Compressor Off-design Performance Prediction with the Similitude Concept for Supercritical CO_2 Cooled Small Modular Reactor

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1. Introduction

The demand for electricity has been steadily increasing over a century due to global industrial expansion. In the response to this trend, the capacities of power plants have been escalated. Subsequently, the researchers in nuclear power area have pursued the development of large size nuclear power plants. This movement resulted in centralization of power generation. However, nowadays, the market demands different kinds of characteristics from power plant. That is, a small scale power system with the feature of load following to accommodate the fluctuation in the electricity grid and diversify energy mix.

Therefore, nuclear industry came up with the idea of small modular reactor (SMR) and many researches are in progress. There are many issues to develop an SMR. One of the issues can be the selection of a power conversion cycle. Conventionally, the majority of nuclear power plants worldwide adopted a steam Rankin cycle, which has proven its efficiency and safety very well over the decades. However, because of its nature, the components of stream Rankine cycle tend to be large, and so is the system size.

One possible solution is to adopt the supercritical CO_2 (S-CO_2) Brayton cycle [1]. On the contrast to most Brayton cycles, the cycle operates with supercritical phase CO_2. S-CO_2 has liquid like density and gas like viscosity. Especially, if compression process occurs near the critical point, the compression work can be greatly reduced, due to the highly non-linear thermodynamics property changes including a reduced compressibility. Also, this cycle can deploy a compact turbomachinery from gas turbine technology. In other words, it may be possible to develop an SMR with high specific power and efficiency. Such example of an SMR using S-CO_2 power cycle is KAIST-MMR [2].

When the design of a system is complete, it is essential to observe the off-design performance for the safe operation of a nuclear power plant. For a system off-design analysis, component level off-design analysis is a prerequisite. One difficulty arises in an S-CO_2 compressor. Since the compressor works near the critical point, the validity of ideal gas base off-design performance model is in question. Hence, in this paper, the compressor off-design performance prediction methods are evaluated and the need to develop a new model for S-CO_2 compressors are proposed.

2. Methods and Results

Off-design operation of a compressor mostly means predicting the efficiency and pressure ratio with respect to off-design mass flow rate, rpm, inlet temperature and pressure. It might be very difficult or impractical to implement the iterations for four variables in a system code.

Instead, the concept of corrected mass flow rate and corrected rpm was originated from the similitude and widely utilized [3]. Specifically, compressor performances such as efficiency and pressure ratio are calculated according to various mass flow rates and rpms with the design point inlet temperature and pressure. To consider the varying inlet temperature and pressure ratio, similitude model converts those changes into mass flow rate and rpm. This is the concept of corrected mass flow rate and corrected rpm.

There exist several similitude models as shown in table 1 [4-6]. However, most of the models were proposed for air condition and not thoroughly evaluated for the S-CO_2 compressor application. To evaluate the accuracy of existing models, 1D-meanline code KAIST-TMD [7], developed by KAIST research team, was used. For comparison, performances of air and S-CO_2 compressors were calculated, and their results were summarized.

Table 1. Correction parameters for each model

	Mass parameter	rpm parameter	Head parameter
IG	$\frac{\dot{m}\sqrt{\gamma RT}}{\gamma P}$	$\frac{N}{\sqrt{\gamma RT}}$	$\frac{\Delta H}{\gamma RT}$
IGZ	$\frac{\dot{m}\sqrt{\gamma RZT}}{\gamma P}$	$\frac{N}{\sqrt{\gamma RZT}}$	$\frac{\Delta H}{\gamma ZRT}$
BNI	$\frac{\dot{m}\sqrt{\gamma RZ_{cr}T_{cr}}}{\gamma P_{cr}}$	$\frac{N}{\sqrt{\gamma RZ_{cr}T_{cr}}}$	$\frac{\Delta H}{\gamma RZ_{cr}T_{cr}}$
Glassman	$\frac{\dot{m}V_{cr}}{P\gamma\left(\frac{2}{\gamma+1}\right)^{\gamma/(\gamma-1)}}$	$\frac{N}{V_{cr}}$	$\frac{\Delta H}{V_{cr}^2}$
CEA	$\frac{\dot{m}\sqrt{n_s RZT}}{n_s P}$	$\frac{N}{\sqrt{n_s RZT}}$	$\frac{\Delta H}{n_s RZT}$

