Pressure Ratio and Enthalpy Rise as Performance Indicators for S-CO_2 Compressor based on Similitude

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1. Introduction

A supercritical CO_2 (S-CO_2) power cycle is a variation of gas Brayton cycle. A gas Brayton cycle utilizes mainly air as a working fluid, but the S-CO_2 power cycle uses supercritical state CO_2 instead. One of the characteristics of gas Brayton cycle is compact turbomachinery, which consists of compressor and turbine. However, a compressor in gas Brayton cycle inherently consumes a large portion of expansion work from turbine. On the contrary, S-CO_2 compressor has a minimized compression work due to the reduced compressibility near the critical point [1].

Current nuclear power plants mostly adopt a steam Rankine cycle for power conversion system. In the steam Rankine cycle, phase change from water to steam occurs, and the steam drives turbine with substantially increased volume. Thus, the size of steam turbine is usually much larger than that of gas turbine, and so is the system overall.

This is why S-CO_2 cycle can be a promising candidate for power conversion system of a small modular reactor (SMR), instead of the steam Rankine cycle. While design and analysis methods for steam-water condition have been investigated over decades and verified, those methods for S-CO_2 condition have not been completed yet. One of those topics is the compressor off-design performance analysis, which is essential to analyze the load following capability of the system and reactor safety. Compressor performance is known as a function of mass flow rate, rpm, inlet temperature and pressure, but it is costly to perform analysis and experiment for these four variables varying independently. Alternatively, the concept of similitude was used, which converts the variation of inlet temperature and pressure into mass flow rate and rpm changes [2]. This is how corrected mass flow rate and rpms are derived. In short, the function can be simplified with two variables, instead of four variables.

Both pressure ratio and enthalpy rise can be used to express compressor performance. However, the similitudes of two performance indicators are not the same. Rather, only under a specific condition, they would mean the same. Previously, the difference between two indicators has been investigated with 1D meanline code, KAIST-TMD [3]. In this paper, the indicators will be compared qualitatively with experimental data in the view point of the similitude.

2. Compressor Test Results

The test loop consists of two control valves, a turbo-alternator-compressor (TAC) as shown in Fig 1. To control thrust force and impose flow resistance, the valves are located at the inlet and outlet of the compressor. For compressor testing, turbine impeller was eliminated temporarily. The design condition of compressor is summarized in Table 1. Table 2 shows the test conditions, and the results are presented in Figs 2-7.

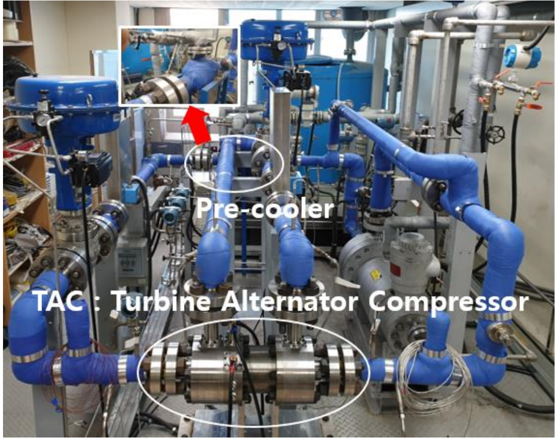

Fig. 1. P&ID of S-CO_2 experiment facility [4]

Table 1. Design condition of S-CO_2 compressor [4]

	Centrifugal Compressor
Specific speed	0.65
Pressure ratio	1.29
Inlet temperature	31.4 °C
Inlet pressure	7.60 MPa
Efficiency	56 %
Mass flow rate	3 kg/s
Design speed	40,000 rpm
Impeller type	Unshrouded impeller
DN factor	1,560,000
Bearing type	Agular contact ball bearing

Table 2. Compressor test conditions summary

	T (℃)	P (MPa)	RPM
Reference	31.17	7.59	32000,36000, 40000
Condition 1	34.3	8.3	32110, 36124
Condition 2	38.5	8	32000,36000, 38758

