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TRANSIENT ANALYSIS OF THE SUPER-CRITICAL CARBON DIOXIDE CYCLE COUPLED TO PRESSURIZED WATER REACTOR FOR NUCLEAR POWERED SHIPS

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ABSTRACT

Recently, nuclear-powered ships have attracted attention due to international regulations on greenhouse gas emissions and the trend of rapid and large-scale ships. 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 study, a super-critical carbon dioxide (S-CO_2) cycle is proposed as a power conversion system for pressurized water reactors (PWR) for marine propulsion. The S-CO_2 cycle has been attracting attention as the next-generation power conversion system that can be an alternative to the steam Rankine cycle due to its small system size and higher efficiency. The conceptual design of the S-CO_2 power conversion system is first performed under the reference reactor conditions, including cycle design and component design. To conduct system analysis, MARS-KS code, one of the nuclear thermal-hydraulic safety analysis codes developed by Korea Atomic Energy Research Institute (KAERI) and actively used for the safety review calculation of a nuclear power plant by Korea Institute of Nuclear Safety, is improved to accurately simulate the S-CO_2 power conversion system combined with PWR. The PID controller based automatic control strategy of the entire system is designed to respond to rapid load changes. Transient analyses are performed with the newly developed system analysis code under various scenarios.

INTRODUCTION

Worldwide trade has been growing due to economic globalization and it is estimated that shipping is responsible for the transport of 95% of global commerce. Due to the trend of constructing large-scale and fast ships while international regulations on greenhouse gas emissions are becoming more stringent, the attention to nuclear-powered merchant ships is increasing. However, many studies suggest that nuclear propulsion systems need to be improved for better economy for the nuclear-powered merchant ship.

Most of the nuclear propulsion systems currently in operation such as naval reactors or icebreakers are using a combination of the pressurized water reactor (PWR) and steam Rankine cycle. Among various types of reactor core, the PWR has been found to be most suitable to nuclear-powered ships in terms of safety and performance although there have been many studies over the past few decades to apply various types of nuclear reactors to ship propulsion. However, there are still some economic drawbacks in using the steam Rankine cycle as the power conversion system for nuclear merchant ships. Due to the very large volume of components such as steam turbine and condenser, cargo carrying capacity is reduced which is critical to economic success of the merchant ship. In addition, system layout becomes complicated due to many auxiliary systems related to steam cycle such as steam quality control, water chemistry control, and large-sized pure water inventory tank. It means that the manning cost is also very high since it requires a lot of crews. Therefore, more compact and simple power conversion system is required for nuclear merchant ships to be economically competitive.

The super-critical carbon dioxide (S-CO_2) Brayton cycle which can be an alternative to conventional Rankine cycle has received substantial attention as the most promising power conversion system due to its simple layout and compactness [1]. System configuration can be much simpler due to lower purification system requirements compared to the steam Rankine cycle. These characteristics offer the potential for significant operational and capital cost benefits. Additionally, an S-CO_2 Brayton cycle keeps single phase all the time during operation, which makes the system to quickly respond to the load change or system disturbance and has less risk of flow instability. Therefore, the S-CO_2 cycle is expected to have many advantages when adopted as a power conversion system of nuclear-powered ships.

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 1. Therefore, in this paper, 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.

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Table 1: 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)
Cargo capacity [tons]		10,000	14,000	8,242
Crew		124	63	80
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)

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. To select a reference reactor core, the engine power required for ship propulsion has to be determined. The total engine power of the recently built diesel-powered large container ships is approximately 100 MW. Based on the current trend of container ship power, thermal characteristics of reactor core 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 [2]. For nuclear propulsion systems which experience frequent power maneuvering, not only the thermal characteristics but also the reactor feedback characteristics are important. Reactor feedback coefficients are referred from the Autonomous Transportable On-demand Reactor Module (ATOM), which is a water-cooled autonomously operating integral type small modular reactor (SMR) under development by a university consortium led by KAIST with the thermal power of 450 MW [3]. 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). To summarize the reference reactor, the primary reactor system is referred to thermal characteristics of SMART reactor while the reactor feedback characteristics of ATOM reactor are adopted. The major parameters of the primary system are summarized in Table 2.

