# Control Feasibility Assessment of an $sCO_2$ Recompression Cycle for Rapid Load Following

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## 1. Introduction

Supercritical carbon dioxide ($sCO_2$) power cycles have been widely investigated for advanced nuclear systems due to their high thermal efficiency and compact components. The high density of $CO_2$ near the critical point reduces compression work, while the recompression layout improves recuperation performance. These characteristics are particularly suitable for marine propulsion system, where compactness and rapid response to large demands variations are crucial [1].

Baek et al. developed a quasi-steady part-load operating strategy for a 100 MWth molten chloride fast reactor (MCFR) coupled to an $sCO_2$ recompression cycle [2]. Inventory control and turbine bypass control were combined to regulate cycle power and turbine rotational speed, while coolant salt mass flow and main compressor inlet temperature (MCIT) were adjusted to prevent salt solidification at lower loads. The analysis established feasible operating points over the full load range. A quasi-steady map, however, cannot determine whether the cycle can move between those points without jeopardizing system stability with excessive rotational speed deviation or compressor surge during a rapid power transition. Transient analysis is therefore required to demonstrate the dynamic controllability of a $CO_2$ based marine power conversion system [3].

Previous dynamic studies provide a practical basis for the test condition. Liese et al. analyzed load following between 10 and 4 MWe (100-40% rated power) and treated operation below 40% as a warm shutdown and startup process [3]. Oh et al. examined an icebreaking marine propulsion system in which the trans-critical CO2 cycle demand decreased from 100% to 50% within 5 s, equivalent to 10% FP/s, while recovery was slower [4]. Accordingly, the present study adopted a 100-40% load range and a ramp rate of 10% FP/s. The same ramp rate was applied during both load reduction and recovery, yielding a deliberately stringent symmetric operation. The 40% lower bound also remains above the MCIT-upshift region of the target MCFR-$sCO_2$ system, shown in Fig. 1,allowing the MCIT to be fixed at nominal value [2]. The objective is to assess whether the existing controls can track this demand stably.

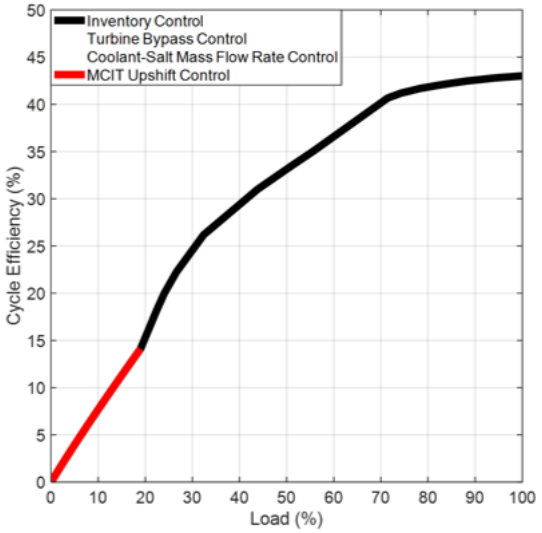



**Fig. 1.** Cycle Efficiency Over Various Load ranges [2]

## 2. Methods and Results

### *2.1 Cycle Model and Analysis Conditions*

The target system is the 100 MWth recompression $sCO_2$ cycle designed in the previous study [2]. The design point maximum temperature and pressure are 630 ℃ and 20.0 MPa, respectively, and the MCIT is 40 ℃. The optimized flow split ratio is 0.71. The design $CO_2$ mass flow rate, net electrical output, and cycle efficiency are 558.08 kg/s, 42.66 MWe, and 42.66%, respectively.