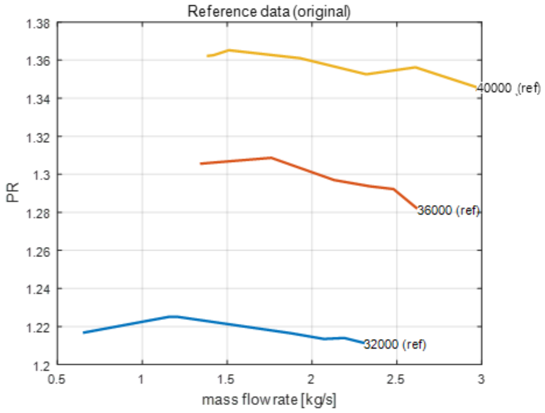

Fig. 2. Pressure ratio at reference condition

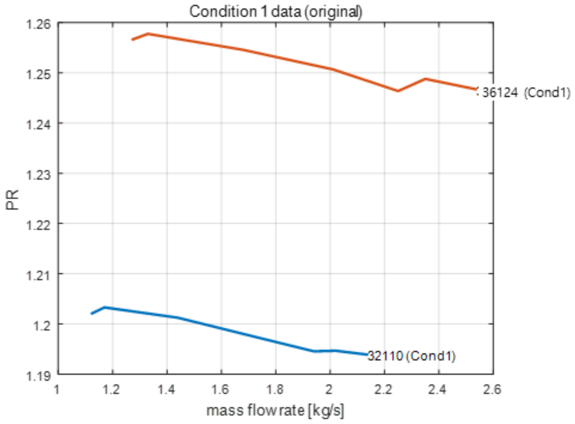

Fig. 3. Pressure ratio at condition 1

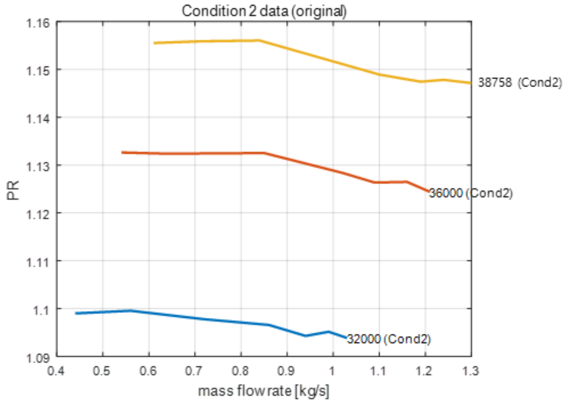

Fig. 4. Pressure ratio at condition 2

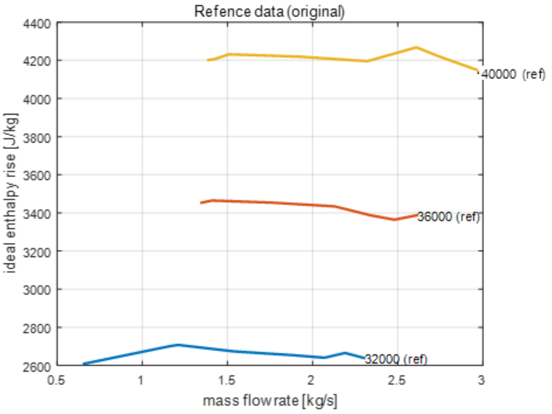

Fig. 5. Enthalpy rise at reference condition

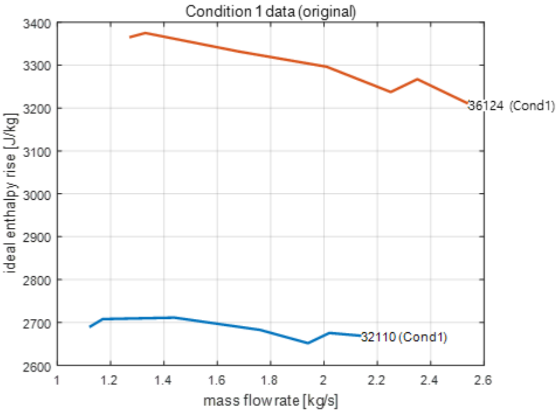

Fig. 6. Enthalpy rise at condition 1

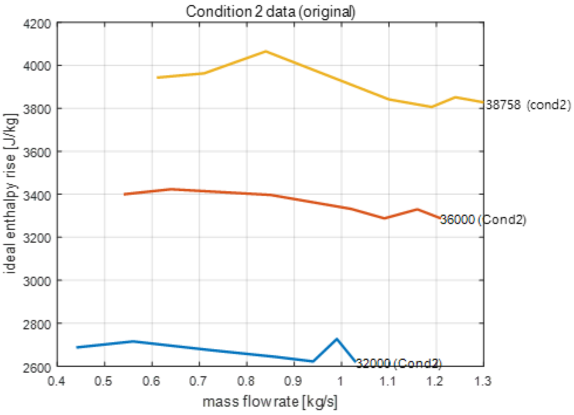

Fig. 7. Enthalpy rise at condition 2

3. Similitude Model

The concept of corrected mass flow rate and rpm reduces the complexity for measuring compressor performance. The concept has been widely used for air condition, and several modifications have been made to reflect a real gas effect deviating from ideal gas assumption. Five models from the open literatures have been collected and presented in Table 3. If the models work perfectly, their head parameters and pressure ratios should be the same, when flow parameters and speed parameters at two different operating conditions are the same. For example, in case of IG model, equations (1) - (3) hold.

$$\mathrm{Fn}\left(\frac{\dot{m}\sqrt{\gamma RT}}{\gamma P}, \frac{N}{\sqrt{\gamma RT}}\right) = \frac{\Delta H}{\gamma RT}, \mathrm{PR} \qquad (1)$$

$$\dot{\mathrm{m}}_{\mathrm{cor}} = \dot{\mathrm{m}}_{\mathrm{off}}\left(\frac{\mathrm{P}_{\mathrm{in,cor}}}{\mathrm{P}_{\mathrm{in,off}}}\right)\sqrt{\frac{\mathrm{T}_{\mathrm{in,off}}}{\mathrm{T}_{\mathrm{in,cor}}}}\sqrt{\frac{\gamma_{\mathrm{cor}}}{\gamma_{\mathrm{off}}}} \qquad (2)$$

