

S-CO₂ Compressor Performance Test Plan Considering Measurement Accuracy

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1. Introduction

The necessity of the next generation nuclear reactors has been constantly brought up because of the global warming, spent fuel issues, and enhanced safety. A supercritical CO₂ (S-CO₂) 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 °C), 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.

It plans to fabricate the S-CO₂ TAC test rig to confirm the effect of high backward angle design and to acquire fundamental test data for S-CO₂ power cycle. Since the measurement accuracy can lead to significant uncertainty propagation to the final performance results, the relative error analysis will be conducted in this study. Lastly, the test matrix will be proposed in consideration of measurement accuracy.

2. Compressor Performance Experiment Plan

2.1 Description of S-CO₂ TAC test rig

The test rig consists of a control valve, an orifice, a TAC and a pre-cooler. The control valve and the orifice is located at the turbine outlet and the compressor outlet, respectively, because it varies the flow resistance to control each performance. The working fluid completes a cycle through a pre-cooler to transfer the heat into water. Fig.1 and Table I shows the schematic diagram of the test rig and cycle design conditions, respectively.

The inlet conditions of compressor were selected to avoid two-phase issue inside the compressor while close to the critical point ($T_c = 304.13$ K, $P_c = 7377$ kPa). S-CO₂ compressors have been designed mainly for extreme operating conditions. DN number, which the product of the average diameter of the bearing (millimeters), D, and the rotational speed (rpm), N, is a representative parameter that shows how challenging it is. The DN numbers used in the existing integral test loops are in the range of 3 to 4 million over the range of generally used gas bearings.

In this study, the TAC with a DN number less than one million was considered in order to improve the operability. The low specific speed was selected

considering manufacturing limit of blade height and DN number referring to the previous study [3]. Finally, the design conditions were selected to have pressure ratio, 1.3, mass flow rate, 3kg/s, and specific speed, 0.33.

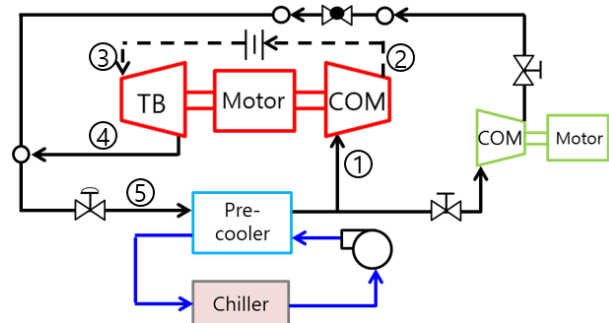


Fig. 1. Schematic diagram of S-CO₂ TAC test rig

Table I: Cycle design conditions of S-CO₂ TAC test rig

	Temperature [°C]	Pressure [MPa]
①	32	7.60
②	40	10.4
③	300	10.3
④	286	7.77
⑤	285	7.67

2.2 Measurement sensitivity analysis

As shown in Eqs. (1)-(2), pressure ratio and isentropic efficiency are representative parameters of a compressor performance. These are derived values from the measurement of pressure, temperature and mass flow. Thus, the measurement sensitivity analysis, which is to calculate perturbation propagation on the final parameters from independent measurement accuracies, should be accompanied to prove reliability of experimental data. The uncertainties were calculated with Eqs. (3)-(5). Relative error is the square-rooted sum of partial derivatives of f with each variable. RTDs (class A accuracy) are used to measure temperature and pressure transmitters which have 0.05% of 10 MPa accuracy are used to measure pressure. A Coriolis mass flow meter which has 0.16% of 5 kg/s accuracy is used to measure mass flow rate.