Table 2: Major parameters of the primary system

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

DESIGN SUMMARY OF S-CO_2 SYSTEM

The S-CO_2 system was conceptually designed under the conditions of the reference reactor. Figure 1 shows the design procedure. First, a power cycle optimization is performed assuming machinery properties such as the pressure drop and effectiveness of heat exchangers, and isentropic efficiency of each turbomachinery. From the results of the cycle optimization, main components are designed in conceptual design level. This procedure is repeated until both pre-assumed machinery properties, such as the turbomachinery efficiency, and physically allowable geometry of components are consistent. Since the system design is not the main topic of this paper, the design is covered briefly.

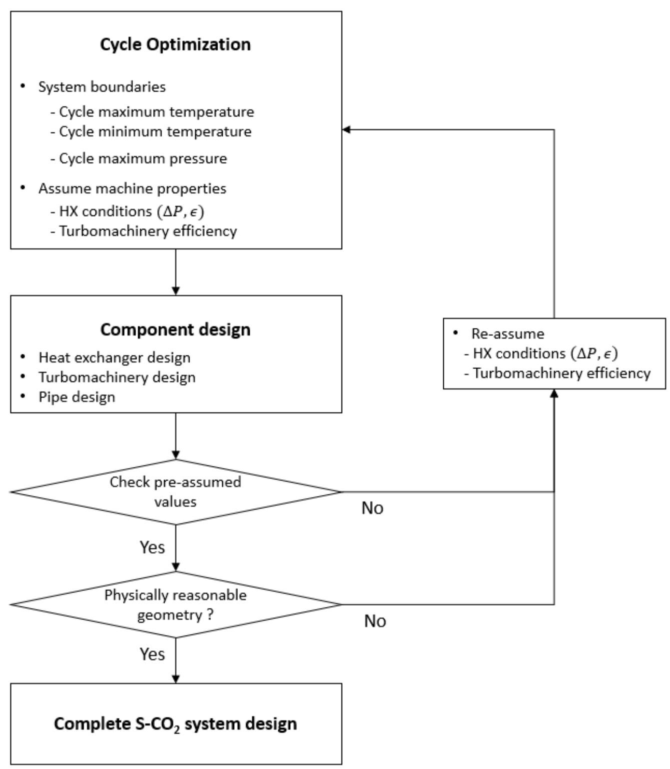


Figure 1: S-CO_2 system design procedure.

Before conducting the design of a thermodynamic cycle, cycle layout has to be selected. Due to the relatively low turbine inlet temperature (TIT) under the PWR temperature conditions, recompression cycle was chosen which is generally known as the most efficient cycle among the basic cycle layouts. The cycle optimization was performed with an in-house S-CO_2 cycle analysis code, named in KAIST-ESCA (Evaluator for Super-critical CO_2 cycle based on Adjoint method) [4]. Table 3 summarizes the optimized results of S-CO_2 cycle design.

Table 3: Cycle design results

Maximum pressure [MPa]	15
Maximum temperature [℃]	315
Minimum temperature [℃]	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

S-CO_2 recompression cycle has three turbomachinery: turbine, main compressor, and recompressing compressor. To design each turbomachinery, the type of turbomachinery was firstly determined. Sandia National Laboratories (SNL) studied the scale dependency of S-CO_2 turbomachinery and element technology [5]. Since the proposed system produces about 100 MW of electric power, turbomachinery is designed in axial type. In case of propulsion configuration, electric propulsion system is considered due to its high flexibility in propulsion arrangement, and all the turbomachinery are directly connected to single shaft. For load transient calculation, the moment of inertia of each component is also important. Since each component attached to the shaft has not been fully designed and optimized in this study, it is assumed that the moment of inertia of the proposed system is scaled from the GFR data which is 2400MW_{th} direct S-CO_2 cooled fast reactor [6]. Each turbomachinery design was obtained from an in-house code, namely KAIST-TMD (TurboMachinery Design) code which is based on 1-D mean stream line analysis adopting a real gas approach to overcome limitations for utilizing the conventional design methods near the critical point [7]. From the KAIST-TMD code, geometry and off-design performance map of each turbomachinery were obtained.