$$\mathrm{N}_{\mathrm{cor}} = \mathrm{N}_{\mathrm{off}}\sqrt{\frac{\mathrm{T}_{\mathrm{in,off}}}{\mathrm{T}_{\mathrm{in.cor}}}}\sqrt{\frac{\gamma_{\mathrm{off}}}{\gamma_{\mathrm{cor}}}} \qquad (3)$$

Table 3. Summary of parameters for existing similitude models [3]

	Flow parameter	**Speed parameter**	**Head parameter**	**Pressure Ratio**
IG	$\frac{\dot{m}\sqrt{\gamma RT}}{\gamma P}$	$\frac{N}{\sqrt{\gamma RT}}$	$\frac{\Delta H}{\gamma RT}$	PR
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	$\frac{\dot{m}\sqrt{n_s ZRT}}{n_s P}$	$\frac{N}{\sqrt{n_s ZRT}}$	$\frac{\Delta H}{n_s ZRT}$	

N:rpm, R:gas constant, T:temperature, P:pressure, Z:compressibility factor, m:mass flow rate, $_{cr}$:critical(sonic), n_s:isentropic exponent, γ:specific heat ratio

In Table 3, one might think that using head parameters and pressure ratio at the same time are redundant since enthalpy rise and pressure ratio are interchangeable quantities thermodynamically. Although head paramters and pressure ratio seem similar in meaning, they are different in terms of the simlitude. Therefore, it would be better to choose one parameter over the other. To make comparison between them, compressor performance data can be used qualitatively. Enthalpy rise and pressure ratio of compressor tend to proportionately increase according to the rise of rpm, as shown in Figs 2-7. In other words, contradiction against this trend can be used to exclude an inappropriate parameter.

