

Influence of Similitude Model Selection on the Performance Prediction of the sCO₂ Power Cycle

Gihyeon Kim^a, Jeong Min Baek^a, Jeong Ik Lee^{a*}

^aDept. of Nuclear & Quantum Eng., KAIST, 291 Daehak-ro, Yuseong-gu, Daejeon 34141, Republic of Korea

*Corresponding author: jeongiklee@kaist.ac.kr

***Keywords :** sCO₂ Brayton cycle, Compressor similitude model, Quasi-steady-state analysis

1. Introduction

Recent advances in artificial intelligence and large language models are accelerating the deployment of large-scale data centers. The International Energy Agency reported that data centers consumed approximately 415 TWh of electricity in 2024 and projected that this demand could reach about 945 TWh by 2030 [1]. Small modular reactors (SMRs) are therefore receiving attention as reliable, low-carbon, distributed power sources for data centers [2].

In terms of efficiency and compactness, the supercritical carbon dioxide (sCO₂) Brayton cycle is a viable power conversion option for SMRs. Compression is generally performed near the critical point, where the high fluid density reduces compression work. The high operating pressure also enables compact turbomachinery and heat exchangers [3, 4]. However, data center power demand varies with computational workload, particularly during AI training and inference. Thus, an sCO₂ power system should maintain stable and efficient operation over a broad load range.

During load-following operation, changes in heat input, system inventory, flow rate, pressure, and shaft speed shift the operating points of sCO₂ turbomachinery [5]. Accurate estimation of compressor performance is particularly important because the compressor operates near the critical point, where CO₂ properties are highly sensitive to temperature and pressure. Therefore, a compressor map generated at the design condition must be transformed to predict off-design performance under different inlet conditions.

Several similitude models have been proposed for sCO₂ compressors. Previous studies have shown that predicted compressor performance depends on the selected model and validation dataset [6,7]. Alsawy et al. also compared several similitude models in dynamic cycle simulations [8]. Although previous studies have examined component-level performance or dynamic cycle responses, the influence of compressor-model selection over a broad cycle operating range has not been sufficiently clarified.

In this study, quasi-steady-state analyses of a recuperated sCO₂ cycle were conducted using different compressor similitude models under identical boundary conditions. Converged operating points were evaluated over a wide load range. Differences in compressor outlet conditions, net power, and cycle efficiency were compared to determine how the effects of model

selection propagate through the overall cycle. The results provide a basis for assessing the importance of compressor similitude model selection in load-following analysis of sCO₂ power systems.

2. Methods and Results

2.1 sCO₂ Brayton Cycle

To evaluate the impact of compressor similitude model selection under off-design operating conditions, a simple recuperated sCO₂ cycle based on the GPT-Marine reactor—designed at KAIST—was used. Although the recompression cycle offers higher efficiency, the simple recuperated cycle was selected to isolate the effects of the compressor similitude models. The design points and design results for the selected simple recuperated cycle are shown in Figure 1 and Table 1, respectively [9].

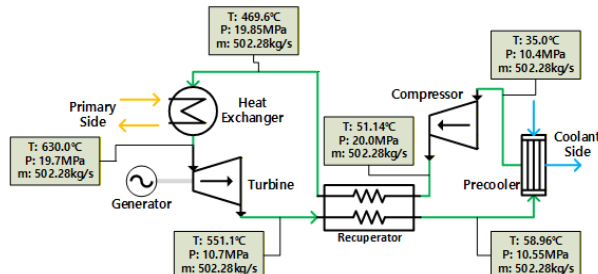


Fig. 1. Design of the simple recuperated sCO₂ cycle [9]

Table 1. sCO₂ cycle design results [9]

Design parameter	Optimization Results
Cycle Efficiency (%)	38.0
Cycle Thermal Input (MW)	100
Minimum Pressure (MPa)	10.4
Mass Flow Rate (kg/s)	502.28
Compressor Pressure Ratio	1.923

Based on the cycle design results in Figure 1, the sCO₂ centrifugal turbomachinery was designed using the KAIST-TMD (Turbomachine Design), an in-house code. Considering the axial force balance and the allowable flow range of the centrifugal turbomachinery, the compressor was configured as two double-suction centrifugal compressor sets, whereas the turbine was configured as two double-discharge radial turbine sets.

