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A study of surge prediction correction for S-CO_2 compressor

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1. Introduction

A large-scale nuclear power plant has served as a base-load electricity generator for decades. The power plant can produce a large amount of electricity economically, but it is challenging to operate in load-following mode when the power plant is already designed for the base load service. In contrast, a small modular reactor (SMR) can be utilized to cope with intermittency issues of renewable energy, due to better load following capability.

Choosing a proper power cycle for thermodynamic energy conversion is equally important to which energy source we will be using. A Supercritical CO_2 (S-CO_2) Brayton cycle can be a potential power conversion cycle for SMRs due to high efficiency and compact layout [1]. S-CO_2 cycle uses gas turbine technology like gas Brayton cycle but with a reduced compression work due to high density, which is attributed to dramatic property changes near the critical point.

To develop an SMR coupled with S-CO_2 cycle, it is necessary to conduct a system level performance analysis. For this reason, GAMMA+ code was modified in KAIST [2]. The use of turbomachinery performance map was introduced with a similitude model used for an air compressor. The validity of the similitude model was studied for normal operation of an S-CO_2 compressor previously [3]. However, the validity of surge prediction with the similitude model has not been investigated yet.

Surge is a fluid dynamic instability caused by flow separation in a compressor as shown. Fig 2 shows how separation destabilize flow in compressor. In Stable operating condition, fluid flows like blue line. However, as mass flow is reduced, fluid flows like red line with constant rotating speed, which means a large incidence angle. This large incidence angle causes separation, and this instability affect whole fluid field in compressor. This is compressor surge phenomenon. Fluid flow during surge induces vibration and noise in compressor. In extreme case, flow can be reversed and the system can be severely damaged.

While an S-CO_2 compressor in an SMR operates in load-following mode, the safety of a nuclear power plant must be guaranteed as well. Therefore, it is natural to consider surge phenomenon in system level analysis for all scenarios. For this reason, this study intends to confirm and develop a proper surge prediction correction method due to inlet conditions changing from the design conditions during operation.

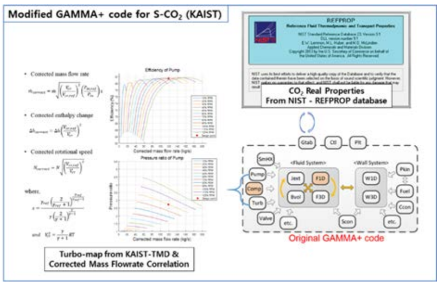

Fig. 1. Organization of Modified GAMMA+ [2]

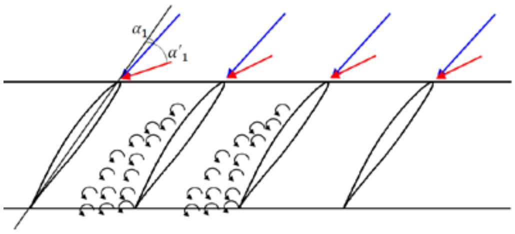

Fig. 2. Schematic diagram of compressor surge mechanism

2. Methods and Results

2.1 Similitude models

It is general to present the performance of compressor in the form of a performance map. A compressor performance map shows pressure ratio (head rise) variation with respect to mass flow rate for multiple constant rotational speed lines as shown in Fig 3. The underlying assumption for the performance map is that the compressor inlet condition is at design point (temperature, pressure). However, naturally a compressor often operates at different inlet condition from the design condition.

A similitude model was adopted to cover the variation of compressor inlet condition. The concept is that variations of inlet temperature and pressure are reflected in the corrected rotational speed and mass flow rate, which is based on dimensional analysis of compressor thermodynamic variables [3]. For the same flow parameter and the speed parameter, the model produces the same head parameter as shown in equations (1) – (4). The validity of the model for normal operation was studied for an S-CO_2 compressor previously [3], but surge was not investigated whether the surge limit can be corrected with the same similitude model or not.

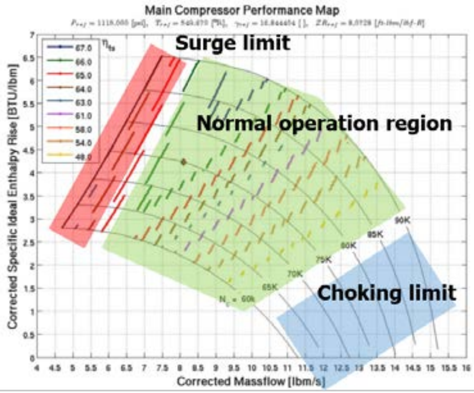

Fig. 3. Example of compressor performance map

$$fn(\Pi_1, \Pi_2) = \Pi_3 \quad (1)$$

$$\Pi_1 = \frac{\dot{m}\sqrt{n_s ZRT}}{n_s P};\, Flow\ parameter \quad (2)$$

$$\Pi_2 = \frac{N}{\sqrt{n_s ZRT}}\ ;\ Speed\ parameter \quad (3)$$

$$\Pi_3 = \frac{\Delta H}{n_s ZRT};\ Head\ parameter \quad (4)$$

2.2 Experimental setup

To confirm validity of surge limit correction, experimental data is used. There are a few experimental facilities with data. For this study, the data from SCIEL(KAERI) [4] and SCO_2PE(KAIST) [5] were used. SCIEL compressor is a double suction type compressor with a shrouded impeller. SCO_2PE compressor is a Turbo-Alternator-Compressor as shown, and turbine was temporarily removed for the compressor testing. The two compressors are shown in Fig 4. SCO_2PE utilized an unshrouded impeller with two backswept angles (-50°, -70°) as shown in Fig 5.

