Pressure Ratio and Enthalpy Rise as Performance Indicators for $S\text{-}CO_2$ Compressor based on Similitude

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Introduction

▣ A supercritical CO_2 power cycle is a variation of gas Brayton cycle with a reduced compression work and compact layout

▣ It is possible to apply S-CO2 power cycle to small modular reactor due to its compactness

▣ While analysis methods for steam-water condition have been investigated over decades and verified, those methods for $S\text{-}CO_2$ condition have not been completed

▣ One of those topics is the compressor off-design performance analysis, which is essential to analyze the load following capabilities of the system and reactor safety

▣ Compressor performance is known as a function of mass flow rate, rpm, inlet temperature and pressure. Because of the effort and time for four variable experiment, the concept of similitude was used

▣ The variation of inlet temperature and pressure can be converted into the variation of mass flow rate and rpm. In short, the function can be simplified with two variables, instead of four variables

Concept of Similitude Models

	Flow parameter	Speed parameter	Head parameter	Pressure parameter
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	$\frac{\dot{m}\sqrt{n_s ZRT}}{n_s P}$	$\frac{N}{\sqrt{n_s ZRT}}$	$\frac{\Delta H}{n_s ZRT}$	

▲ *Summary of parameters for existing similitude models*

▣ When two operating conditions have the same flow parameters and speed parameters, the performance parameters such as head parameter and pressure ratio should be the same according to the model

$fn(D, N, m, P_{in}, T_{in}, R, \gamma, \mu) = P_{out}, T_{out}, \Delta H$ (IG model)

$\rightarrow fn\left(\frac{\dot{m}\sqrt{\gamma RT_{in}}}{\gamma P_{in}}, \frac{N}{\sqrt{\gamma RT_{in}}}\right) = PR, \frac{\Delta H}{\gamma RT_{in}}, \eta$; corrected mass flow & rpm

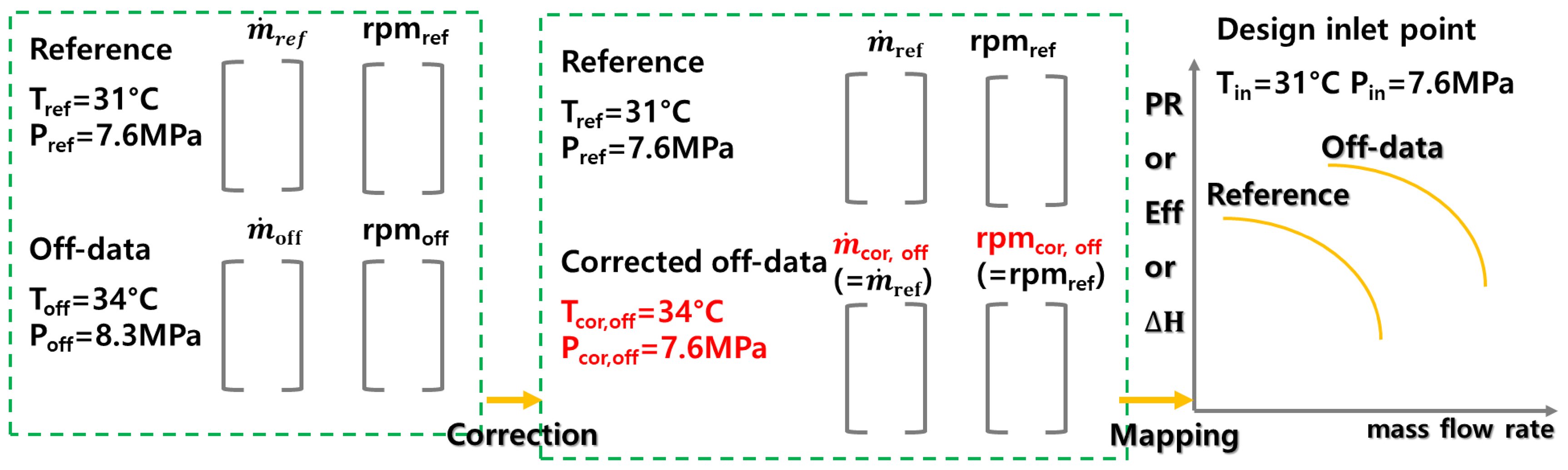
▣ Both pressure ratio and enthalpy rise can be used to express compressor performance. However, the similitudes of two performance indicators are not the same. In this paper, the differences between these two parameters are compared through a experiment

