Investigation of high back-sweep angle effect on supercritical CO_2 power system compressor

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1. Introduction

Distributed power generation refers to installing small and medium-sized power generation sources near power demands. Distributed power generation is attracting attention because it can improve system stability, reduce initial investment and the number of transmission facilities. The supercritical CO_2 (sCO_2) system is a power conversion system using CO_2 at the supercritical phase as a working fluid that can be a common technology for distributed power generation [1]. In the sCO_2 system, the fluid is compressed near the critical point, so the pressure increases efficiently with low energy input. It allows the sCO_2 system to have compact turbomachinery.

For designing the sCO_2 system, the design of the turbomachinery is a major factor. Cho's study of the sCO_2 turbomachinery showed that the compressor for sCO_2 could achieve higher efficiency by applying a high backsweep angle design approach, and that structural integrity problem did not arise because of the low increase in enthalpy and the low inlet Mach number [2].

Since the distributed power generation has to generate the amount of electricity that meets the demand requirements, evaluation of the off-design performance is necessary to use the high backsweep angle compressor. The off-design point of the distributed power generation is mainly caused by the part-load operation, and thus it is necessary to analyze the long-term final part-load conditions rather than the short-term change [3]. Therefore, this study analyzes the system off-design performances with the high backsweep angle compressor using the quasi-steady state analysis.

2. Methods and Results

2.1 Steady-state Design

To analyze the effect of the high backsweep angle compressor on the off-design condition, the sCO_2 recuperated power Brayton closed-cycle composed of a single compressor is set as the system layout. The system conditions for system optimization are based on KAIST-MMR. KAIST-MMR combines the power system using the sCO2 cycle and the reactor core into one module and has a size that can be transported by a truck or ship [4]. Therefore, it is suitable for use as a distributed power supply.

The design parameters of the system based on KAIST-MMR are shown in Table 1. Under these conditions, system optimization is performed using the KAIST-CCD (Closed Cycle Design) code. Cycle optimization results are calculated and presented in Table 2.

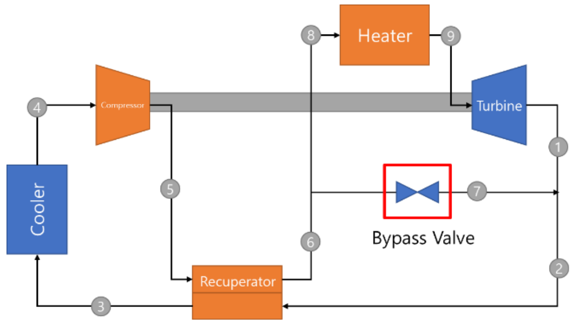

Fig 1. Simple recuperated closed Brayton cycle layout

Table 1. Fixed value for the cycle optimization

Fixed value			
Max P (Mpa)	20	Cycle net work (MWe)	10
Min T (°C)	35	Max T (°C)	550
Turbine eff. (%)	90	Compressor eff. (%)	85
Recuperator effectiveness	0.9	Recuperator pressure drop (kPa)	130-150
Cooler pressure drop (kPa)	950	Heater pressure drop (kPa)	100

Table 2. Cycle optimization results

Design parameter	Optimization Results
Cycle thermal efficiency (%)	30.18
Cycle work (MW_e)	10
CO_2 mass flow rate (kg/s)	134.66
Thermal heat (MW_{th})	33.13
Pressure ratio	2.536
Min. Pressure (MPa)	7.886

2.2 Turbomachinery Design

To evaluate the performance of the system under off-design conditions, the components must be designed as well. The list of components to be designed includes the compressor (MC), recuperator (HXE), and turbine (T). To show the effect of the backsweep angle compressor on the performance of the system, the compressor is designed with two options where the backsweep angle is 50° and 70°, respectively.

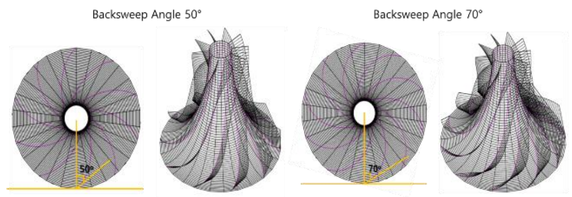

Fig 2. Compressor with Different Backsweep Angle

Based on the optimized on-design conditions from KAIST-CCD, the turbomachinery design used in the system is performed with KAIST-TMD [5]. KAIST-TMD is a code developed by the KAIST research team to predict turbomachinery geometry, on-design, and off-design performances using the 1D mean-line method. The geometry and performance map of two types of compressors and turbines designed via KAIST-TMD are shown below.