2.1 S-CO_2 compressor case

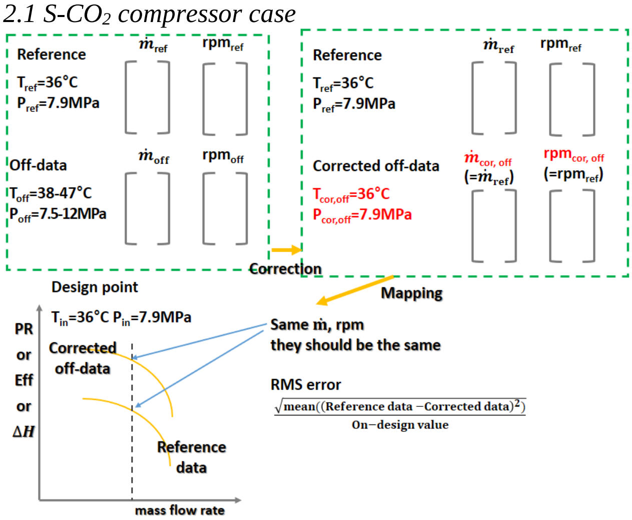

Figure 1. Correction and mapping procedure diagram

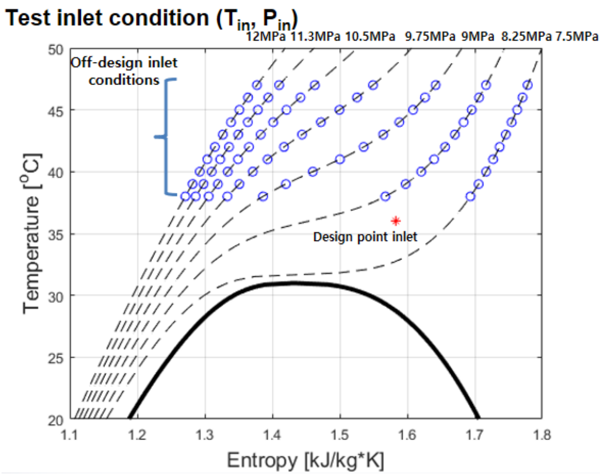

Figure 2. Test off-design inlet condition

Table 2. Design point inlet condition

Design point			
T (°C)	36	*ρ (kg/m³)*	329.4
P (MPa)	7.92	*γ*	9.0
m (kg/s)	129.14	*Z*	0.41
rpm(rev/min)	15000	*n_s*	1.54

Table 3. Range of studied inlet condition

	min	*max*	*resolution*
T (°C)	38	47	10
P (MPa)	7.5	12	7
rpm(rev/min)	4500	16500	9

To evaluate the accuracy of correction models, an example compressor was designed first and its performance was calculated with respect to various mass flow rate and rpm, but with design inlet temperature and pressure. Next, arbitrary off-design inlet conditions (temperature, pressure) were prescribed as shown in Fig 2 and Table 3. Additionally, their performance were calculated so that the off-design performance can be corrected into the design inlet condition (temperature, pressure). The detailed correction procedure is shown in Fig 1. The implication of this method is that it is possible to predict the compressor performance at design inlet temperature and pressure with off-design inlet temperature and pressure data. However, since the similitude does not always hold perfectly, discrepancies occur. For example, in Figs. 3 and 4, the red lines indicate the performance of design point inlet condition data, and the black lines indicate the off-design inlet condition data which originally has 45°C and 9MPa, but converted into 36°C and 7.9MPa to predict the design point performance. Because of the imperfect similitude, the error occurs, otherwise the red and black lines should be overlapped precisely.