$$PR = \frac{P_{out}}{P_{in}} \quad (1)$$

$$\eta = \frac{h_{out,isen} - h_{in}}{h_{out} - h_{in}} = \frac{h_{out,isen} - h_{in}}{\dot{W} / \dot{m}} \quad (2)$$

$$\frac{\sigma_f}{f} = \left\{ \sum \left[\left(\frac{1}{f} \frac{\partial f}{\partial x_i} \sigma_{x_i} \right)^2 \right] \right\}^{1/2} \quad (3)$$

$$\frac{\sigma_{PR_o}}{PR_o} = \left[\left(\frac{\sigma_{P_{o,out}}}{P_{o,out}} \right)^2 + \left(\frac{\sigma_{P_{o,in}}}{P_{o,in}} \right)^2 \right]^{1/2} \quad (4)$$

$$\frac{\sigma_\eta}{\eta} = \left[\left(\frac{1}{h_{out,isen} - h_{in}} \sigma_{h_{out,isen}} \right)^2 + \left(\frac{-1}{h_{out,isen} - h_{in}} \sigma_{h_{o,in}} \right)^2 + \left(\frac{1}{\dot{m}} \sigma_{\dot{m}} \right)^2 + \left(\frac{-1}{\dot{W}} \sigma_{\dot{W}} \right)^2 \right]^{1/2} \quad (5)$$

Fig. 2 shows the distribution of predicted uncertainties, which are measurement errors by installed RTDs, pressure transmitters and mass flow meter, for the designed compressor efficiency on temperature and pressure plane. The relative error increases rapidly as the compressor operating condition approaches to the critical point. It is because dramatic change on the thermodynamic property of CO₂ near the critical point (31 °C, 7400 kPa) and small isentropic enthalpy rise for low pressure ratio. The uncertainty of compressor efficiency is estimated to be about 80 % of the design condition. Whereas the uncertainties for pressure ratio is about 0.3 %.

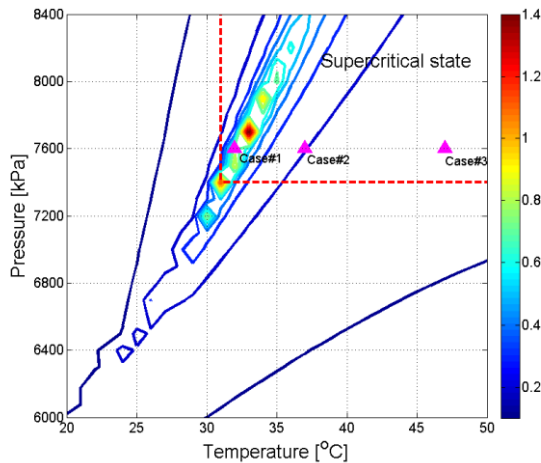


Fig. 2. Uncertainty prediction for the designed compressor efficiency on temperature and pressure plane

2.3 Selection of test conditions

As described in Table II, the test matrix are selected in consideration of measurement error and compressibility factor. Although it has high error near the critical point, off-design performance (e.g. such as

operating range, surge, pressure ratio and isentropic efficiency trend on mass flow rate) will be observed depending on backward angle. In the previous study, 1D calculation results showed the compressibility factor does not affect an S-CO₂ compressor performance. Thus, case 2 and case 3 are chosen not only to acquire low uncertainty data but also to confirm its effect.

Table II: Selected operating conditions for compressor test

Case #	Case 1	Case 2	Case 3
Inlet pressure [MPa]	7.6	7.6	7.6
Inlet temperature [°C]	32	37	47
Density [kg/m ³]	578	263	208
Compressibility factor [-]	0.23	0.49	0.60
Relative Error [%]	77	20	13
Backward angle at rotor exit [°]	-30 / -50 / -70		

3. Summary and further works

The research team plans to install S-CO₂ TAC test rig to prove the effect of high backward angle design and to acquire fundamental test data. However, because independent measurement accuracies can cause substantial uncertainty on the final parameters due to perturbation propagation, the measurement sensitivity analysis was carried out in this study. As a result, the relative error of compressor efficiency was estimated to be about 80% at the design condition due to dramatic change on the thermodynamic property of CO₂ near the critical point and small isentropic enthalpy rise. Thus, alternative operating conditions were selected for the compressor test.

As further works, the start-up strategy for the TAC operation and the plan to minimize the axial thrust force will be figured out.

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