately simulate the $S\text{-}CO_2$ power conversion system. Fig. 2 shows the conceptual diagram of MARS code improvements. MARS code has been improved to accurately analyze system transients of the nuclear propulsion system which consists of pressurized water cooled small modular reactor and $S\text{-}CO_2$ power conversion system. To summarize improvements, three options are added to the original MARS code. Firstly, in order to accurately predict physical properties of $S\text{-}CO_2$, NIST database is directly imported into MARS code. Secondly, to simulate realistic transient behavior of heat exchangers, PCHE heat transfer correlation is added to heat structure sets in MARS code. Finally, a new turbomachinery model based on the off-design performance map and CEA similitude method are added to accurately simulate $S\text{-}CO_2$ turbomachinery.

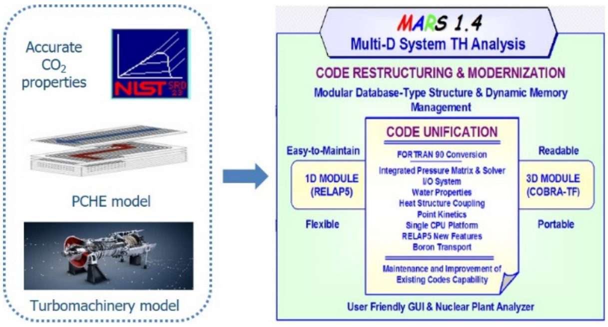

Fig. 2. Conceptual diagram of MARS code improvements

To demonstrate the reliability of the newly developed code, code validation has been performed with experimental data. The selected experimental loop is SCIEL (Supercritical CO_2 Integral Experiment Loop) facility installed in KAERI. Experimental data is generated during compressor performance test of SCIEL and data when compressors are maintaining their rotational speed at 35,000 RPM is used for validation. Fig. 3 shows description of the test section of SCIEL facility and MARS model. Compressor performance test was conducted by adjusting control valve area to reduce the pressure of compressed fluid. Since the geometrical information of the precooler is unknown, it was processed as a boundary. Therefore, the purpose of this validation is to ensure that the developed code can accurately simulate the flow near the critical point and newly added compressor model. Fig. 4 shows results of code validation which compare pressure and temperature at each point between experimental data and MARS code simulation result. The results of validation suggest that the improved MARS code can well simulate the flow near the critical point and $S\text{-}CO_2$ turbomachinery.

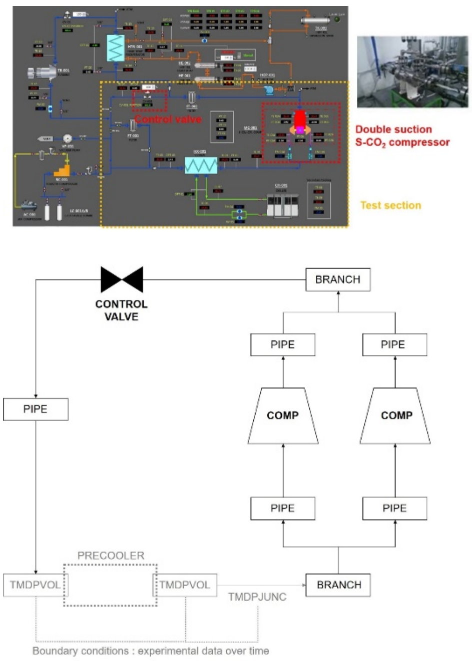

Fig. 3. Schematic diagram and MARS modeling of SCIEL facility

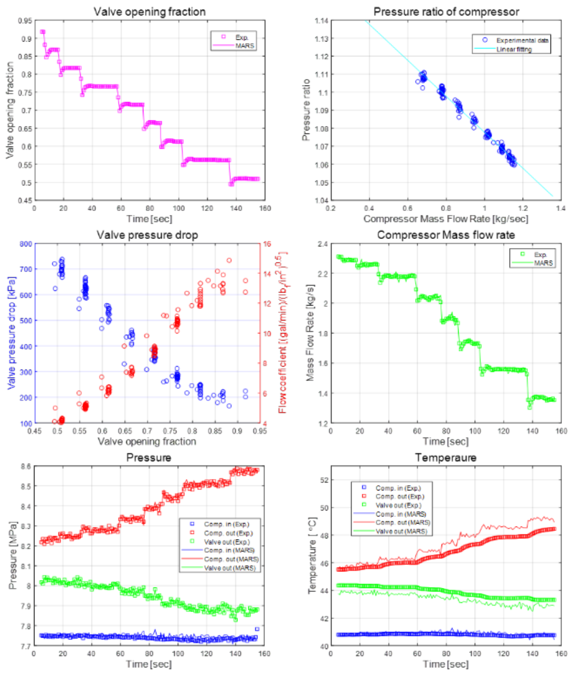

Fig. 4. Code validation results

4. Results

To demonstrate feasibility of the proposed system to ship propulsion, transient behavior under fast load changes has been analyzed with the developed system analysis code. Fig. 5 shows the nodalization diagram of input deck of the whole system. Fig. 6 compares the design values with the converged steady state values from the MARS code simulation. The error at every point is less than 1 %, indicating that the entire system is very accurately modeled with the developed code.