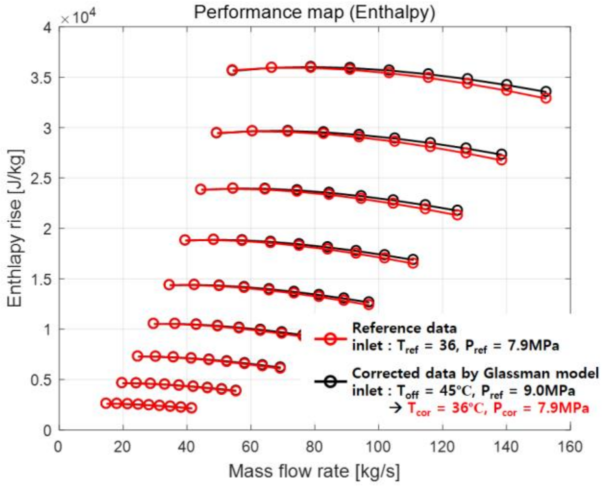

Figure 3. Performance comparison example (Enthalpy rise)

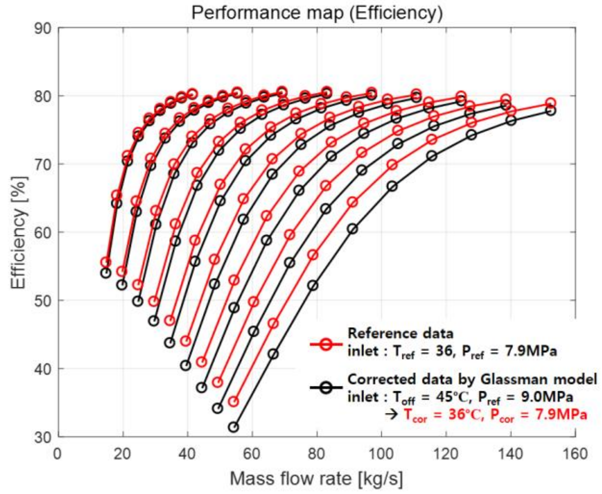

Figure 4. Performance comparison example (Efficiency)

As mentioned above, there are several models for correction. Thus, for the inlet conditions in Table 3, the discrepancies were quantified as a normalized RMS. The results were summarized in Table 4. Overall, the prediction using enthalpy rise showed more accurate prediction than pressure ratio. Especially, IGZ and CEA models have superior accuracy. Efficiency prediction has approximately 10% errors, which is higher error than enthalpy rise.

Table 4. Performance discrepancy error (normalized RMS error) summary (unit : [%])

	PR error	Eff error	ΔH error	PR error (PR by ΔH)
IG	19.7	13.6	7.16	3.46
IGZ	20.2	8.8	2.04	1.24
BNI	8.24	12.5	10.1	3.56
Glassman	9.9	15.1	9.04	3.83
CEA	48.0	9.63	2.83	1.27

2.2 Air compressor case

Table 5. Design point inlet condition

Design point			
T (°C)	20.3	ρ (kg/m³)	1.266
P (MPa)	7	γ	1.4
m (kg/s)	129.14	Z	1
rpm(rev/min)	15000	n_s	1.4

Table 6. Range of studied inlet condition

	min	max	resolution
T (°C)	15	40	6
P (MPa)	75	250	8
rpm(rev/min)	3300	12100	9

Table 7. Performance discrepancy error (normalized RMS error) summary (unit : [%])

	PR error	Eff error	ΔH error	PR error (PR by ΔH)
IG	0.493	0.778	0.753	0.459
IGZ	0.522	0.773	0.805	0.493
BNI	0.462	0.773	0.747	0.456
Glassman	0.471	0.782	0.750	0.457
CEA	0.475	0.774	0.750	0.457

To compare the correction model accuracy for S-CO_2 and air environment, the same procedure for an air compressor was performed as in section 2.1. Design and off-design conditions were tabulated in Tables 5 and 6. The results are summarized in Table 7. The air compressor results showed less than 1% error for all indicators. Noticeably, regardless of the models, the results displayed almost the same accuracy.

3. Summary and Conclusions

To ensure the safe operation of an SMR with the S-CO_2 power cycle, the compressor off-design performance prediction method derived from similitude analysis was investigated. Among existing models, five models were selected and their prediction accuracies were tested with 1D meanline code, KAIST-TMD. For comparison, both air and S-CO_2 cases were calculated. In case of an air compressor, all the correction methods show an equal level of accuracies with high fidelity to the direct performance prediction. However, the errors for an S-CO_2 case were uneven up to the similitude models. Moreover, the overall values are noticeably larger than the air case. In conclusion, applying the existing similitude correction models, developed under air conditions, to the off-design performance prediction of an S-CO_2 compressor may result in significant errors. Consequently, the cause of errors should be studied and a new model needs to be developed for an S-CO_2 compressor.

4. Acknowledgement

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