# Preliminary Study of $sCO_2$ Compressor Inlet Guide Vane (IGV) for Molten Salt Reactor

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## 1. Introduction

Most of the international trade is carried out by maritime transportation, which relies on fossil fuels. The International Maritime Organization (IMO) has established greenhouse gas reduction regulations with the objective of minimizing shipping's carbon emissions [1]. As a result, research into alternative propulsion systems to replace traditional fossil fuels is surging in both academic and industry. Nuclear power is one of these alternatives, and using small modular reactors suitable for maritime transportation is gaining momentum.

Propulsion systems that use molten salt reactors (MSRs) as a heat source and coupled with supercritical carbon dioxide ($sCO_2$) Brayton cycles have good potential for marine reactors. First, the high core power density of MSRs makes them ideal candidates for nuclear-based ship propulsion systems in terms of weight and volume [2]. In addition, the high-temperature nature of MSRs allows the $sCO_2$ cycle to achieve higher efficiencies than conventional steam Rankine cycles. Therefore, the choice of the $sCO_2$ Brayton cycle as a ship propulsion system is advantageous in many respects compared to the conventional steam Rankine cycle.

The characteristics of the $sCO_2$ cycle are primarily due to the compressor. In this cycle, the compressor operates near the critical point of $CO_2$, which minimizes the compression work and the size of the machine. Therefore, the design of the compressor is a key point in the design of the entire $sCO_2$ system. In addition, the power conversion system used in ships inevitably requires off-design operation. In the $sCO_2$ cycle, the pressure, mass flowrate and temperature of the system change during off-design operation. Therefore, for the off-design performance of the $sCO_2$ Brayton cycle, the compressor requires stable performance and high efficiency for changing flow and pressure.

For a typical industrial centrifugal air compressor, the compressor inlet swirl is controlled by adjusting the angle of the inlet guide vane (IGV) to maintain high efficiency over changing flowrates [3]. As variable inlet guide vanes operating at high pressures of sCO2 are currently being studied at the laboratory level, this study analyzes which choice of fixed IGV angle is optimal from an off-design operational perspective as a preliminary study.

To analyze the $sCO_2$ cycle off-design performance as a function of IGV angle, a 10 MWe $sCO_2$ cycle for marine propulsion designed based on the Molten Salt Reactor Experiment is utilized. Previous studies have concluded that a recompression cycle with two compressors is the most suitable, but in this study, the simple recuperated cycle with a single compressor is selected to observe the off-design performance. The compressor is designed using KAIST-TMD (Turbomachinery Design Code), an in-house code, by varying the IGV angle while keeping all other conditions the same. For the off-design performance analysis, a quasi-steady state analysis is performed with the KAIST-QCD (Quasi-steady state Cycle Design) code.

## 2. Methods and Results

This section describes the modeling process and results of the $sCO_2$ compressor, including the compressor design conditions, the compressor design using KAIST-TMD, and the results of the off-design performance evaluation using KAIST-QCD.

### *2.1 Compressor Design Condition*

The inlet and outlet temperature and pressure conditions for the $sCO_2$ compressor design were based on a previously designed 10 MWe MSR-$sCO_2$ system. The MSR information was established based on the Molten Salt Reactor Experiment, while the $sCO_2$ cycle output and design conditions were based on existing marine propulsion research [4]. Among the three cycles presented, a simple recuperated cycle shown in Figure 1 was used to limit the number of compressors to one to better observe the changes in off-design performance due to compressors.

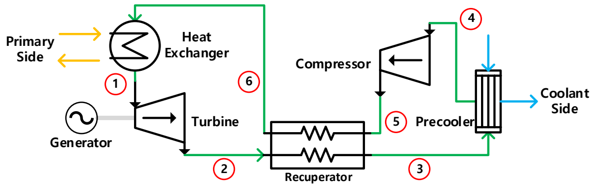


Fig. 1. Simple recuperated $sCO_2$ cycle

Considering the output power, the compressor was selected as a single-stage centrifugal compressor, and the compressor speed and inlet axial velocity were set based on Balje's $n_s$-$d_s$ diagram. The loss model and design parameters of the compressor were set by referring to existing studies. Table 1 shows the parameters used in the compressor design. The compressor inlet and outlet design conditions were chosen as points to optimize the efficiency of the cycle. In addition, figures such as impeller vane were chosen based on existing lab compressors in use.

Table 1. Design parameters of $sCO_2$ compressor [5], [6]

| Parameter | Value |
|---|---|
| Inlet temperature (°C) | 35 |
| Inlet Pressure (MPa) | 12.78 |
| Outlet Pressure (MPa) | 25.0 |
| Mass flowrate (kg/sec) | 123.5 |
| Rotating speed (rpm) | 24,000 |
| Axial velocity (m/sec) | 35 |
| Number of impeller vanes | 10 |
| Rotor hub diameter at exit (m) | 0.04 |
| Backswept angle (°) | 50 |
| IGV angle (°) | 0, 30, 50, 70 |

*2.2 Compressor Design Results*

For four different IGV angles, the compressor was designed using KAIST-TMD with all other variables being the same. Table 2 shows the design results of the four types of compressors.