The selected transient scenario is the load decrease of 100% to 10% in 1 second (90%/sec) after 100 seconds of normal operation, and then load recover to 90% in 8 seconds (10%/sec). This scenario indicates more severe load changes compared with the conventional nuclear merchant ships shown in Table I. It means that if the proposed system meets this load change requirement, its applicability to nuclear merchant ships is demonstrated. It is determined by considering two criteria. First, total system should be stably operated under these fast load transients without significant fluctuations of operational parameters. Second, all the safety related variables should be kept with sufficient margin including fuel centerline temperature (FCT), peak cladding temperature (PCT), the minimum departure from nucleate boiling ratio (MDNBR), shaft speed, and compressor surge margin.

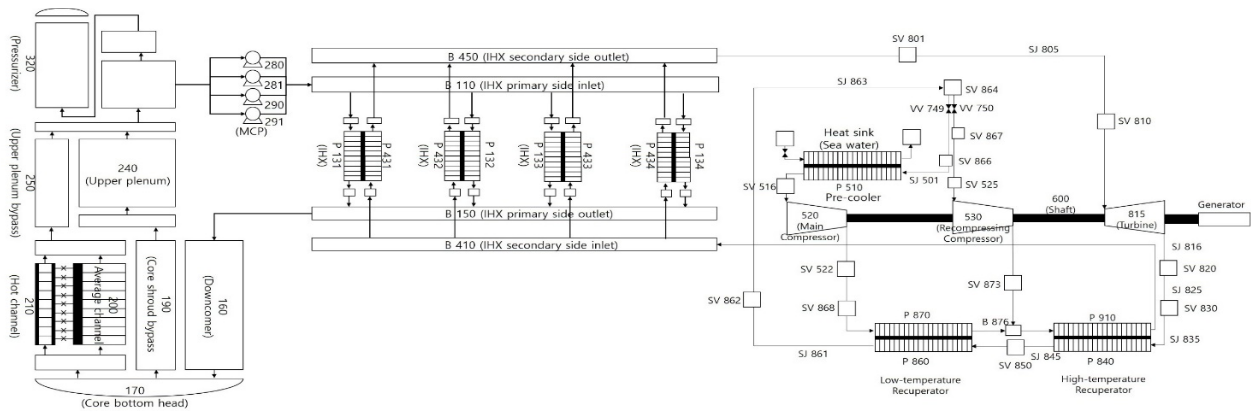

Fig. 5. Nodalization diagram of total system modeling with the improved MARS code

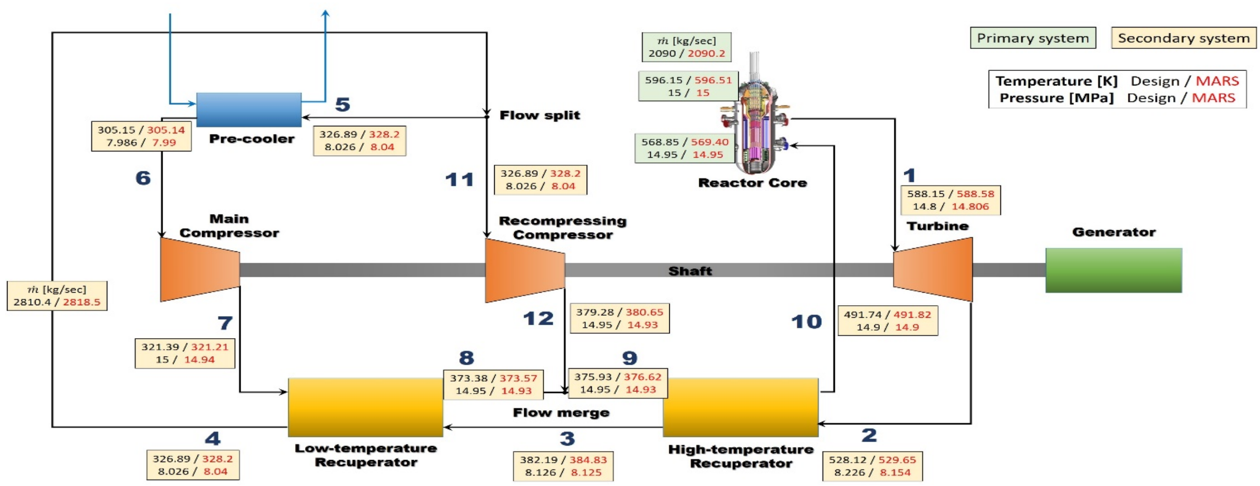

Fig. 6. Comparison between design values and the results of steady-state analysis