4. Comparison Results

In Table 2, three sets of data have different inlet temperatures and pressures, but conditions 1 and 2 data can be converted to have the same inlet temperature and pressure with the reference condition, assuming the simlitude works. For conversion, Pham model was selected. As a result, data in Figs 3 and 4 are combined into Fig 2, and data in Figs 6 and 7 are combined into Fig 5. Then, Figs 8 and 9 are produced.

In Fig 8, the reference and condition 1 data show larger pressure ratio as rpm increases, but condition 2 data do not. In contrast, enthalpy rise in Fig 9 show continnous increase as rpm increase. Furthermore, the data whose rpms are similar appear to have similar enthalpy rises. This observation implies enthalpy rise should be used with the simlitude.

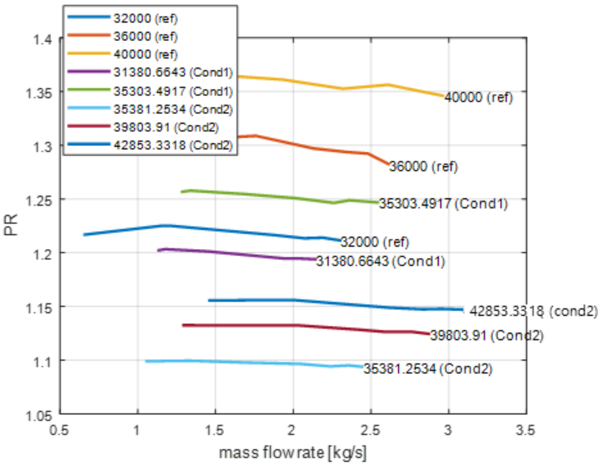

Fig. 8. Pressure ratio with converted data

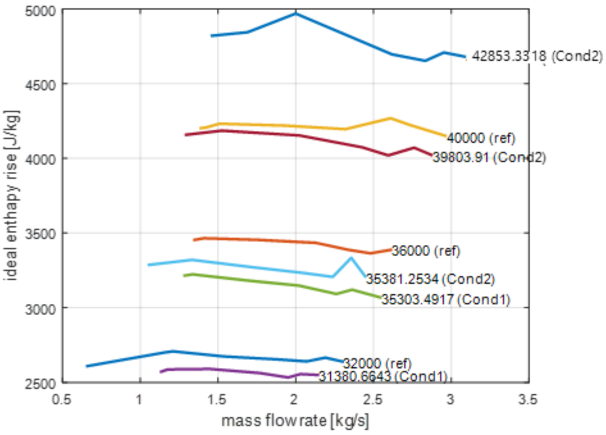

Fig. 9. Enthalpy rise with converted data

The similitude of pressure ratio indicates equation (2), but that of enthalpy rise means equation (5). Equation (5) can be manipulated to equation (9) through equations (6)-(8). The values of equations (4) and (9) may be the same in ideal gas cases, where the thermodynamic property does not change greatly. The derivation in equations (10)-(13) implies that when specific heat ratio is constant, the values of equations (4) and (9) can be the same.