The proposed system has four heat exchangers: intermediate heat exchanger (IHX), high temperature recuperator (HTR), low temperature recuperator (LTR), and precooler (PC). Since the volume of the S-CO_2 turbomachinery is typically much smaller than that of the heat exchanger, the size of the S-CO_2 power conversion system is closely related to the size of the heat exchanger. In this respect, except PC, the type of heat exchangers was selected as printed PCHE (Printed Circuit Heat Exchanger) which is a robust heat exchanger combining compactness, low pressure drop, high effectiveness and the ability to operate with a very large pressure difference between hot side and cold side. PC was designed as the shell and tube heat exchanger since PCHE is not recommended when sea water is used as cooling medium due to impurity related issues such as fouling and scaling. Each heat exchanger was designed with an in-house code, KAIST-HXD (Heat eXchanger Design) which is based on the 1-D finite difference method (FDM) and the overall heat transfer coefficient (U) with counter-current flow configuration [8]. In case of PCHE correlations, Kim suggested a CFD-aided correlation covering wide range of Reynolds number to facilitate PCHE designs for the S-CO_2 Brayton cycle application [9]. For the design of shell and tube type precooler, Gnielinski correlation is used.

Pipe design is also important since it is directly related to the capital cost, the total amount of fluid mass, and the size of total system. However, most of procedures in pipe design are based on the water or steam system and there is very limited research on the pipe design of the S-CO_2 system. Therefore, in this study, pipes are preliminarily designed with a simple method using the optimal flow velocity and ASME standard.

After the S-CO_2 power conversion system is designed, the size of main machinery room is estimated as presented in Figure 2. Table 4 compares the machinery room size of NS Savannah and the proposed system. From the results of conceptual design, it is demonstrated that the total volume of power conversion system can be significantly reduced when the S-CO_2 cycle is adopted.

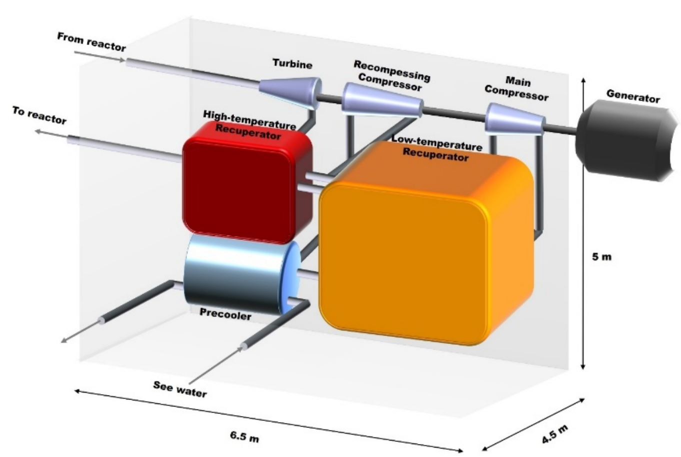


Figure 2: Configuration of S-CO_2 power conversion system.

Table 4: Main machinery room size of NS Savannah and the proposed system

	NS Savannah	Proposed system
Thermal power	74 MW_{th}	330 MW_{th}
Power conversion system	Steam cycle (9-stage HPT, 7-stage LPT)	$S\text{-}CO_2$ recompression cycle
Length	17 m	6.5 m
Width	24 m	4.5 m
Height	9.8 m	5 m
Volume	3998.4 m^3	146.25 m^3

DEVELOPMENT OF SYSTEM ANALYSIS CODE

Multi-dimensional Analysis of Reactor Safety (MARS) code was developed by Korea Atomic Energy Research Institute (KAERI). The code was developed for realistic multi-dimensional thermal hydraulic system transient analysis of water-cooled reactor and has been actively used for the safety review calculation of a nuclear power plant by Korea Institute of Nuclear Safety (KINS). The code was developed on the basis of the RELAP5/MOD3.2.1.2 and the COBRA-TF code of USNRC. The MARS code basic field equations consist of two phasic continuity equations, two phasic momentum equations, and the phasic energy equations for the two field non-equilibrium model [10].

