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Load-Following Analysis of a Molten Salt Reactor and Supercritical CO_2 Power Cycle for Marine Propulsion

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1. Introduction

Global efforts to address climate change have prompted the International Maritime Organization (IMO) to set a target of zero carbon emissions from ships by 2050. To achieve this, the maritime industry must accelerate the transition to carbon-free propulsion technologies. Among the promising alternatives, nuclear-powered vessels equipped with Molten Salt Reactors (MSRs) have gained attention for their potential to provide stable, carbon-neutral energy at sea. For MSRs to be successfully integrated into commercial shipping, their system integration, safety, and ability to handle fluctuating power demands must be ensured.

A significant engineering challenge in marine nuclear propulsion is minimizing the size of the onboard systems. While reducing the size of the reactor core is constrained by design and safety requirements, optimizing the power conversion cycle presents a significant opportunity to reduce the overall ship footprint. The supercritical CO_2 (sCO_2) Brayton cycle, known for its high thermal efficiency and compact design, is particularly well-suited for space-constrained marine environments.

However, in MSR-sCO_2 systems, an important design consideration is the prevention of molten salt solidification. The temperature of the molten salt coolant must be maintained above its melting point to ensure system stability and avoid operational issues. This study incorporates the consideration of molten salt melting points into the design and operation of the power conversion system, highlighting its crucial role in achieving reliable performance.

The successful application of sCO_2-based systems in marine environments also requires robust control strategies to manage frequent load fluctuations at sea. This study investigates the load-following capability of an MSR-sCO_2 power conversion system, with a focus on ensuring operational stability across varying conditions while addressing the challenges posed by molten salt solidification.

2. Methods and Results

2.1 Target System

The reference reactor for this study is the K-MSR, which was specifically developed for marine applications. It has a thermal output of 100 MW and utilizes a molten salt coolant loop to transfer heat from the reactor core to the power conversion system. The reactor employs NaCl-KCl-UCl_3 as the fuel salt and NaCl-KCl-$MgCl_2$ as the coolant salt. The thermophysical properties of these salts, including their compositions, are adopted from previous research to ensure consistency with established data. The reactor's main design and operational parameters are also based on prior work by this research group, maintaining alignment with the K-MSR specifications [1].

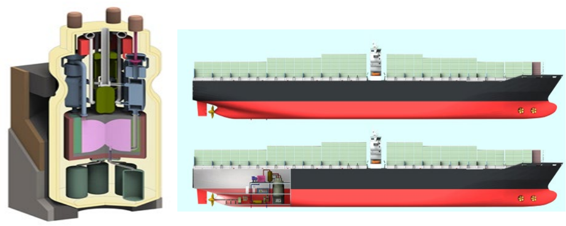

Fig. 1. Configuration of K-MSR

2.2 sCO_2 Cycle Design

A supercritical CO_2 Brayton cycle can typically be configured in either a simple recuperated or a recompression layout. When applied to marine propulsion system, factors such as refueling intervals and thermal efficiency must be carefully considered. Previous studies have shown that the recompression cycle is more advantageous in these aspects, making it a more suitable choice for shipboard applications [1]. Based on these findings, this study adopts the recompression cycle and designs the system using the in-house code KAIST-CCD to optimize its performance for marine integration [2].

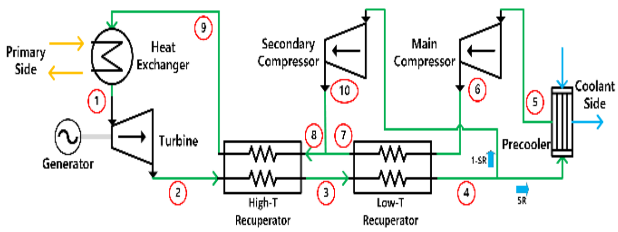

Fig. 2. Recompression Cycle Layout

Table I: Cycle Design Results

Points	T [°C]	P [MPa]	$\dot{m}$ [kg/s]
1	635.0	19.55	555.48
2	541.63	9.46	555.48
3	217.96	9.31	555.48
4	85.03	9.16	555.48
5	40.0	9.01	394.39
6	76.18	20.0	394.39
7	202.83	19.85	394.39
8	189.71	19.85	555.48
9	490.17	19.70	555.48
10	159.49	19.85	161.09

2.3 Cycle Components Design

The recompression sCO_2 cycle designed in this study, as illustrated in Fig. 2 and detailed in Table I, consists of four heat exchangers and three turbomachinery components. The heat exchangers include a high-temperature recuperator (HTR), a low-temperature recuperator (LTR), a precooler, and an intermediate heat exchanger (IHX). In sCO_2 cycles, where system operating pressures are high and space constraints are critical, Printed Circuit Heat Exchanger (PCHE) type heat exchangers are the preferred choice due to their compact size and efficient thermal performance. To optimize these components for the designed cycle, KAIST-HXD, an in-house code developed specifically for PCHE design, was employed [3].