The compressor design results are presented in Figures 2 and 3 and Table 2.

Table 2. Compressor Design Results

Parameter	Value
Compressor Power per Flow Path (MW)	1.985
Pressure Ratio (-)	1.923
Efficiency (%)	80.07
Rotating Speed (RPM)	12,000
Inlet Axial Velocity (m/s)	32
Number of Vanes (-)	18
Rotor Hub Diameter (m)	0.1

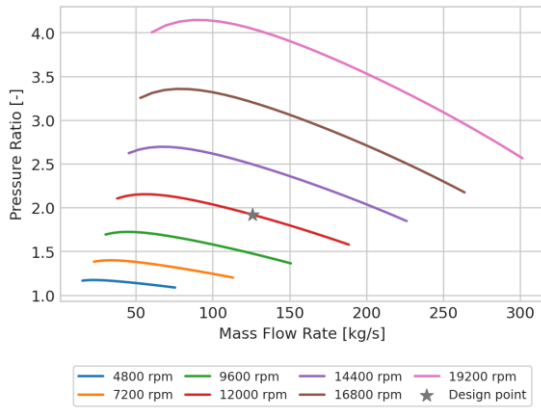


Fig. 2. Compressor pressure ratio map

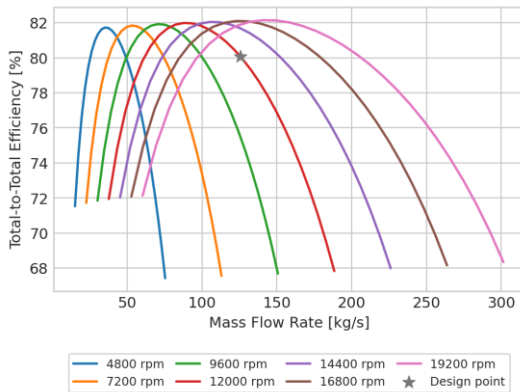


Fig. 3. Compressor efficiency map

2.2 Compressor Similitude Model

A similitude model predicts turbomachinery performance under various operating conditions by correcting mass flow rate and shaft speed according to the compressor inlet conditions. The corrected mass flow rate and rotational speed are calculated from the off-design inlet conditions using dimensionless variables originally developed for an ideal gas. As the model utilizes the compressor map, it enables fast performance estimation at low computational cost. However, as the similitude model is based on the ideal gas law, modified models have been proposed to account for the strong real gas effect of $s\text{CO}_2$. Table 3 summarizes the similitude models proposed in the literature.

Table 3. Similitude models in the literature [7]

Similitude model	Flow parameter	Speed parameter	Head parameter
IG	$\frac{\dot{m}\sqrt{\gamma RT}}{\gamma P}$	$\frac{N}{\sqrt{\gamma RT}}$	$\frac{\Delta h}{\gamma RT}$
IGZ	$\frac{\dot{m}\sqrt{\gamma ZRT}}{\gamma P}$	$\frac{N}{\sqrt{\gamma ZRT}}$	$\frac{\Delta h}{\gamma ZRT}$
Glassman	$\frac{\dot{m}\sqrt{\gamma RT_{cr}}}{\gamma P_{cr}}$	$\frac{N}{\sqrt{\gamma RT_{cr}}}$	$\frac{\Delta h}{\gamma RT_{cr}}$
BNI	$\frac{\dot{m}\sqrt{\gamma ZRT_{cr}}}{\gamma P_{cr}}$	$\frac{N}{\sqrt{\gamma ZRT_{cr}}}$	$\frac{\Delta h}{\gamma ZRT_{cr}}$
Pham	$\frac{\dot{m}\sqrt{n_s ZRT}}{n_s P}$	$\frac{N}{\sqrt{n_s ZRT}}$	$\frac{\Delta h}{n_s ZRT}$

Figure 4 shows how the corrected mass flow rate and corrected compressor speed change under off-design conditions. The mass flow rate and compressor speed were held at the design values, and the corrected mass flow rate and corrected compressor speed were calculated by applying the five models in Table 3. The calculations covered inlet temperatures from 35 to 50 °C and inlet pressures from 7.5 to 20.0 MPa, using increments of 1 °C and 0.5 MPa, respectively. The corrected variables were referenced to 35 °C and 10.4 MPa, which is compressor design condition, and the required CO_2 properties were evaluated using REFPROP. The location of the corrected operating points varied by models, and some conditions required extrapolation beyond the compressor map range. While more than 98% of the inlet conditions for the IG and Glassman models fell within the compressor map range, only about 80–85% of the inlet conditions for the remaining three models fell within the compressor map range. This highlights the need to analyze how these differences among the similitude models affect off-design operation.