Experiment Facility

▲ *Bird view of the experiment facility*

	Design condition
Specific speed	0.65
Pressure ratio	1.29
Inlet Temperature	31.4 ℃
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

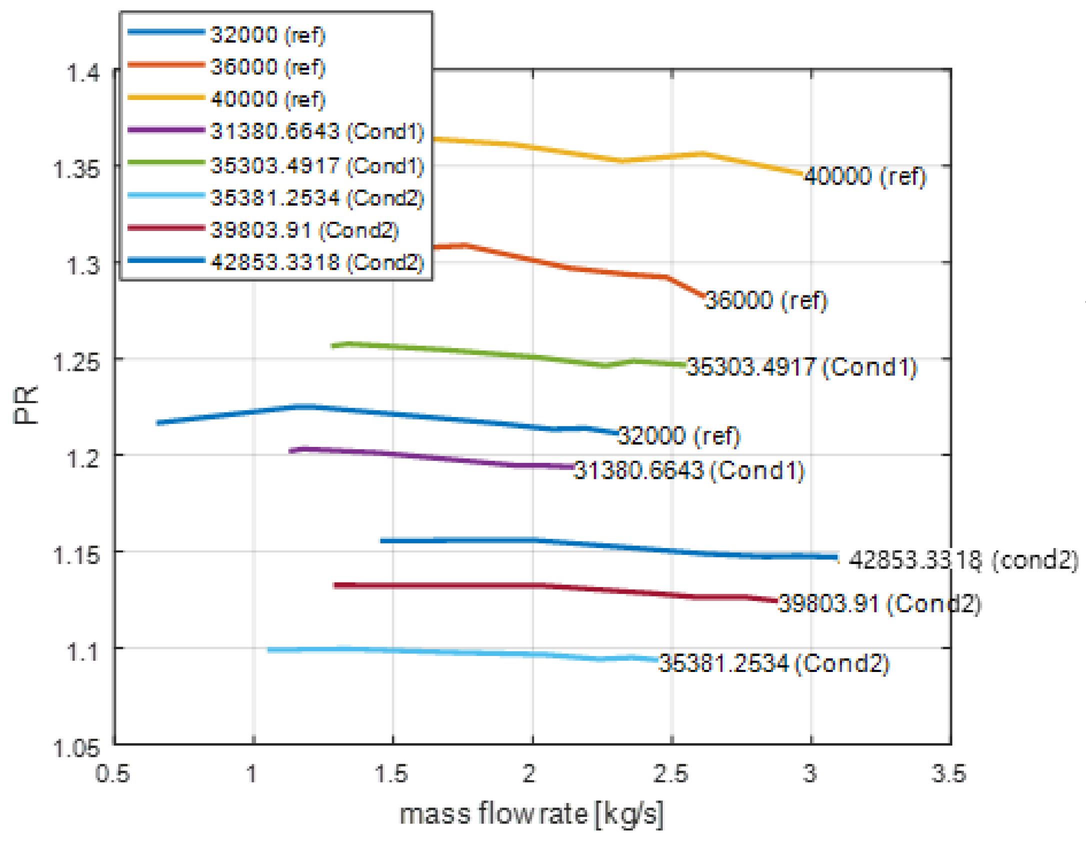
Results and Discussion



▲ *Summary of conversion process for off-design data*

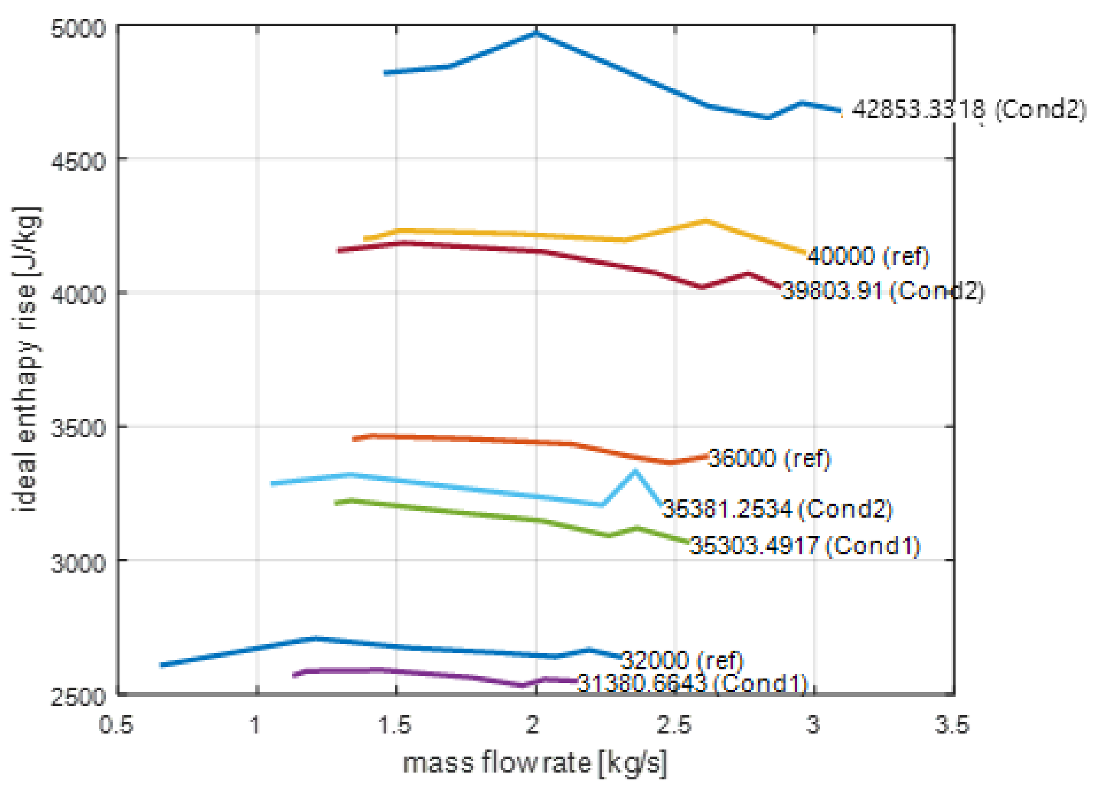
▣ Compressor performance data obtained at different inlet conditions are converted into reference inlet condition data with Pham model as below

	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



▣ The pressure ratio and enthalpy rise of compressor normally tend to increase as rpm rise

▣ In pressure ratio case, condition 2 data do not follow the above-mentioned trend



▣ Enthalpy rise case shows the continuous increase as rpm rise

▣ This observation can imply enthalpy rise should be used with the similitude

▲ *Converted performance data at reference inlet condition*

$$PR_{cor} = PR_{off} \quad \text{<------------ (a)}$$

$$\left(\frac{\Delta H}{\gamma RT}\right)_{cor} = \left(\frac{\Delta H}{\gamma RT}\right)_{off} \quad \text{<------ (b)}$$

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

$$H_{out,isen} = H_{in} + \Delta H_{cor}$$