Figs. 7 and 8 show the responses of the reactor core and the S-CO_2 power conversion system, respectively. As shown in Fig. 7, reactor power follows the load changes using only reactor feedback coefficients without significant fluctuations. Since the reactor system has the strong moderator temperature coefficients, the small change in the primary coolant temperature effectively adjusts core thermal power even under the severe load changes. Although the primary side pressure rapidly increases, it is recovered to the stable operating range within few seconds. In case of safety parameters, even if there is an increase of about 5℃ for PCT and about 70℃ for FCT, it does not seriously affect the reactor safety since these are in the range of normal operations. MDNBR also does not show significant reduction since reactor power exhibits fast response, which indicates there are no safety issues in the primary system.

The S-CO_2 power conversion system also shows stable responses as shown in Fig. 8. Since the turbine bypass is the main mechanism responding to the load changes, turbine plays the major role with the load changes while the total compressor work remains nearly constant. Due to the automatic operation of the turbine bypass valve, the turbine torque is rapidly adjusted with the changed load and the rotational speed of the shaft is well controlled within the range of 0.2 Hz. Although there is a deviation of about 1℃ from the design point of the MCIT, it is quickly controlled to the design point by regulating the mass flow rate of heat sink sea water. Since compressors have enough surge margins, the flow split ratio is controlled to the design value by operations of two motor valves. From the results, it is ensured that the proposed system which couples the S-CO_2 recompression cycle to soluble boron free PWR exhibits fast responses under the severe load changes.

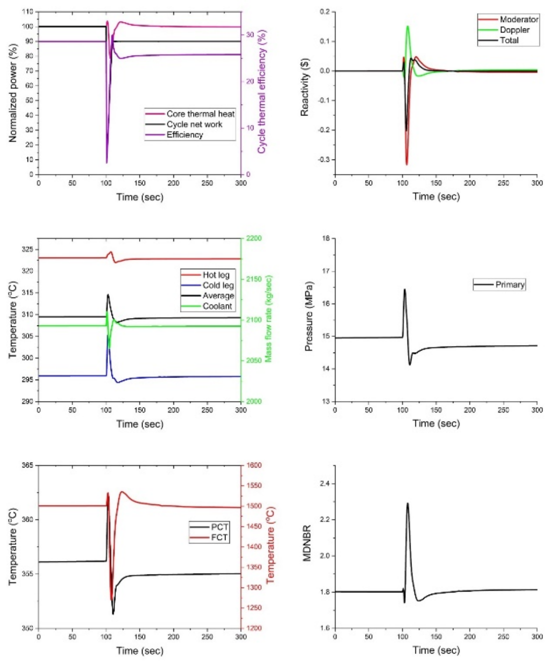

Fig. 7. Reactor core response under given load changes

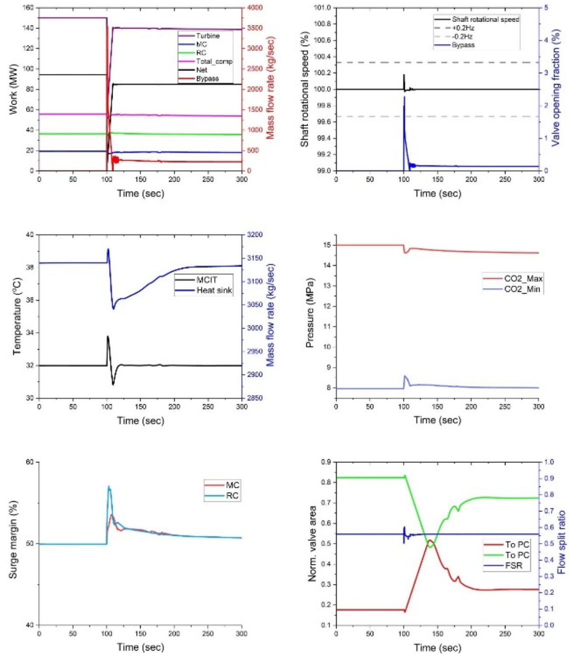

Fig. 8. S-CO_2 cycle response under given load changes

5. Conclusions

In this paper, transient responses under severe load changes of the S-CO_2 cycle coupled to PWR were analyzed to investigate its applicability to nuclear propulsion system. To accurately conduct transient simulations, the system analysis code is developed based on the MARS code. From the results of transient simulations, it is verified that the proposed system exhibits fast and stable response under severe load change conditions.

ACKNOWLEDGEMENT

This research was supported by Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Science, ICT & Future Planning (NRF-2016R1A5A1013919).

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