The turbomachinery components consist of two compressors and one turbine. The net electric power output of the designed cycle is approximately 40 MW_e. At this power level, radial-type compressors are suitable. However, an axial-type turbine is required to ensure efficient operation. Consequently, all three turbomachinery components were designed using KAIST-TMD, an in-house tool developed for the design and optimization of compressors and turbines [4]. This approach ensures that the cycle achieves the desired performance while maintaining compatibility with the compact and high-efficiency requirements of marine propulsion applications.

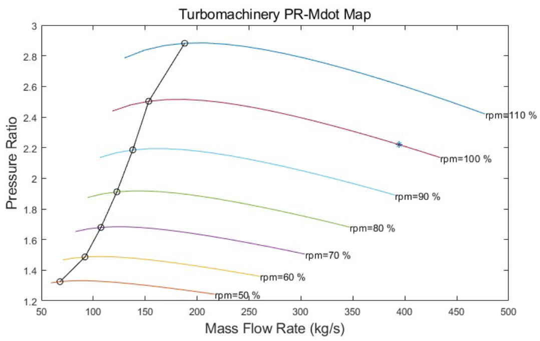

Fig. 3. Main Compressor Off-Design Map

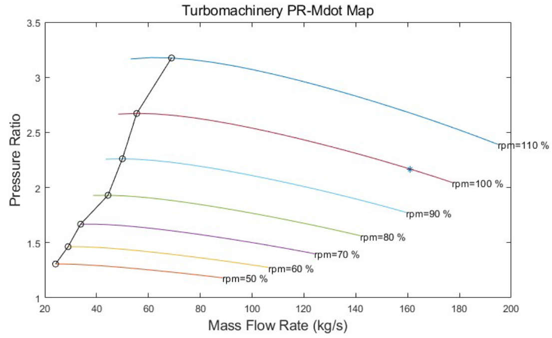

Fig. 4. Recompressor Off-Design Map

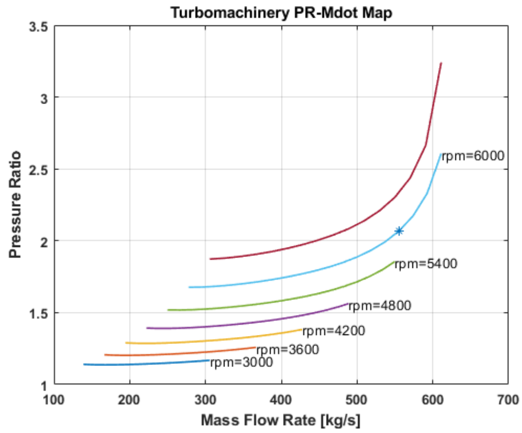

Fig. 5. Turbine Off-Design Map

2.4 Control Strategy

Load-following capability is crucial in maritime propulsion, as power demands can vary significantly due to weather changes, route variations, and operational conditions. This study assumes the lack of detailed route data and evaluates the system's ability to transition from the design point to 0% power output while maintaining stable operation. Common load-following techniques used in sCO_2 systems include turbine bypass, turbine throttling, and inventory control [5]. Turbine bypass provides rapid response and a broad power control range, while inventory control helps maintain high efficiency when operating away from the design point. This study employs a hybrid approach, combining turbine bypass with inventory control, to evaluate load-following performance.