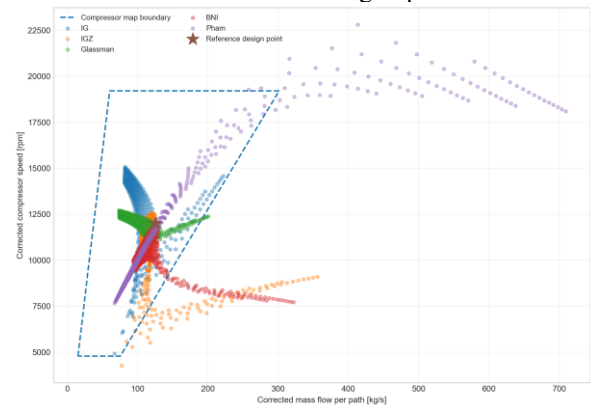


Fig. 4. Distribution of corrected operating conditions by similitude model

2.3 Quasi-Steady-State Off-Design Analysis

To examine the effect of the compressor similitude model on off-design performance, a quasi-steady-state analysis was performed using the in-house code KAIST-QCD. The analysis examined system control strategies for inventory control, heater control, and compressor

inlet control. To simulate inventory control, the total mass flow rate was adjusted; for heater control, the turbine inlet temperature (TIT) was adjusted; and for compressor inlet control, the compressor inlet temperature (CIT) was adjusted. The analysis range and intervals are summarized in Table 4.

Table 4. Quasi-steady-state analysis parameters

Parameter	Range	Interval
Compressor Inlet Temperature (°C)	35.0-50.0	5.0
Turbine Inlet Temperature (°C)	550.0-630.0	20.0
Mass Flow Rate (kg/s)	50.23-552.5	12.56

Figures 5 and 6 show the cycle efficiency as a function of mass flow rate at a CIT of 35 °C and a TIT of 630 °C, and at a CIT of 50 °C and a TIT of 550 °C, respectively. In Figure 5, both temperatures were maintained at the design values, whereas Figure 6 shows the temperature combination furthest from the design values. On the graphs, solid lines with circular markers represent points within the map, while dotted lines with “x” markers represent extrapolated points. Although efficiency predictions are similar regardless of the model near the design values, it can be observed that the differences in efficiency predictions between models increase as the conditions deviate further from the design values. In particular, the numerical solutions were obtained with the Pham model at a CIT of 50 °C, but none were located within the compressor map. Therefore, selecting an appropriate similitude model is required to accurately predict off-design performance over a wide range.

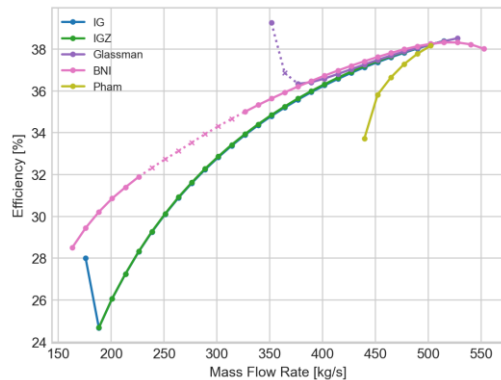


Fig. 5. Cycle efficiency comparison (CIT: 35 °C, TIT: 630 °C)

At the design condition, the differences between the highest and lowest predictions were 0.088 percentage points in cycle efficiency, 0.334 MPa in compressor inlet pressure, and 0.990 MW in net power. On the other hand, as shown in Figure 7, at a CIT of 45 °C, a TIT of 610 °C, and a mass flow rate of 502.28 kg/s, the differences between the similitude models increased to 7.367 percentage points, 8.484 MPa, and 15.895 MW, respectively. These results show that the effects of the similitude model become more significant as the operating conditions deviate from the design condition.