In order for nuclear power to be applied to ship propulsion, the system has to be capable of operating over a wide range of power levels, especially during the ingress and egress to ports. It also should exhibit much faster response power changes than land-based nuclear reactors. To analyze rapid power transients of the proposed system, the system code has to conduct realistic performance analysis of power conversion system, as well as the safety analysis of the reactor core. However, since 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. Figure 3 shows the conceptual diagram of MARS code improvements. 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.

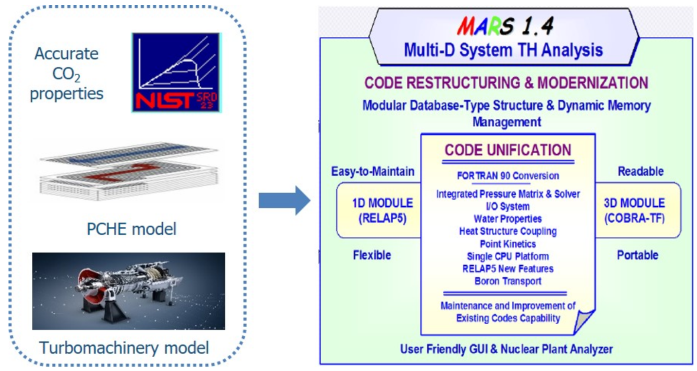


Figure 3: Conceptual diagram of MARS code improvements.

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. Figure 4 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. Figure 5 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.

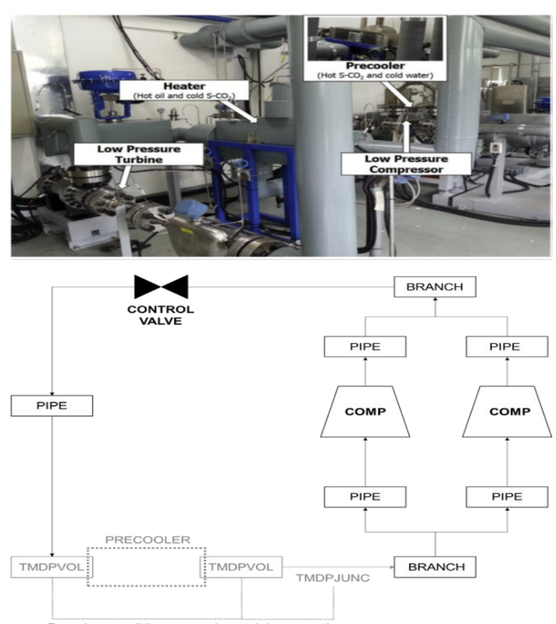


Figure 4: MARS modeling and SCIEL facility.