For the transient operation, MARS-KS code is used. The MARS-KS model includes the intermediate heat exchanger (IHX), high and low temperature recuperators, cooler, turbine, main compressor, recompressor, inventory tanks, and associated control valves. The converged full-power steady state result reproduced the design point efficiency, net output, and mass flow rate as 42.652%, 42.627 MWe, and 557.780 kg/s, respectively. This state was used as the initial condition for the transient calculation

### *2.2 Control Configuration*

Fig. 2 shows the MARS-KS nodalization and valve locations. V1 is the turbine-bypass valve, which responds to turbine rotational speed deviation during a power mismatch. V2 and V3 connect the low and high pressure inventory tanks to the cycle and are actuated for

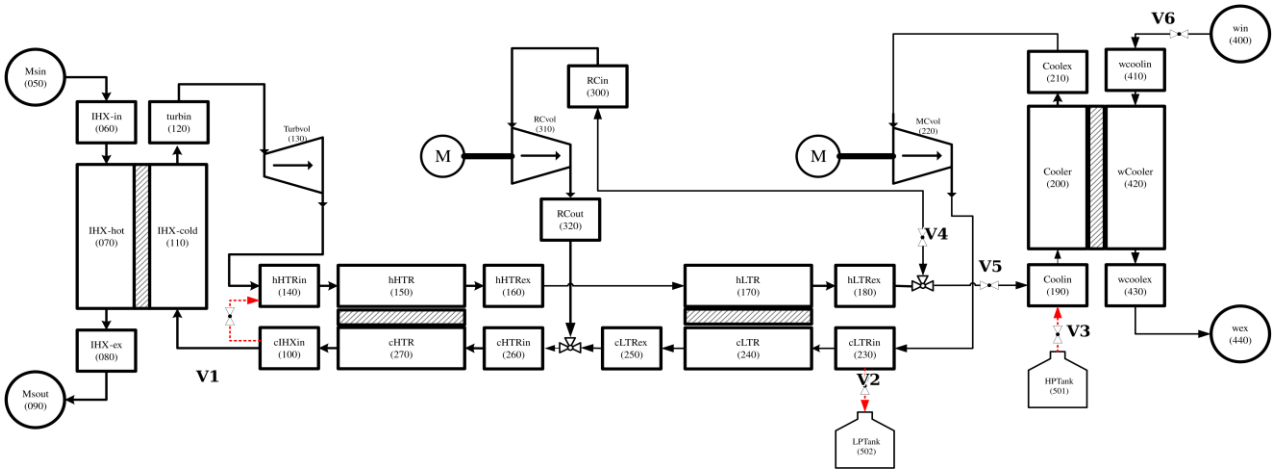



**Fig. 2.** MARS-KS nodalization and control valve locations

$CO_2$ discharge and charge, respectively. Inventory adjustment provides higher off-design efficiency, whereas the turbine bypass provides the rapid response to the demand. These three valves therefore constitute the principal load-following operation.

V4 and V5 serve as supporting regulators that maintain the flow split ratio near its design value of 0.71 as cycle pressure and flow resistance change. Similarly, V6 adjusts the cooling water flow rate to maintain the MCIT design value of 40 °C. These variables are held near the design point throughout the transient. The valve opening areas are determined by the corresponding proportional-integral controllers.

### *2.3 Transient Scenario and Feasibility Criteria*

After the full power steady state input was established, the cycle power demand was reduced from 100% to 40% at 10%FP/s, held at 40%, and then restored to 100%. Feasibility was assessed by whether the calculated power followed the power demand without oscillation, the turbine rotational speed and flow split ratio remained close to its nominal value, and the compressor surge margins are well above the limit.

### *2.4 Transient Results*

As shown in Fig. 3, the calculated cycle power closely followed the prescribed 100–40–100% demand with 10% FP/s. During ramp down, the inventory control system reduced the total $CO_2$ inventory from 100% to 85%, while the turbine bypass valve opened rapidly and then settled toward the 40% load position. During ramp up, the charging valve temporarily raised the inventory to approximately 104%. The inventory subsequently