Fig. 4. SCIEL compressor in KAERI (left) [4]
SCO_2PE compressor in KAIST (right) [5]

Fig. 5. Different backswept impellers for SCO_2PE compressor

2.3 Non-dimensionalized experiment data

SCIEL compressor was tested at two different inlet conditions. These two conditions are relatively close and have similar thermodynamic properties as shown in Table 2. Fig 6 shows non-dimensionalized performance map for the SCIEL compressor. X axis and Y axis indicate non-dimensionalized mass and enthalpy rise, respectively. The values next to solid lines are non-dimensionalized rotational speed. Dashed bold lines mean surge limit. Different colors tell that these lines have different inlet conditions. The inlet condition close to the critical point are named as reference condition.

Surge limits from two inlet conditions overlap quite well in Fig 6, which means the similitude holds and no additional correction is needed. Figs. 7 and 8 are performance maps for -50° and -70° backsweep angle impellers, respectively. Their operating conditions are tabulated in Tables 3 and 4. Surge limits in the data does not appear to be overlapping with each other. This disagreement implies the necessity for additional correction model. Unlike Fig. 6, these two cases have relatively large inlet property variations. These variations are presumed to be the cause of disagreement in surge limits.

Although current experiment data presents the necessity for additional correction method to cover property variations of S-CO_2, it is early to suggest how surge limit can be corrected. Therefore, a supplementary experiment will be conducted in the future.

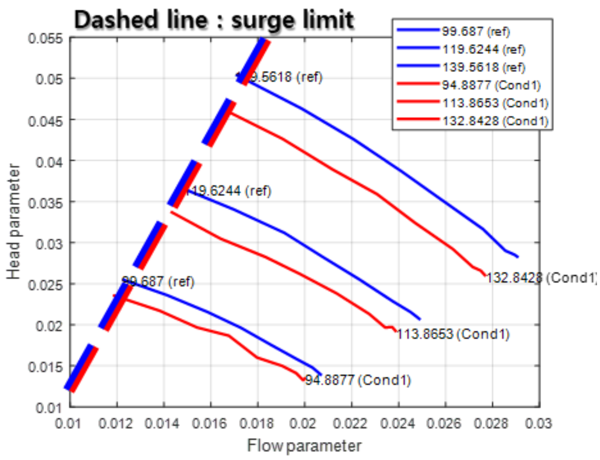

Fig. 6. Non-dimensionalized performance map of SCIEL compressor

Table 2. Summary of operating point (SCIEL)

	Ref	Cond 1
T (°C)	36	40
P (MPa)	7.6	7.8
ρ (kg/m³)	274.05	251.14
γ	5.41	3.88
Z	0.47	0.52
n_s	1.44	1.42
RPM	25000, 30000, 35000	

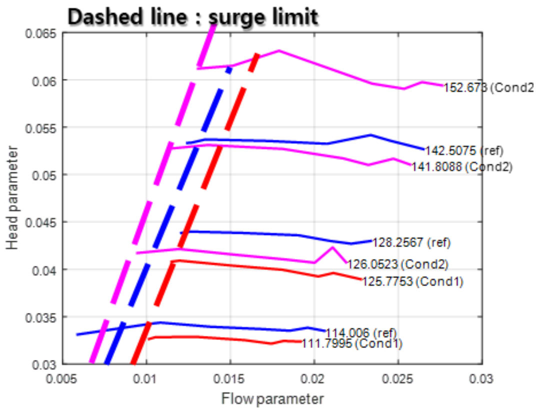

Fig. 7. Non-dimensionalized performance map of SCO_2PE compressor (50^o)

Table 3. Summary of operating point (SCO_2PE, 50^o)

	Ref	Cond 1	Cond 2
T (°C)	31	35	40
P (MPa)	7.6	8.3	8
ρ (kg/m³)	625	608	290
γ	10.27	8.89	5.46
Z	0.21	0.24	0.46
n_s	4.13	3.84	1.49
RPM	32000, 36000, 40000	32110, 36124	32000, 36000, 38758

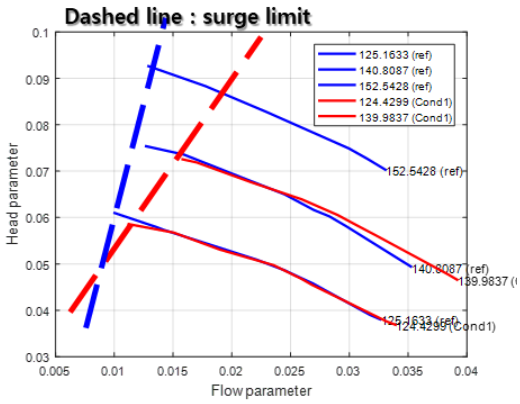

Fig. 8. Non-dimensionalized performance map of SCO_2PE compressor (70^o)

Table 4. Summary of operating point (SCO_2PE, 70^o)

	Ref	Case 1
T (°C)	31.5	40
P (MPa)	7.6	8
ρ (kg/m³)	595	280
γ	14.85	4.89
Z	0.222	0.484
n_s	3.26	1.47
RPM	32000, 36000, 39000	32000, 36000

3. Summary and Conclusions

Nowadays, a small modular reactor is drawing attention to cope with the intermittency problem of renewable energy in the grid. S-CO_2 power cycle can be a power conversion system for SMR because of its high efficiency and compactness. For load-following capability of nuclear power plant, compressor should operate at various inlet conditions. This requires not only performance prediction for normal operation, but also surge limit prediction to evaluate how much operational margin is left in the system. In prior research, performance prediction for normal operation was conducted. In this paper, experimental data was processed to confirm the validity of surge limit prediction with similitude model. The results suggest the necessity of an additional correction for predicting the surge limit. In the future, complementary experiment will be conducted, and an additional correction model will be developed.

ACKNOWLEDGEMENTS

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