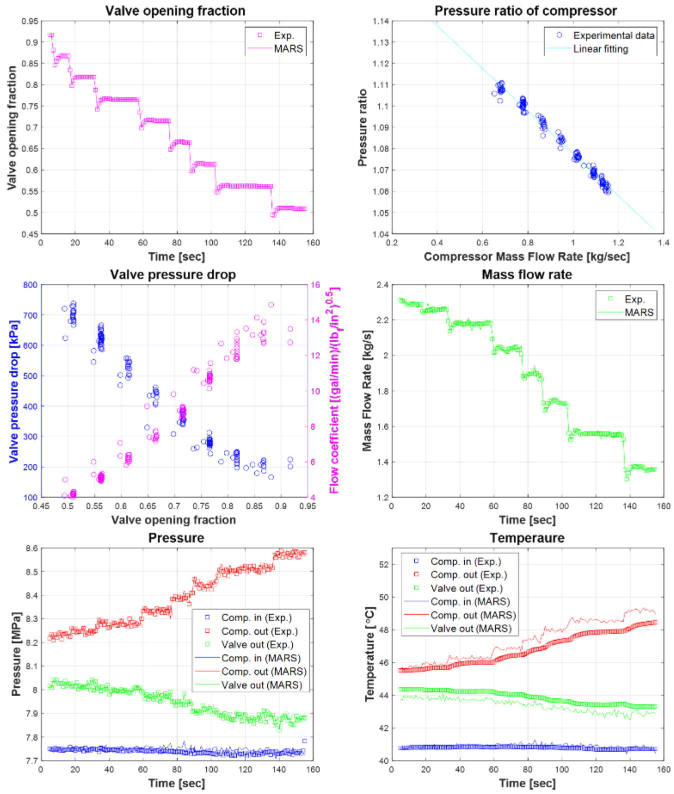


Figure 5: Code validation results.

SIMULATION RESULTS

To conduct system analysis, the total system which consists of reactor core and the designed S-CO_2 power conversion system is modeled with the improved MARS code. Figure 6 shows the nodalization diagram of steady state input deck of the whole system. The primary side is modeled similar to the modeling of a conventional PWR. The reactor core is modeled with hot channel and average channel. The reactor system consists of a reactor core, four main coolant pumps, and a pressurizer. Although the number of designed IHX is twelve, it is modeled in four trains to reduce the complexity of input deck. S-CO_2 power conversion system is modeled with design values of each component including heat exchangers, turbomachinery, and pipe. Turbine, main compressor, and recompressing compressor are connected to single shaft, and the generator component is also connected to shaft component at only steady state simulation. Flow split is modeled by two motor valves keeping the flow split ratio constant at design value. Heat sink side of precooler is modeled boundary volumes which represents the sea water. Table 5 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.

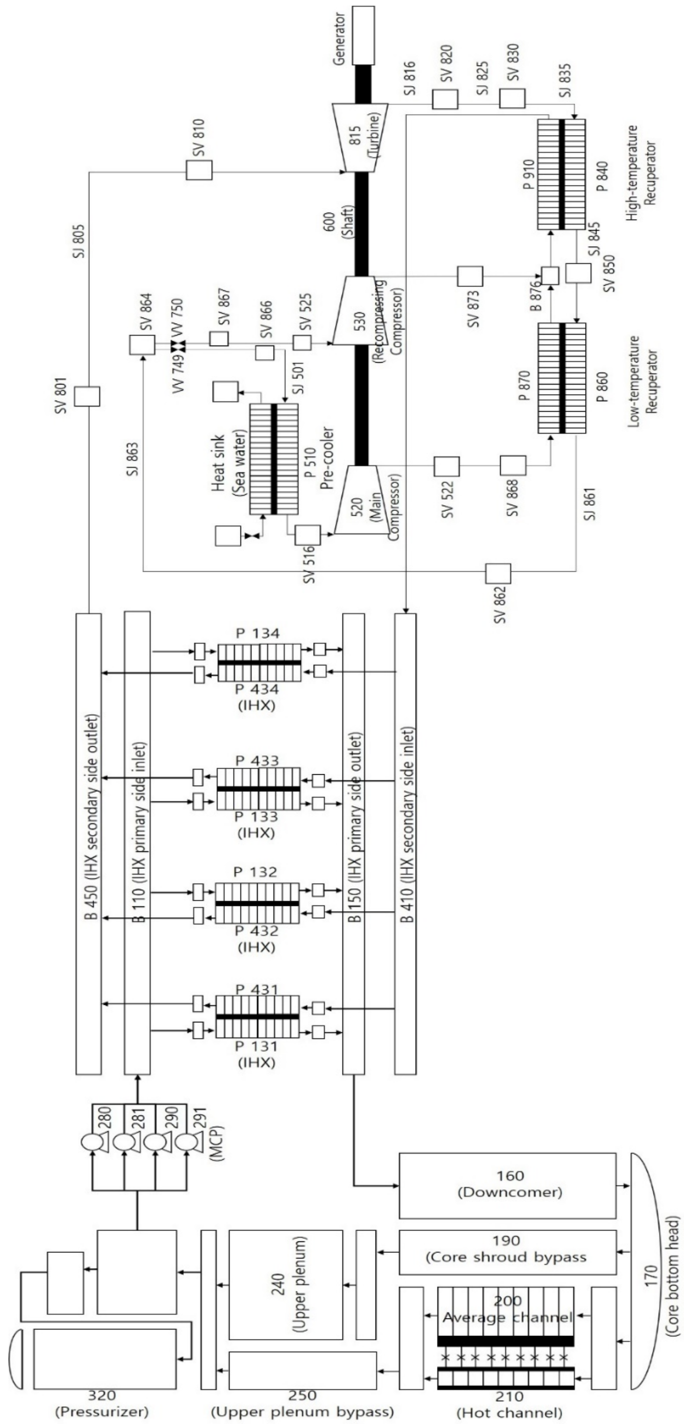
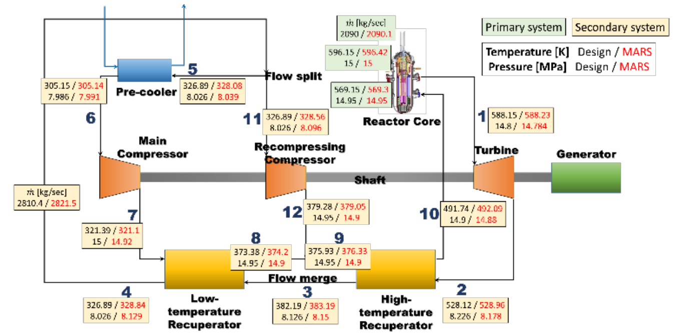