Table 2. $sCO_2$ compressor design results

| IGV angle | Pressure Ratio | Efficiency (%) | Work (MW) |
|---|---|---|---|
| **0°** | 1.956 | 77.42 | 2.4 |
| **30°** | 1.956 | 81.91 | 2.27 |
| **50°** | 1.956 | 84.06 | 2.21 |
| **70°** | 1.956 | 85.32 | 2.18 |

To evaluate the performance of the four designed compressors, the compressor maps are shown in Figures 2 and 3. Figure 2 shows the relationship between pressure ratio and mass flowrate, and Figure 3 shows the relationship between compressor efficiency and mass flowrate. The solid line in Figure 2 shows the pressure ratio for a change in mass flow rate at the same speed. The curves of the same color are the result of changing only the speed on the same compressor. Also, the dashed lines in Figure 2 show the surge line for each compressor.

The results in Table 2 and Figure 3 show that the larger the IGV angle, the higher the efficiency. The smaller the relative velocity between the fluid and the compressor blades, the lower the incidence losses at the compressor inlet. For $sCO_2$ compressors, the fluid inlet velocity is slow because the density of the fluid is large near the critical point. This means that the velocity of the blades is greater than the fluid inlet velocity, and to reduce losses by reducing the relative velocity between the fluid and the compressor blades, it is advantageous to deflect the fluid as much as possible in the direction of rotation of the compressor. In other words, a large IGV angle minimizes incidence losses and increases compressor efficiency.

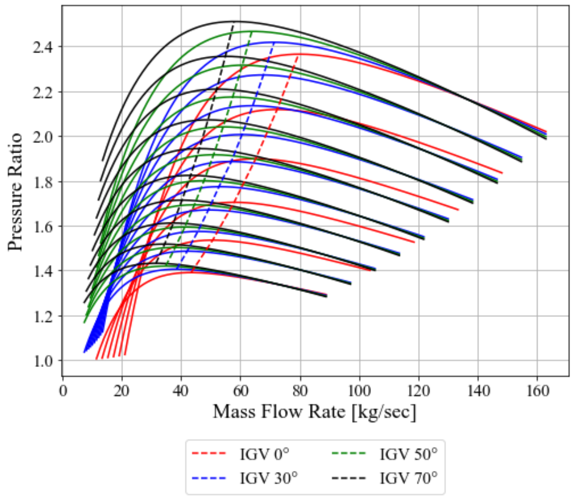


Fig. 2. Pressure ratio map of four $sCO_2$ compressors

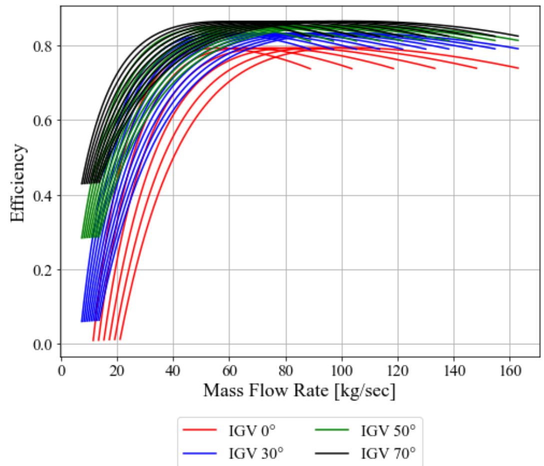


Fig. 3. Efficiency map of four $sCO_2$ compressors

*2.3 Quasi-steady State Analysis*

The off-design performance of the cycle was analyzed using the in-house code KAIST-QCD. Among the different methods used for load-following operation of $sCO_2$ cycles, inventory control is generally known to be more efficient in off-design operation, so this study used inventory control to evaluate off-design. Since the MSR-$sCO_2$ system is a molten salt to heat $sCO_2$, unlike a typical gas heater coupled with a power generation system, the temperature cannot go higher than the design temperature. Therefore, the maximum temperature was fixed at the design temperature of 630°C. In addition, the mass flowrate of the system was varied to simulate inventory control. Originally, inventory control would change the total fluid mass in the system, but due to the lack of detailed design of the system, such as pipes, it was not possible to estimate the total mass of $sCO_2$ in the system. Fortunately, the change in the system-wide fluid inventory due to inventory control is consequently reflected in the form of mass flowrate, so the system off-design performance was evaluated according to mass flowrate.