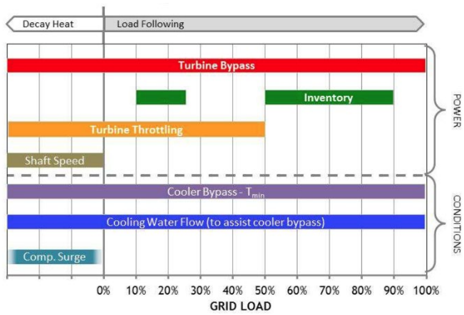

Fig. 3. sCO_2 Cycle Control Strategy

2.5 Solidification of Molten Salt

In MSR-sCO_2 cycle systems, unlike conventional PWR-based systems, the solidification of molten salt must be carefully considered. The coolant used in this study, NaCl-KCl-$MgCl_2$ (15.11-38.91-45.98 wt%), requires specific thermal conditions to prevent solidification [6]. To address this, the designed IHX was analyzed to determine the minimum CO_2 inlet temperature necessary to ensure that the molten salt does not solidify.

Theoretically, molten salt solidifies when its temperature drops below its melting point. However, in practical applications, additional temperature margins are applied to ensure that the molten salt remains well above its melting point, rather than simply preventing it from dropping below its melting point. This study established a temperature margin based on two considerations. First, the composition of molten salt may vary slightly during actual operation, introducing a level of uncertainty. For example, even with a nominal NaCl-$MgCl_2$ composition of (58.0-42.0 mol%), variations in actual composition may occur, affecting phase stability. To account for this uncertainty, a 20 K margin was added.

Second, previous studies indicate that a temperature margin must be maintained for plant operation to reduce the risk of coolant solidification and ensure system stability [7]. However, there is no universally defined margin for this purpose. Given the lack of a definitive approach, this study arbitrarily applied a 30 K operational margin in line with industry practices. Combined with the 20 K margin for composition uncertainty, a total temperature margin of 50 K was set to ensure safe operation. Accordingly, the coolant salt temperature should not drop below 724.55 K, which is 50K above the melting point of NaCl-KCl-$MgCl_2$.

To determine the corresponding CO_2 temperature at the IHX inlet, a single-channel thermal-hydraulic analysis was conducted for a PCHE hot-cold channel pair [8]. The same modeling approach used in previous studies, including modifications for hydraulic diameter and equivalent thickness, was applied. Based on these margin criteria, the minimum CO_2 inlet temperature at the IHX was calculated for each load-following conditions. This calculated values were subsequently used as a constraint in evaluating the system's load-following performance.

Table II: Summary of thermophysical properties of the NaCl-KCl-$MgCl_2$ (15.11-38.91-45.98 wt%)

Property	Values or correlations with T [K]
Melting point [K]	674.55
Heat capacity [J/kg·K]	$C_p = 1437.96 - 0.5 \times T[K]$
Viscosity [Pa·s]	$\mu = 7.0645 \times 10^{-4} \times \exp\left(\frac{1204.11345}{T[K]}\right)$
Density [kg/m^3]	$\rho = 2112.84 - 0.56355 \times T[K]$
Thermal conductivity [W/m·K]	$\lambda = 0.6532 - 0.00026 \times T[K]$

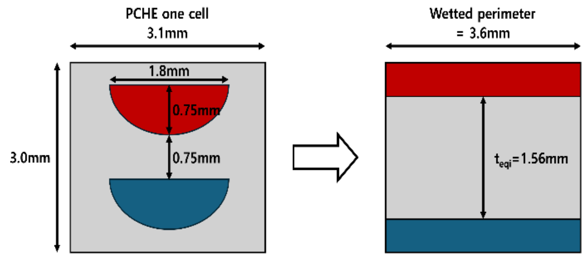

Fig. 4. (Left) PCHE channel geometry
(Right) Equivalent plate thickness in the 1-D model

2.6 Quasi Steady State (QCD) code

In this study, the KAIST-QCD code was used for quasi-steady-state analysis. This in-house code integrates KAIST-CCD, KAIST-HXD, and KAIST-TMD, enabling the performance analysis of the cycle at off-design conditions. The code considers key variables that change as the system follows load variations. In this study, the primary variables selected for analysis are the transferred heat from the coolant salt to the system, the bypass ratio for the IHX and turbine, and the system mass flow rate.

The transferred heat from the coolant salt to the system varies as the system follows load changes. In this study, the heat input range was set from the design value of 100 MW_{th} to a minimum of 5 MW_{th}. This range was established to encompass the overall variations in heat transfer from the coolant salt to the system during load-following operation.