Figure 6: Nodalization diagram of total system modeling with the improved MARS code.

Table 5: Errors of steady state analysis



	Location	Property	Error [%]
Primary system	Hot leg	Temperature	0.06
		Pressure	0.0
	Cold leg	Temperature	0.097
		Pressure	0.0
	Total	Mass flow rate	0.01
Secondary system	1	Temperature	0.073
		Pressure	0.04
	2	Temperature	0.3
		Pressure	0.87
	3	Temperature	0.69
		Pressure	0.012
	4	Temperature	0.4
		Pressure	0.17
	5	Temperature	0.4
		Pressure	0.17
	6	Temperature	0.003
		Pressure	0.05
	7	Temperature	0.056
		Pressure	0.4
	8	Temperature	0.05
		Pressure	0.13
	9	Temperature	0.18
		Pressure	0.13
	10	Temperature	0.016
		Pressure	0.0
	11	Temperature	0.4
		Pressure	0.17
	12	Temperature	0.36
		Pressure	0.13
	Core	Mass flow rate	0.29
	-	Flow split ratio	0.0

To analyze the transient response of the proposed system, development of control logic should be preceded. Figure 6 shows the control scheme of the proposed power conversion system. There are five parameters to be controlled in the S-CO_2 cycle: low pressure, high pressure, flow split ratio (FSR), main compressor inlet temperature (MCIT), and shaft frequency. the main control mechanism responding to power change is turbine bypass which is generally known to show the most rapid response to load transients.

Low pressure is controlled to keep the cycle minimum pressure above the critical pressure during part load operation. The pressure controls are accomplished through the limited inventory control. Although the system inventory is not continuously controlled to match varying loads, when the LTR outlet pressure drops below 7.5MPa, the fluid is charged from the low pressure tank and discharged from the high pressure tank when the HTR inlet pressure exceeds the primary side pressure as shown in Figure 7.

