Study of non-dimensional number analysis for the conceptual design of S-CO_2 compressor

Seong Kuk Cho [a], Jekyoung Lee [b], Yongju Jeong [a], Jeong Ik Lee [a*]
[a] *Dept. Nuclear & Quantum Eng., KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea*
[b] *Jinsol Turbo Machinery, 94-17, Techno 2-ro, Yuseong-gu, Daejeon, 34014, Republic of Korea*
[*] *Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

The necessity of the next generation nuclear reactors has been constantly brought up because of the global warming, reprocessing the spent nuclear fuel, and improving the passive safety. A supercritical CO_2 (S-CO_2) Brayton cycle has received attention as the prospective power technology for the next generation nuclear reactors due to high thermal efficiency at relatively moderate turbine inlet temperature (450~650 ^oC), simple cycle layout, compact component volume (i.e. turbomachineries and heat exchangers), and the mitigation of turbine blade erosion compared to the conventional steam Rankine cycle [1]. Despite these advantages, some technical challenges (i.e. compressor operation near the critical point, elementary technologies for the turbomachinery, and system control logics) still have to be resolved for the successful commercialization.

As a part of its efforts, much research on the S-CO_2 compressor, including the system transient analysis and the integral loop experiment, has been performed. The non-dimensional number analysis is very important because it chooses main design parameters for a compressor (i.e. turbomachinery type, rotation speed, the number of stages and diameter). The well-known method is to use the Balje's non-dimensional diagram. Since it is based on constant or linear thermodynamic property variation assumption, the diagram cannot cover the case for non-linear thermodynamic properties' variation of S-CO_2 near the critical point. The existing diagram should be re-confirmed for a S-CO_2 compressor. Thus, this study aims at confirming its feasibility in order to design a reliable S-CO_2 compressor.

2. Methods

To estimate non-dimensional parameters, a turbomachinery design in-house code, namely KAIST-TMD, is utilized in this study. The following paragraphs describe KAIST-TMD and the boundary conditions for the non-dimensional analysis, respectively.

2.1 KAIST-TMD

Many researchers have tried to develop their own codes for the S-CO_2 turbomachinery analysis. Most of these codes utilized the existing commercial codes with minor modifications. Due to this reason many codes have convergence issues near the critical point. KAIST research team tried to develop and integrate radial turbomachinery types using 1D mean stream line method and loss models [2]. The REFPROP thermodynamic property database distributed by NIST is coupled to KAIST-TMD for S-CO_2 real gas properties near the critical point.

The calculation procedure is mainly based on calculating enthalpy and pressure. The reason why enthalpy is chosen over temperature for stage design procedure is because the enthalpy based calculation is more straightforward and has less error for adopting the definition based static to stagnation conversion method directly [2]. Since the relation between stagnation to static is defined with enthalpy and velocity, the enthalpy based calculation procedure is more convenient than the pressure and temperature based calculation. Furthermore, pressure and temperature based stage calculation method cannot be used for the S-CO_2 compressor since ratio of specific heats and specific heat at constant pressure is no longer a constant. Table I summarizes the selected loss models. The loss models are an empirical correlation for irreversibility estimation of a turbomachinery. Since KAIST-TMD is validated with the S-CO_2 compressor experimental data, the design results can be believed to have high fidelity under various different design conditions.

Table I: List of loss models

Loss classification		**Lee's set [2]**
Internal loss	Incidence loss	Conrad
	Blade loading loss	Coppage
	Skin friction loss	Jansen
	Mixing loss	Johnston and Dean
	Clearance loss	Jansen
External loss	Disk friction loss	Daily and Nece
	Recirculation loss	Oh
	Leakage loss	Aungier

2.2 Balje's non-dimensional number analysis

Balje's non-dimensional number analysis, often called $n_s d_s$ diagram, is a typical method to estimate rough total to static efficiency, rotation speed, the number of stage and size of a turbomachinery at the early design stage. It helps designers to narrow broad analysis range to smaller one. This conceptual design is performed with non-dimensional numbers;

The compressor conceptual design is performed with two non-dimensional parameters; specific speed, n_s, and specific diameter, d_s. Each parameter is defined in Eqs. (1) and (2). Non-dimensional parameters, n_s and d_s, are derived from the dimensional analysis. When two different compressors have same n_s and d_s, these are similar with regard to the geometric, the kinematic and the dynamic.