Figures 4 through 6 show the system's heater power, net work and efficiency, while the mass flow rate varies from 0.5 to 1.1 times the design value of 123.5 kg/sec. The effect of changing the compressor IGV angle on the heater power is negligible because the maximum temperature and flow rate of the system are fixed. However, changes in compressor efficiency cause differences in net work. This is because as the IGV angle increases, the net work increases because the compressor efficiency increases. Since the amount of input heat is almost independent of the compressor IGV angle, the system efficiency is therefore higher for larger designed compressor IGV angles, as is the case with the system efficiency. Comparing the graphs between cycle net work and efficiency in Figure 7, for all sections, a larger IGV angle results in a larger efficiency for the same net work.

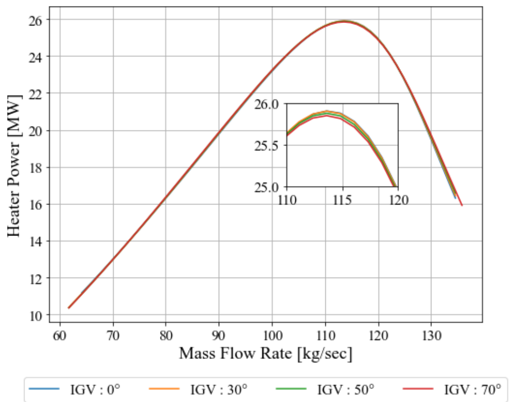


Fig. 4. Heater power to mass flow rate of 4 different $sCO_2$ compressor systems

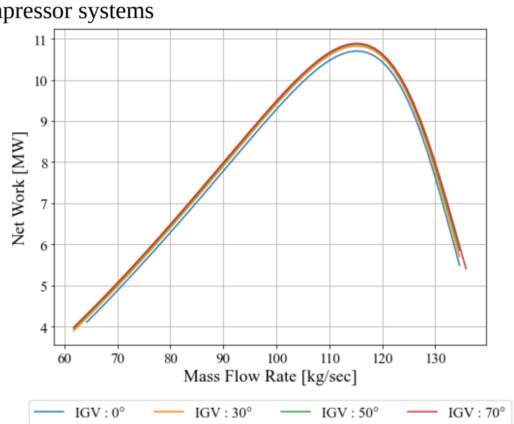


Fig. 5. Net work to mass flow rate of 4 different $sCO_2$ compressor systems

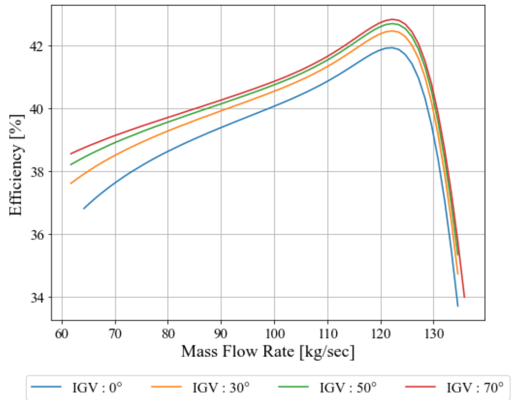


Fig. 6. Efficiency to mass flow rate of 4 different $sCO_2$ compressor systems

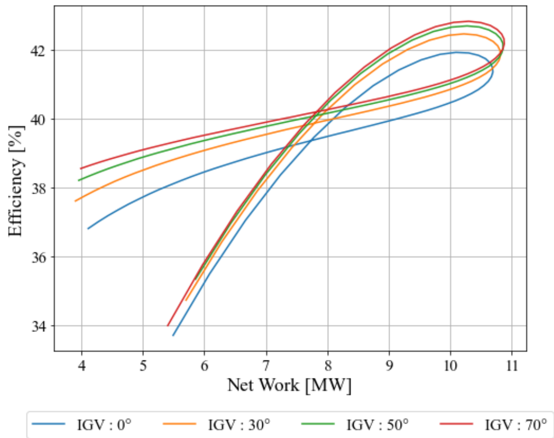


Fig. 7. Cycle efficiency to net work of 4 different $sCO_2$ compressor systems

## 3. Conclusions

Molten salt reactors with $sCO_2$ power conversion systems can be a suitable propulsion system for marine transportation. Compressor design is a key factor in $sCO_2$ systems, and four different compressors were compared having different IGV angle. First, the four compressors were compared on a compressor machine scale. A larger IGV angle reduces the relative velocity between the inlet fluid and the compressor blades, which increases the isentropic efficiency of the compressor. Next, the system off-design analysis was performed. Since the larger IGV angle increases the isentropic efficiency of the compressor, the system off-design thermal efficiency also increases. Therefore, this paper recommends designing a large IGV angle for the compressor in the MSR-sCO2 ship propulsion system.

## ACKNOWLEDGEMENTS

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