In the S-CO_2 recompression cycle, flow split ratio has to be controlled to be operated stably and prevent compressor surge. It is basically maintained as the designed value during system transients by adjusting opening fractions of two motor valves. The reason for keeping the flow split ratio at the design value is to allow two compressors to operate as close to the design point as possible. In addition, compressor surge should be prevented by controlling the flow split ratio. Under all the possible transients, system has to be operated maintaining sufficient compressor surge margin. It is conducted by measuring the mass flow rate at the LTR outlet and the mass flow rate at the PC inlet. The compressor surge limit is determined as 10 % in this study.

The main compressor inlet temperature is controlled to not deviate significantly from the critical temperature. If MCIT falls below the critical temperature, the liquidation of CO_2 may occur, resulting in problems of the system integrity, and if it rises above the critical temperature, the cycle efficiency rapidly decreases. MCIT control is conducted by regulating the mass flow rate of heat sink depending on the deviation from the designed MCIT.

As the load changes, the rotational speed of the shaft is changed by the shaft dynamic. Since the electric propulsion system with single shaft configuration is considered, the rotational speed of shaft should be maintained during load transients. To control the shaft speed, turbine bypass valve is designed to be autonomously operated based on the proportional-integral-differential (PID) controller. Ziegler-Nichols rule is applied for tuning PID parameters [11]. PID gains for turbine bypass valve is optimized under the 10% step reduction from 100% load.

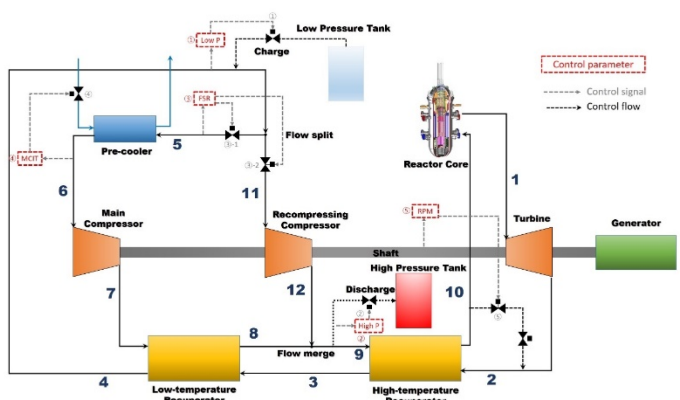


Figure 7: Control scheme of S-CO_2 power conversion system.

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. In this paper, transient response is investigated under the actual load change requirement for nuclear merchant ships operated in the past as shown in Table 1: NS Savannah, NS Otto Hahn, and NS Mutsu. The applicability to nuclear merchant ships is examined 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. The criteria for shaft rotational speed is set to 0.2Hz which is the frequency acceptance limit of typical nuclear power plants. The limit for compressor surge margin is 10 % as mentioned previously in the control scheme development section. In all cases, load transient is given after 100 seconds of 100 % full power operation. The maximum time step is set to 0.005 seconds considering the severe load changes.

Since the three load change requirements are similar, the simulation results showed almost the same trend. Therefore, only the results from the NS Savannah case are shown in this paper. Figures 8 and 9 show the responses of the reactor core and the S-CO_2 power conversion system, respectively, under the NS Savannah requirement. As shown in Figure 8, 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 the fast response, which indicates there are no safety issues in the primary system.

The S-CO_2 power conversion system also shows stable responses under the NS Savannah load change requirement as shown in Figure 9. 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. Similar results were found in other two requirements. Therefore, it is confirmed that the proposed system can be stably operated under load change requirement for ship propulsion.