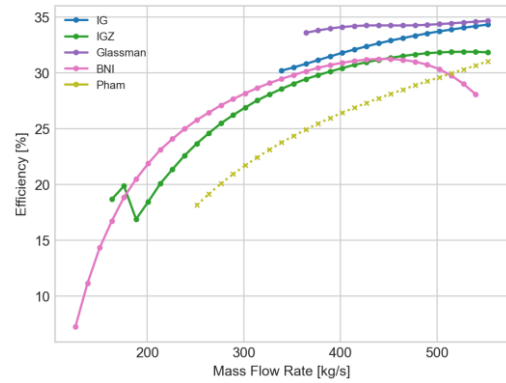


Fig. 6. Cycle efficiency comparison (CIT: 50 °C, TIT: 550 °C)

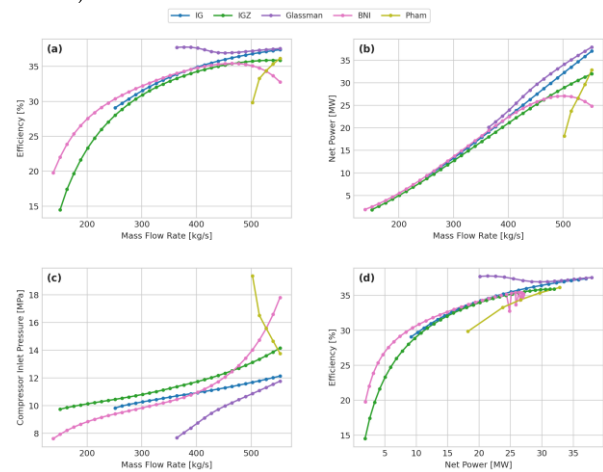


Fig. 7. Comparison of (a) cycle efficiency, (b) net power, (c) compressor inlet pressure as functions of mass flow rate, and (d) cycle efficiency as a function of net power (CIT: 45 °C, TIT: 610 °C)

In terms of cycle efficiency, selecting the operating condition that maximizes efficiency at a given net power demand is preferable. Figure 8 shows the operating envelope. For the IGZ model at a CIT of 35 °C, the upper boundary obtained by selecting the maximum efficiency among the TIT curves at each net power value represents the preferred operating conditions.

Figure 9 compares the operating envelopes obtained for each model. The comparison shows that the predicted power range within the compressor map, off-design efficiency, and the conditions that maximize the cycle efficiency depend strongly on the similitude model. The predicted power range within the compressor map extended from 0.49 to 38.96 MW for BNI but from 16.25 to 40.44 MW for Glassman, while the maximum predicted cycle efficiency ranged from 38.17% for Pham to 39.26% for Glassman.

Therefore, to determine the off-design operating points for an actual system, an accurate compressor similitude model must first be selected across a wide range prior to conducting transient analysis or quasi-steady-state analysis incorporating additional control strategies.

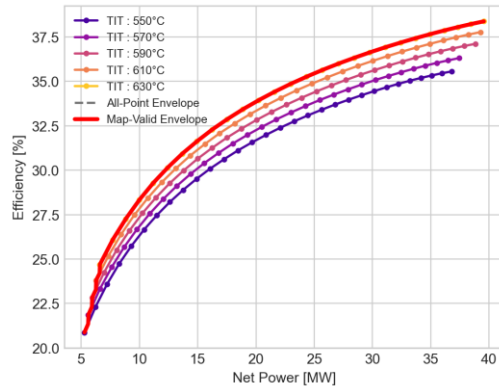


Fig. 8. Operating envelope (IGZ, CIT: 35°C)

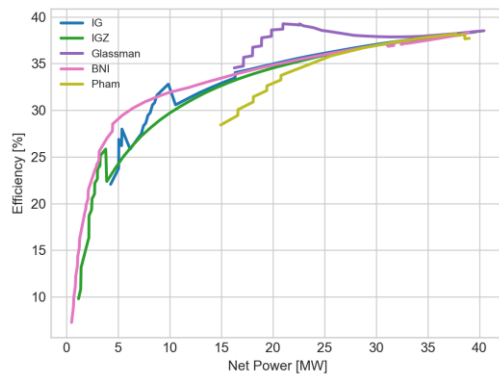


Fig. 9. Operating envelope comparison by model

3. Summary and Conclusions

This study presented a comparative evaluation of five compressor similitude models—IG, IGZ, Glassman, BNI, and Pham—to investigate their effects on the quasi-steady-state off-design performance of a simple recuperated sCO₂ Brayton cycle. The same compressor pressure ratio map and efficiency map were used for all models, while the corrected mass flow rate and corrected compressor speed were calculated using each similitude model. The analysis covered compressor inlet temperatures of 35–50 °C, turbine inlet temperatures of 550–630 °C, and mass flow rates of 50.23–552.5 kg/s, corresponding to 10–110% of the design value.