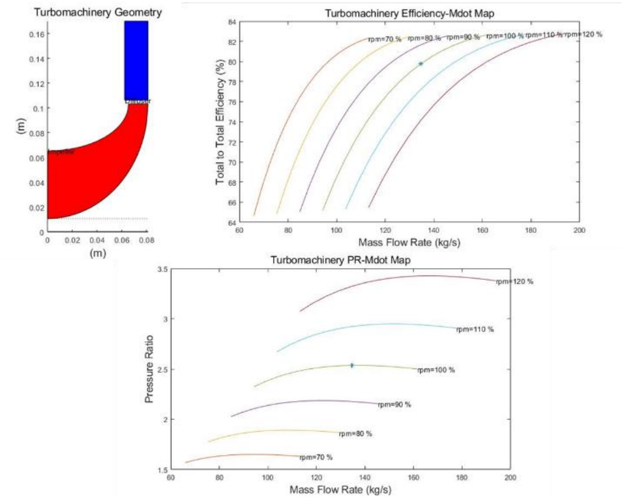

Fig 3. Compressor (backsweep angle = 50°) geometry and performance map

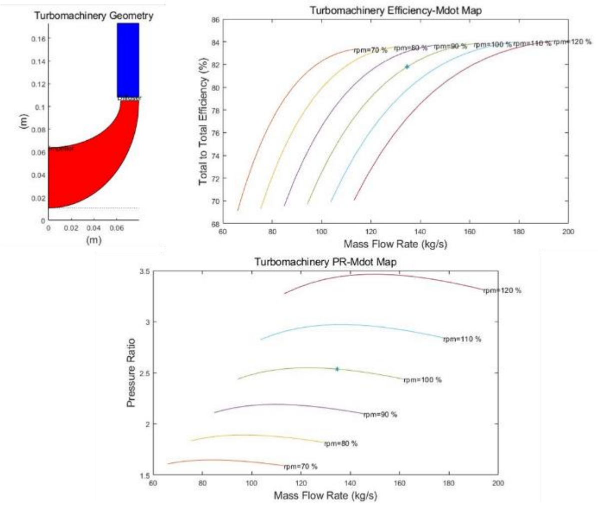

Fig 4. Compressor (backsweep angle = 70°) geometry and performance map

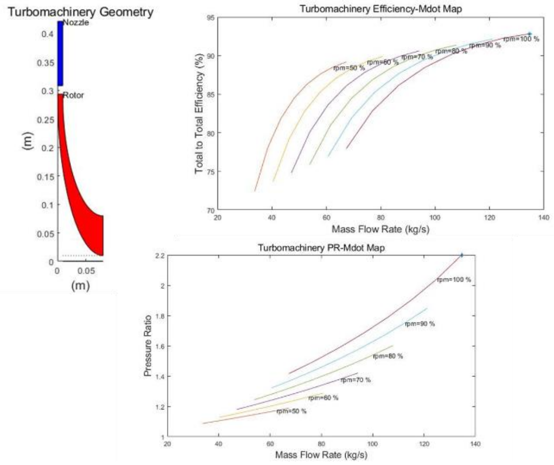

Fig 5. Turbine geometry and performance map

2.3 Quasi-steady State Analysis

Off-design performance is predicted by quasi-steady-state analysis. The control strategy for off-design performance calculation is as follows. The heat output of the heater, the outlet temperature of the cooler, and the mass of CO_2 in the system are maintained. Bypassing the heater and turbine using a bypass valve and reducing the angular velocity of the turbine and compressor to change the output of the system [6]. However, since it bypasses using the bypass valve, the maximum bypass flow rate is 50% of the total flow rate, and the turbine and compressor are connected to the same shaft, so they have the same angular velocity.

The result of performing quasi-steady-state analysis for a compressor with a backsweep angle of 50 degrees and of 70 degrees, the change in the output value concerning the changed bypass ratio and the number of revolutions of the turbomachine is shown in the following graph, respectively.

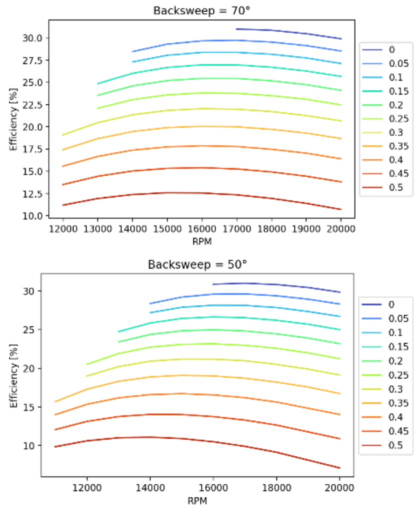

Fig 6. Off-design Efficiency

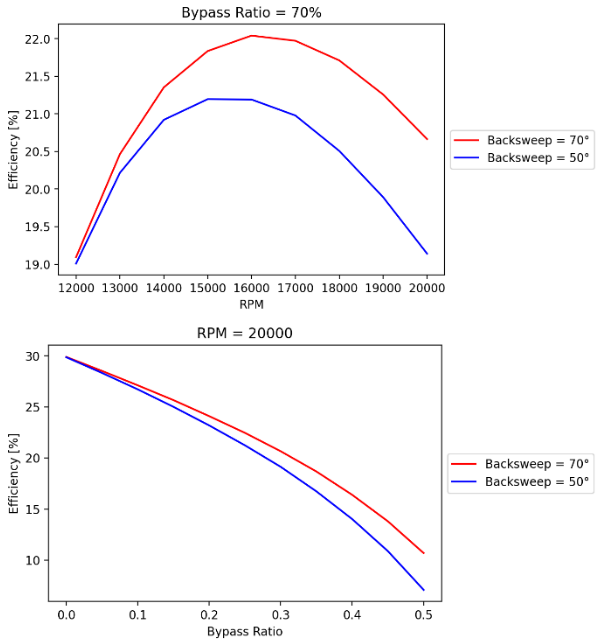

Fig 7. Off-design efficiency comparison for two different backsweep angle compressor

3. Conclusions

As a result of analyzing off-design performance with quasi-steady-state analysis, the cycle efficiency is higher when the higher backsweep angle compressor (70°) is used than when the low backsweep angle compressor is used. The difference in efficiency becomes more pronounced as the bypass flow rate increases and the rotational speed of the compressor is increased. Other control methods such as inventory control will be investigated in the future if the conclusion is still the same. Moreover, a transient analysis will be performed to understand the response as well.

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