Effect of Backswept Angle Changes on Supercritical CO_2 Centrifugal Compressor Performance

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1. Introduction

The necessity of the next generation nuclear reactors has been constantly brought up because of the global warming, the spent fuel reprocessing, and enhanced safety. A supercritical CO_2 (S-CO_2) Brayton cycle is the promising power technology for the next generation nuclear reactors due to high thermal efficiency at moderate turbine inlet temperature (450~650 ^oC), compact cycle configuration, and the alleviation of turbine blade erosion in comparison with the steam Rankine cycle [1]. Because of these advantages, it has been considered as a future power system for various heat sources (i.e. fossil fuel, waster heat, solar thermal and fuel cells) as well as nuclear.

While designing a turbomachinery, the complexity of analysis and practical machinability have to be considered, which leads to fixing the design parameters from experience of each vendor. However, an S-CO_2 Brayton cycle is not yet mature power generation technology. Therefore, this paper will cover the effect of backswept angle changes on compressor performance using 1D mean stream-line method.

2. Methods

A turbomachinery in-house code, namely KAIST-TMD, is utilized in this study. The following paragraphs describe KAIST-TMD and a benchmark compressor.

2.1 KAIST-TMD

There have been many efforts to develop an S-CO_2 compressor analysis tool. Most of researchers have utilized the existing commercial codes with minor modifications. For this reason many codes have convergence issues near the critical point.

KAIST research team developed and integrated radial turbomachinery design tools using 1D mean stream line method and loss models. The REFPROP thermodynamic property database is coupled to KAIST-TMD for S-CO_2 real gas properties. 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. Furthermore, as shown in Eqs. (1)-(2), pressure and temperature based stage calculation method cannot be used for the S-CO_2 compressor design and analysis since ratio of specific heats and specific heat at constant pressure is no longer a constant.

$$h_o = h_s + \frac{V^2}{2} \tag{1}$$

$$\frac{P_o}{P_s} = \left(\frac{T_o}{T_s}\right)^{\frac{\gamma}{\gamma-1}} = \left(1 + \frac{\gamma-1}{2}M^2\right)^{\frac{\gamma}{\gamma-1}} \tag{2}$$

KAIST-TMD adopts empirical loss models and slip factor to estimate the S-CO_2 compressor performance. 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 [2]. Table I summarizes the selected loss models and Figs. 1-2 illustrate the mechanisms of each loss. The flow cannot be perfectly guided by impeller blades. It causes the flow angle at the impeller exit leans to the opposite direction of rotating direction. As a result, the tangential component of absolute velocity decreases as shown in Fig. 3. β_2 and $\beta_{2,i}$ represent the flow angle and the blade angle at the impeller outlet, respectively.

Table I: List of adopted loss models [2]

Classification of loss type		Model
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	Ali
	Recirculation loss	Oh
	Leakage loss	Aungier

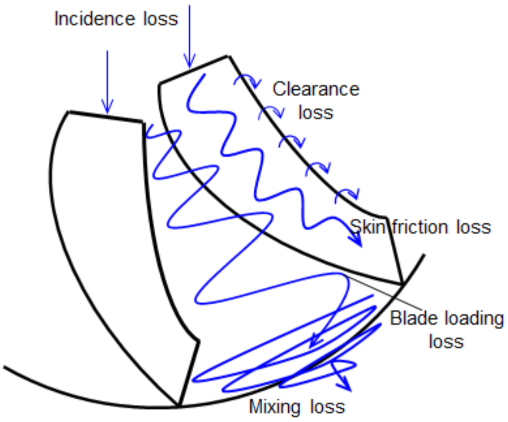

Fig. 1. Internal loss mechanism

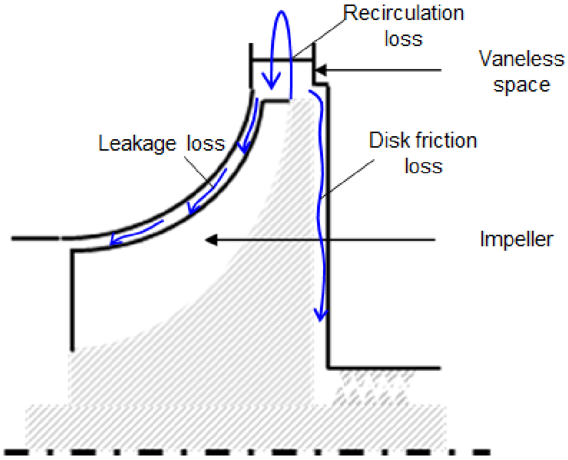

Fig. 2. External loss mechanism

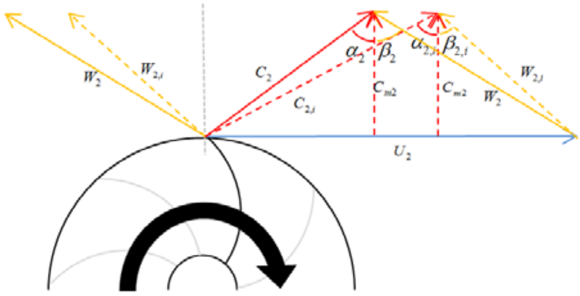

Fig. 3. Flow slip mechanism

2.2 Reference Compressor

The S-CO_2 compressor as shown in Fig. 4 was selected to investigate the effect of change of backswept angle at impeller outlet ($\beta_{2,i}$) on compressor performance. Among various design parameters, the backswept angle was chosen because it affects both the slip and the losses. The operating conditions and main design parameters for the reference compressor are presented in Table II.