$$P_{out} = fn(S_{in}, H_{out,isen})$$

$$PR = P_{out}/P_{in} \quad \text{<------------ (c)}$$

$$\frac{T_{out}}{T_{in}} = \left(\frac{P_{out}}{P_{in}}\right)^{(\gamma-1)/\gamma}, \quad C_P = \frac{\gamma R}{\gamma-1}$$

$$\Delta H = H_{out} - H_{in} = C_P(T_{out} - T_{in})$$

$$= C_P T_{in}\left(\frac{T_{out}}{T_{in}} - 1\right)$$

$$= \frac{\gamma}{\gamma-1} RT_{in}\left(\left(\frac{P_{out}}{P_{in}}\right)^{(\gamma-1)/\gamma} - 1\right)$$

$$\frac{\Delta H}{\gamma RT_{in}} = \frac{1}{\gamma-1}\left(\left(\frac{P_{out}}{P_{in}}\right)^{\frac{\gamma-1}{\gamma}} - 1\right)$$

$$= fn(P_{out}/P_{in}) \quad \text{<----------------- (d)}$$

▣ The similitude of pressure ratio indicates equation (a), but that of enthalpy rise means equation (b). Equation (b) can be manipulated to equation (c). The values of equation (a) and (c) may be the same in ideal gas cases, where thermodynamic property does not change greatly.

▣ The derivation of equation (d) implies that when specific heat ratio is constant, the values of equation (a) and (c) can be the same, which is not correct for $S\text{-}CO_2$

▣ In conclusion, it is more likely that enthalpy rise should be used instead of pressure for off-design analysis