$$n_s = \frac{NQ^{0.5}}{(gH_{ad})^{0.75}} = \frac{\phi^{0.5}}{\psi^{0.75}} \qquad (1)$$

$$d_s = \frac{ND^{0.5}}{(gH_{ad})^{0.75}} = \frac{\psi^{0.25}}{\phi^{0.5}} \qquad (2)$$

The existing n_s-d_s diagram shown in Fig. 1 is obtained with a compressor dealing with ideal gas and having te same geometrical constrains such as ratios of clearance gap to blade height and disk gap to impeller diameter. However, this diagram should be re-confirmed for a $S\text{-}CO_2$ compressor case because it is based on constant or linear thermodynamic property variation assumption.

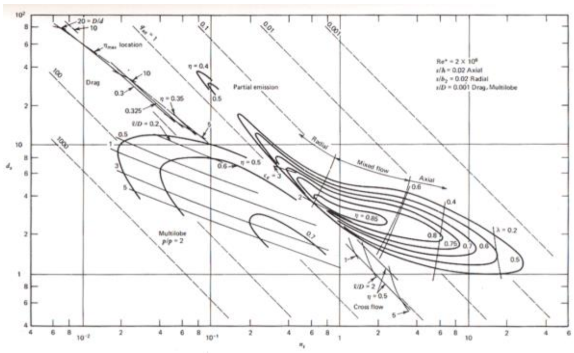

Fig. 1. n_s-d_s diagram for single stage compressor [3]

3. Results

The n_s-d_s diagram generation near the critical point was conducted by using KAIST-TMD code. For generating the diagram for $S\text{-}CO_2$ compressor case it was assumed that different compressors still have the same tip clearance to blade height ratio of 0.02. 31°C in temperature and 7400kPa in pressure were selected as the compressor inlet static condition. The re-calculated diagram by KAIST-TMD showed a good agreement with the previous diagram as shown in Fig. 2 despite that the compressor inlet condition is even very close to the critical point (T_c = 30.98°C, P_c = 7377kPa). However, it is noticeable that the total to static efficiency slope is steeper than the Balje's n_s-d_s diagram in 0.65 to 0.7 of n_s range because of different design criteria.

The design criteria adopted by KAIST-TMD maintains the diffuser outlet velocity to be the same with the impeller inlet velocity while the optimum inlet velocity increases when n_s increases. It implies that there is a static pressure recovery potential at high n_s. In other words, the total to static efficiency can be improved if different compressor design criteria are utilized. Thus, the Balje's n_s-d_s diagram can be still used for the conceptual design step of a $S\text{-}CO_2$ compressor.

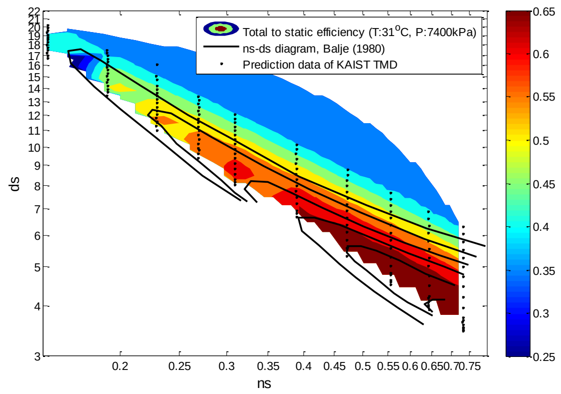

Fig. 2. Comparison of Blje's *ns-ds* diagram generation result of KAIST-TMD

4. Summary and further works

The well-recognized Balje's non-dimensional analysis for any working fluids is re-examined for a $S\text{-}CO_2$ compressor design case because its assumption cannot cover non-linear thermodynamic properties of $S\text{-}CO_2$ near the critical point. To resolve this issue, a turbomachinery design in-housed code, namely KAIST-TMD, is utilized. The re-generated diagram for a $S\text{-}CO_2$ compressor show good agreement with the existing diagram except for the different efficiency trend at high n_s region.

Although this difference is caused by the different design criteria between KAIST-TMD and Balje's diagram, further investigation will reveal the cause of difference in more detail.

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