Near the design condition, the five models produced similar cycle efficiency predictions. However, as the operating conditions deviated from the design conditions, the locations of the corrected operating points varied among the models. Consequently, different pressure ratios and efficiencies were obtained from the same compressor map. These differences affected the compressor inlet pressure, turbomachinery power balances, net power, and cycle efficiency. At a CIT of 45 °C, a TIT of 610 °C, and a mass flow rate of 502.28 kg/s, the difference in net power among the models reached 15.895 MW, although all five corrected operating points were located within the compressor map. Moreover, although numerical Pham solutions were obtained at a compressor inlet temperature of 50 °C, none were located within the compressor map. These results

suggest that the reliability of off-design system performance analyses may depend not only on the type of compressor similitude model but also on the operational range of the compressor map.

The operating envelopes obtained for the five models also showed different net power ranges, off-design efficiencies, and operating conditions for maximum efficiency. Therefore, the selection of the compressor similitude model affects not only the predicted off-design cycle performance but also the preferred operating conditions for load-following operation.

Future research should investigate the impact of compressor similitude models under a wider range of control strategies, cycle configurations, and transient operating conditions. Comparisons between model predictions and experimental data during transient operation are required to quantify model accuracy under dynamic conditions and to assess how different control logics influence compressor behavior and overall cycle performance.

ACKNOWLEDGEMENTS

"This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIT) (No. RS-2025-25454059)."

REFERENCES

- [1] International Energy Agency, Energy and AI, IEA, Paris, 2025.
- [2] S. Cha, "The potential role of small modular reactors (SMRs) in addressing the increasing power demand of the artificial intelligence industry: A scenario-based analysis," *Nuclear Engineering and Technology*, Vol. 57, No. 4, Article 103314, 2025. doi:10.1016/j.net.2024.11.016.
- [3] V. Dostal, M. J. Driscoll, and P. Hejzlar, *A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors*, MIT-ANP-TR-100, Massachusetts Institute of Technology, Cambridge, MA, 2004.
- [4] Y. Ahn, S. J. Bae, M. Kim, S. K. Cho, S. Baik, J. I. Lee, and J. E. Cha, "Review of supercritical CO₂ power cycle technology and current status of research and development," *Nuclear Engineering and Technology*, Vol. 47, No. 6, pp. 647–661, 2015. doi:10.1016/j.net.2015.06.009.
- [5] N. A. Carstens, *Control Strategies for Supercritical Carbon Dioxide Power Conversion Systems*, Sc.D. Dissertation, Department of Nuclear Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA, 2007.
- [6] Y. Jeong, S. Son, S. K. Cho, S. Baik, and J. I. Lee, "Evaluation of supercritical CO₂ compressor off-design performance prediction methods," *Energy*, Vol. 213, Article 119071, 2020. doi:10.1016/j.energy.2020.119071.
- [7] Y. Jeong, S. K. Cho, I. W. Son, and J. I. Lee, "Evaluation of off-design scaling methods of

supercritical CO₂ compressor with experimental data,”
Energy, Vol. 278, Article 127730, 2023.
doi:10.1016/j.energy.2023.127730.

[8] T. Alsawy, M. L. Elsayed, R. H. Mohammed, and O. Mesalhy, “Accuracy assessment of the turbomachinery performance maps correction models used in dynamic characteristics of supercritical CO₂ Brayton power cycle,” Energy, Vol. 309, Article 133112, 2024.
doi:10.1016/j.energy.2024.133112.

[9] G. Kim, et al. "Study of sCO₂ System Compressor Inlet Temperature Control Strategy for Marine Propulsion." The International Supercritical CO₂ Energy Technologies Symposium, Pittsburgh, PA, USA. 2026.