$$\mathrm{PR}_{\mathrm{cor}} = \mathrm{PR}_{\mathrm{off}} \qquad (4)$$

$$\left(\frac{\Delta \mathrm{H}}{\gamma \mathrm{RT}}\right)_{\mathrm{cor}} = \left(\frac{\Delta \mathrm{H}}{\gamma \mathrm{RT}}\right)_{\mathrm{off}} \qquad (5)$$

$$\Delta \mathrm{H}_{\mathrm{cor}} = (\gamma \mathrm{RT})_{\mathrm{cor}} \left(\frac{\Delta \mathrm{H}}{\gamma \mathrm{RT}}\right)_{\mathrm{off}} \tag{6}$$

$$\mathrm{H}_{\mathrm{out,isen}} = \mathrm{H}_{\mathrm{in}} + \Delta \mathrm{H}_{\mathrm{cor}} \tag{7}$$

$$\mathrm{P}_{\mathrm{out}} = \mathrm{fn}(\mathrm{S}_{\mathrm{in}}, \mathrm{H}_{\mathrm{out,isen}}) \tag{8}$$

$$\mathrm{PR} = \mathrm{P}_{\mathrm{out}}/\mathrm{P}_{\mathrm{in}} \tag{9}$$

$$\frac{\mathrm{T}_{\mathrm{out}}}{\mathrm{T}_{\mathrm{in}}} = \left(\frac{\mathrm{P}_{\mathrm{out}}}{\mathrm{P}_{\mathrm{in}}}\right)^{(\gamma-1)/\gamma} \tag{10}$$

$$\mathrm{C}_{\mathrm{P}} = \frac{\gamma \mathrm{R}}{\gamma-1} \tag{11}$$

$$\begin{aligned} \Delta \mathrm{H} &= \mathrm{H}_{\mathrm{out}} - \mathrm{H}_{\mathrm{in}} = \mathrm{C}_{\mathrm{P}}(\mathrm{T}_{\mathrm{out}} - \mathrm{T}_{\mathrm{in}}) \\ &= \mathrm{C}_{\mathrm{P}}\mathrm{T}_{\mathrm{in}}\left(\frac{\mathrm{T}_{\mathrm{out}}}{\mathrm{T}_{\mathrm{in}}} - 1\right) \\ &= \frac{\gamma}{\gamma-1}\mathrm{RT}_{\mathrm{in}}\left(\left(\frac{\mathrm{P}_{\mathrm{out}}}{\mathrm{P}_{\mathrm{in}}}\right)^{(\gamma-1)/\gamma} - 1\right) \end{aligned} \tag{12}$$

$$\begin{aligned} \frac{\Delta \mathrm{H}}{\gamma \mathrm{RT}_{\mathrm{in}}} &= \frac{1}{\gamma-1}\left(\left(\frac{\mathrm{P}_{\mathrm{out}}}{\mathrm{P}_{\mathrm{in}}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right) \\ &= \mathrm{fn}(\mathrm{P}_{\mathrm{out}}/\mathrm{P}_{\mathrm{in}}) \end{aligned} \tag{13}$$

5. Summary and Conclusion

S-CO$_2$ power cycle is one of the candidates for power conversion system of SMR. While design and analysis methods for steam Rankine cycle have been well investigated, those of S-CO$_2$ cycle need to be further developed. One of those topics is an S-CO$_2$ compressor off-design performance prediction. To simplify the prediction, the concept of corrected mass flow rate and rpm can be adopted with the similitude analysis. Either pressure ratio or enthalpy rise should be used to express compressor performance based on the similitude. To compare these two performance indicators in the view point of the similitude, three sets of compressor testing data were used qualitatively in this paper. As a result, the observation implies that enthalpy rise should be used instead of pressure ratio.

Acknowledgement

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REFERENCES

[1] Ahn, Yoonhan, et al. "Review of supercritical CO2 power cycle technology and current status of research and development." Nuclear Engineering and Technology 47.6 (2015): 647-661.

[2] Saravanamuttoo, H. I., Rogers, G. F. C., & Cohen, H. (2001). Gas turbine theory. Pearson Education.

[3] 정용주, et al. "Similitude models for turbine off-design performance prediction under supercritical CO2 condition." 2019 KNS 추계학술발표회. 한국원자력학회, 2019.

[4] 조성국, 정용주, and 이정익. "S-CO2 Compressor Performance Test Plan Considering Measurement Accuracy." 2019 한국원자력학회 추계학술발표회. 한국원자력학회, 2019.