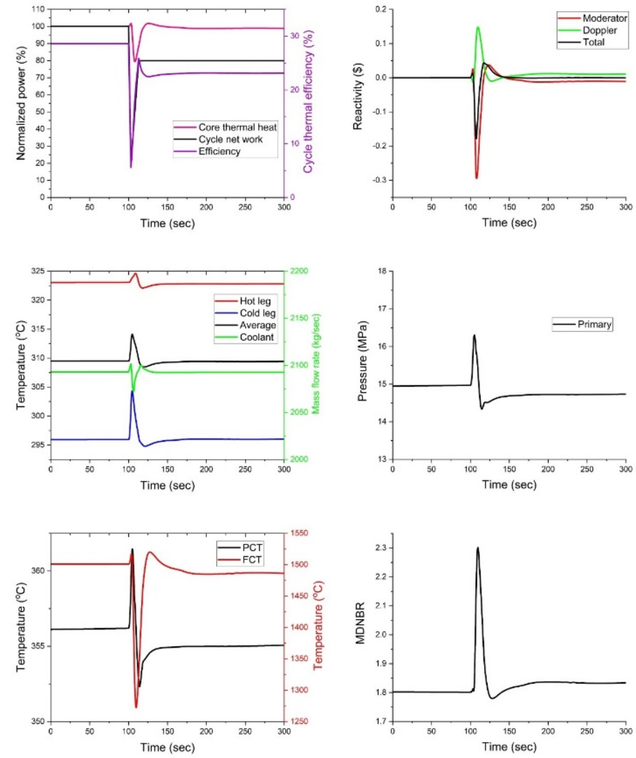


Figure 8: Reactor core response under NS Savannah load change requirement.

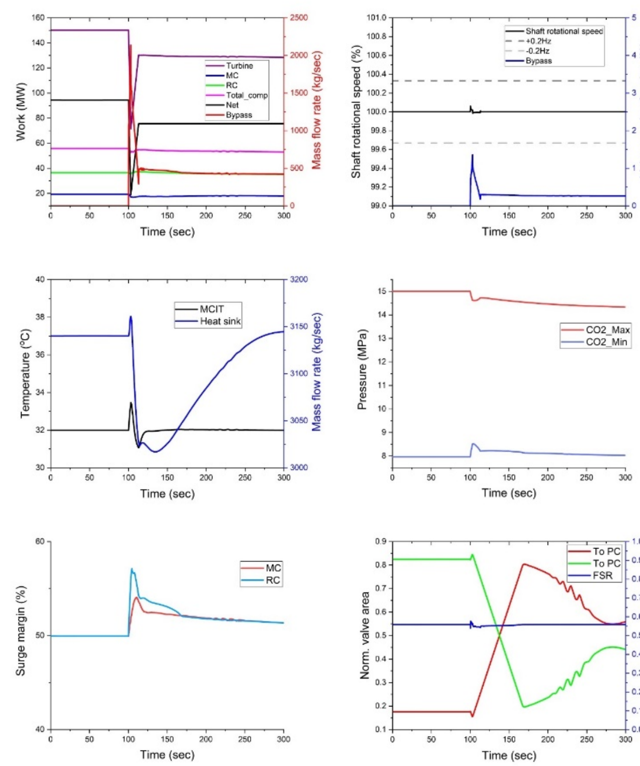


Figure 9: S-CO_2 cycle response under NS Savannah load change requirement.

SUMMARY AND 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. Reactor primary system is referred to thermal characteristics of SMART reactor and reactor kinetics of ATOM reactor. The S-CO_2 power conversion system is designed under the primary reactor conditions including cycle design, component design, and pipe design. It is confirmed that the size of power conversion system is significantly reduced compared to conventional shipboard steam power system. MARS-KS code is improved to accurately simulate the S-CO_2 power conversion system combined with PWR. To demonstrate the reliability of the newly developed code, code validation is performed with experimental data of SCIEL facility. The control logic of the S-CO_2 power conversion system is developed based on the turbine bypass control considering the severe load changes. To investigate applicability of total system to nuclear propulsion system, transient simulations have been performed under actual load change requirements of the nuclear merchant ships. The proposed system exhibits stable response under the load change requirements without significant fluctuations of operational parameters and reduction in safety margins. This proves the potential of the proposed system. In the near future, more transients will be analyzed to further prove the applicability of the proposed system.

NOMENCLATURE

$\dot{m}$ mass flow rate
ΔP pressure drop

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