The bypass ratio was determined based on the mass flow rate range of the axial turbine map. For the axial turbine designed in this study, it was observed that the mass flow rate at the design rotational speed covers only up to approximately 50% of the design mass flow rate. This limitation occurs because, as the inlet mass flow rate decreases, the flow angle at the stator exit and the angle at which the blade receives the flow differ, leading to an increase in the attack angle. This increase in attack angle results in greater losses or turbine instability. Therefore, the maximum bypass ratio was set at 50%, and calculations were performed only for cases where the product of the mass flow rate and the bypass ratio exceeded 50% of the design mass flow rate.

Additionally, to ensure the stable operation of the compressor, the surge margin for both the main compressor and recompressor was set at 10%. The minimum inlet temperature of CO_2 at IHX, previously determined to prevent coolant salt solidification, was also considered. Furthermore, the minimum mass flow rate condition at the turbine inlet was incorporated into the calculations.

2.7 Load Following Performance Analysis

The load-following performance of the system, incorporating all the previously discussed constraints, is illustrated in Fig. 6. The figure shows that below approximately 8.34% of work, neither the (IHX + Turbine) bypass nor inventory control alone can achieve further reduction in power. The blue line in Fig. 6 represents the highest efficiency points for each work level. Up to approximately 33% of work, the efficiency decline is gradual, but beyond this point, the slope steepens significantly, indicating a sharp efficiency drop. This shift occurs because inventory control is primarily engaged up to 33% work, while beyond this threshold, (IHX + Turbine) bypass becomes dominant.

The efficiency trend observed in Fig. 6 aligns with expectations. The gradual decline in efficiency up to 33% work suggests that inventory control effectively manages power reduction without significant efficiency losses. However, the sharp decline beyond this point indicates the onset of bypass control, which inherently introduces greater inefficiencies. This result confirms that inventory control provides better off-design performance compared to bypass strategies but is limited by the system's minimum mass flow rate constraint.

To reach lower work levels, two potential methods were considered: reducing Q_{in} and increasing the bypass ratio. However, each method presents challenges. Reducing Q_{in} lowers the CO_2 outlet temperature, increasing the risk of molten salt solidification. Conversely, increasing the bypass ratio reduces CO_2 mass flow through the IHX, leading to excessive outlet temperatures that exceed acceptable limits.

A viable solution is to implement a turbine-only bypass. While this approach may reduce overall cycle efficiency, it mitigates the issues associated with CO_2 temperature constraints, enabling stable operation at lower power levels. By selectively bypassing only the turbine while maintaining sufficient mass flow through the IHX, it is expected that lower power levels can be achieved without violating thermal constraints.

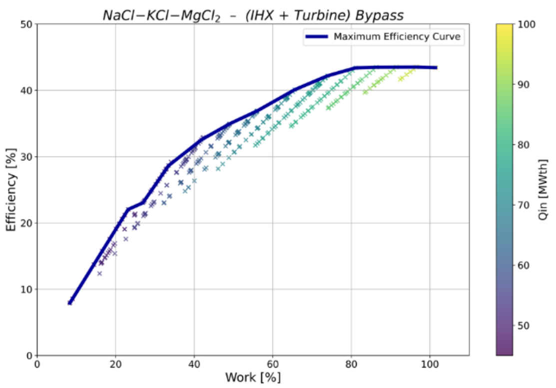

Fig. 6. Load-Following Data of NaCl-KCl-$MgCl_2$

3. Summary and Conclusions

This study examined the load-following behavior of an MSR-sCO_2 power conversion system for marine propulsion, focusing on (IHX + Turbine) bypass, inventory control, and CO_2 temperature limits required to prevent partial salt solidification. Unlike PWR-based systems, MSR systems must account for coolant solidification constraints, which limit the ability to achieve lower work levels. The results indicate that the recompression sCO_2 cycle can be effectively adapted to space-limited marine environments by leveraging its small footprint and high thermal efficiency. However, maintaining CO_2 temperature above the threshold for salt integrity emerged as a critical design constraint, significantly influencing the selection and effectiveness of bypass strategies.

Although the combined (IHX + Turbine) bypass approach expanded the load-following range, it ultimately encountered temperature-related limits, preventing further reductions in power. The findings suggest that bypassing only the turbine, rather than both the IHX and turbine, could allow the system to reach lower work levels while mitigating the challenges associated with molten salt solidification. Future research should refine control strategies, optimize temperature margins, and incorporate real-world operational profiles to further validate the feasibility of MSR-sCO_2 propulsion in achieving IMO's stringent zero-emission goals.

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