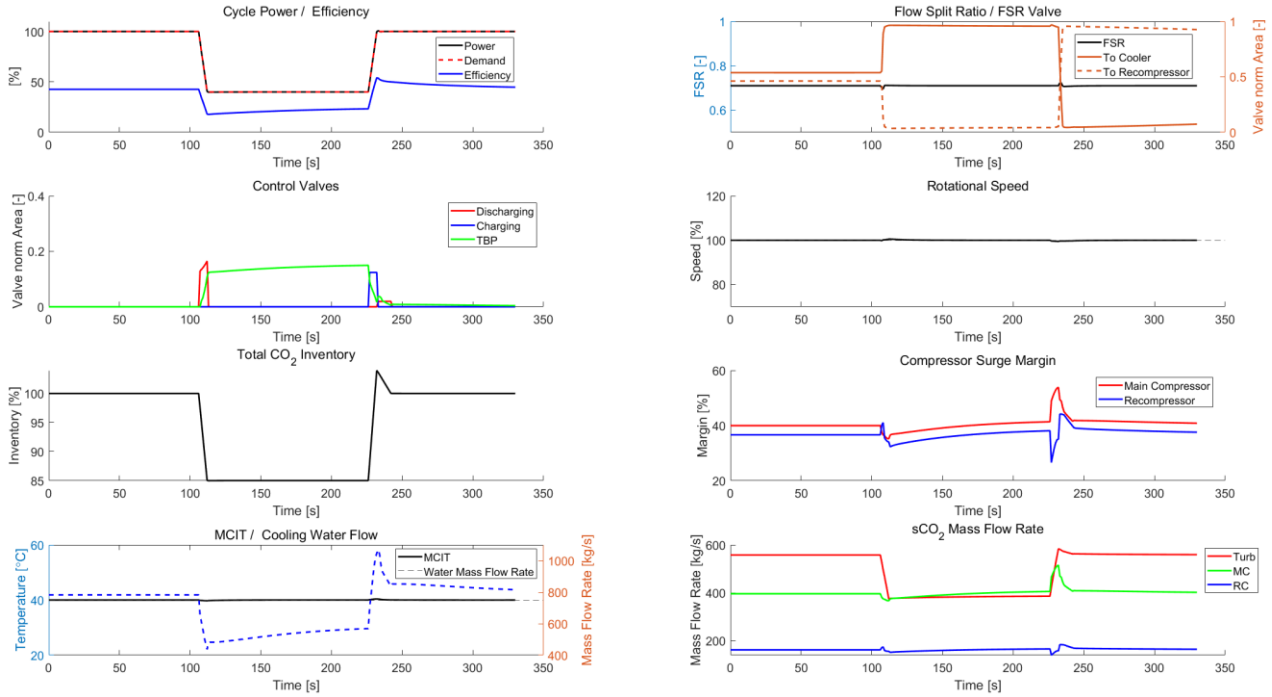



**Fig. 3** 100-40-100% Load Variation Transient Results

returned to 100% as the turbine bypass valve approached its full-power position.

Throughout the transient, V4 and V5 adjusted their openings to maintain the flow split ratio near 0.71, and V6 varied the cooling water flow rate while MCIT remained near 40 °C. The turbine rotational speed deviation remained within approximately 0.5% of nominal. The limiting compressor response occurred in the recompressor, whose minimum surge margin was approximately 27%. No oscillation or control failure was observed throughout the operation. The prescribed 10% FP/s transient was therefore successfully completed.

## 3. Conclusions

Transient MARS-KS calculation was performed to assess whether the 100 MWth $sCO_2$ recompression cycle could follow a rapid 100–40–100% power demand. The load range was selected from previous work that treated 40–100% as a load-following regime, while the 10% FP/s rate was based on the rapid load reduction considered for an icebreaking trans-critical $CO_2$ marine propulsion system [3,4]. Applying this rate in both directions produced a more demanding ramp up than that used in the reference marine case.

The combined turbine bypass and inventory controls tracked the prescribed demand without oscillation, while the supporting control valves maintained the flow split ratio and MCIT near their design point. The turbine rotational speed deviation remained within approximately 0.5%, the limiting recompressor surge margin was approximately 27%, and the total $CO_2$ inventory varied between 85% and 104% before returning to its nominal level. These results demonstrate cycle level control feasibility for the 10% FP/s transient.

## ACKNOWLEDGEMENT

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