Table II: Specifications of a reference compressor

Operating conditions	
Inlet static temperature	304.15 K
Inlet static pressure	7.4 MPa
Target total pressure	20 MPa
Rotational speed	23500 RPM
Mass flow rate	103 kg/s
Design parameters	
Inlet hub diameter	0.0135 m
Inlet shroud diameter	0.0674 m
Impeller outlet diameter	0.15 m
Number of blades	16
Impeller outlet backswept angle	-56 ^{o}
Ratio of clearance to blade height	0.02

The compressor inlet condition was selected very close to the critical point (T_c = 304.13 K, P_c = 7.377 MPa) where the thermodynamic properties change most rapidly. In order to minimize loss at the compressor inlet, non-swirl condition was selected in inlet blade design. The impeller outlet backswept angle was adopted in the range of -50 ^{o} to -60 ^{o} which is widely used in the conventional compressors operating with air.

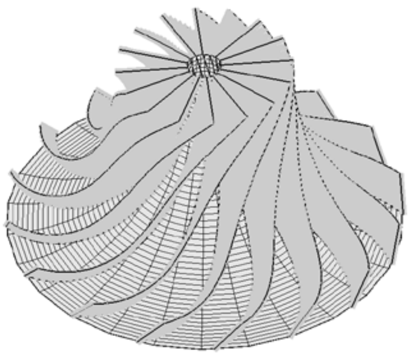

Fig. 4. Benchmark impeller of S-CO_2 compressor

3. Results

Compressor performance was examined when the backswept angle varied from 0 ^{o} to -77 ^{o}. As shown in Fig. 5, S-CO_2 compressor showed the highest efficiency at -70 ^{o}, which is larger than previously known. The backswept angle change affected the efficiency but did not affect the pressure ratio. In order to understand the reason why the backswept angle change affected the efficiency, the compressor loss distribution with varying angle was examined as shown in Fig. 6.

The remarkable thing is that the percentage of blade loading loss is minimized at -70 ^{o} having the highest efficiency. The flow separation caused by the difference in pressure load between the suction side and the pressure side results in the blade loading loss. In this respect, low blade loading loss means a relatively even pressure field distribution on blades, and generally the highest compressor efficiency is observed at the lowest blade loading point. Although the point having the highest efficiency differs from the previously widely adopted range, the results in Fig. 6 correspond to what is known about the blade loading loss. Also, the skin friction loss, the leakage loss and the disk friction loss are proportional to the impeller size. These loss terms increased because the more the backswept angle increases the more the diameter increase as shown in Fig. 7.

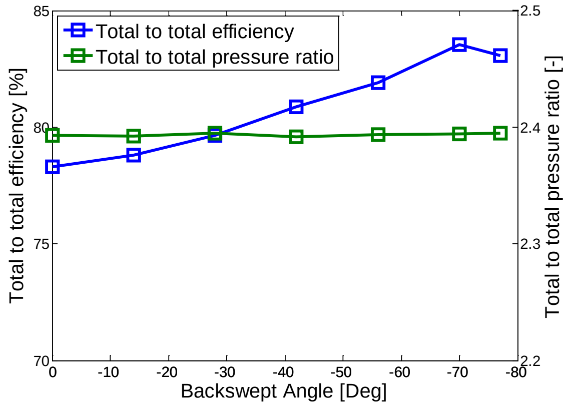

Fig. 5. Benchmark impeller of S-CO_2 compressor

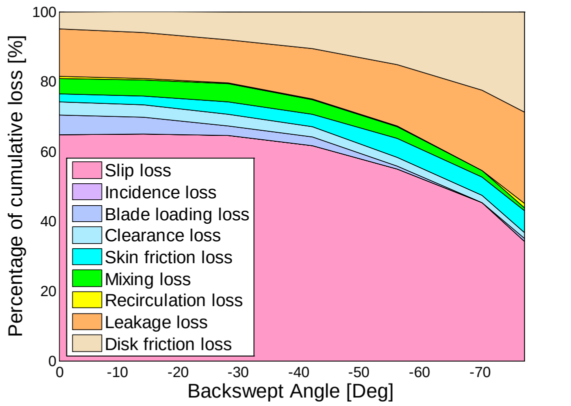

Fig. 6. Benchmark impeller of S-CO_2 compressor

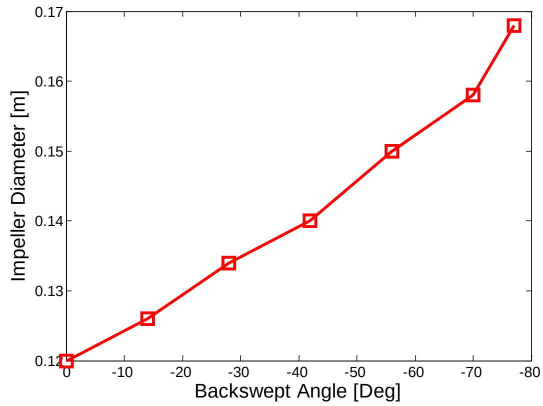

Fig. 7. Benchmark impeller of S-CO_2 compressor

4. Summary and further works

This paper was dealt with the effect of backswept angle changes on S-CO_2 compressor performance. As a result, the best efficiency was achieved at a larger backswept angle than the conventional region and the skin friction loss, the leakage loss and the disk friction loss increased when the angle increases. This was because larger dimeter is obtained at larger backswept angle.

As further works, the effect of various design parameters on the S-CO_2 compressor performance and the effect of working fluid change on the blade profile will be investigated.

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