Validation of KAIST-TMD with recent supercritical CO_2 Turbine-Alternator-Compressor test data

Seungkyu Lee, Jeong Ik Lee*
Department of Nuclear and Quantum Engineering, KAIST, Daejeon, South Korea
**Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

In an effort to attain high cycle thermal efficiency, numerous working fluids have been investigated and tested so far. Supercritical carbon dioxide (sCO_2) is a competitive working fluid with a unique thermal property compared to conventional air and steam. High density near the critical point can reduce compressor work and provide high efficiency for a wide range of heat source temperature, especially for nuclear fission energy. Only a few small, compact components are needed for the sCO_2 Brayton Cycle. Thus, this cycle is applicable to both microreactors and small modular reactors [1].

Similar to the Sandia National Lab (SNL) or the USDOE STEP testing loops, the KAIST research team constructed a sCO_2 Brayton Cycle testing loop named Autonomous Brayton Cycle (ABC) loop. The KAIST research team adopted an Active Magnetic Bearing Turbine Alternator Compressor (AMB-TAC). Both compressor and turbine are radial types. When a turbine and a compressor are coupled on the same shaft, the turbine can assist compressor in rotating while consuming less electricity [2]. The KAIST-TMD code is a 1-D streamline code and is suitable for the sCO_2 turbomachinery by using material properties of NIST's REFPROP database. This code was validated with data from SNL, KAERI and KAIST-SCO_2PE loop, which was the previous experimental loop operated by the KAIST research team.

By using the recently obtained AMB-TAC test results under various RPM conditions from 18,000 RPM to 29,000 RPM, the pressure ratio depending on the mass flow rate of a compressor and a turbine obtained from KAIST-TMD will be validated in this paper. It is emphasized that KAIST-TMD compressor module was validated multiple times with test data, but the turbine module is validated with actual sCO_2 test data for the first time in this paper.

2. Methods and Results

2.1 Experimental facility

A diagram of the ABC loop is shown in Fig. 1. The orange line represents the flow of sCO_2, and the blue line represents the cooling water line. The ABC loop CO_2 line is equipped with a compressor, a turbine, a heater, a recuperator, and two pre-coolers. Thermocouples were calibrated with a constant temperature bath containing a high precision temperature measurement.

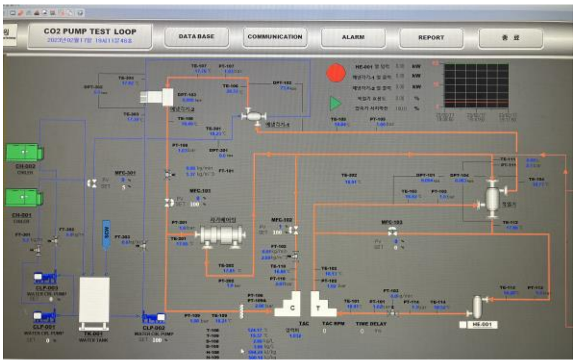

Fig. 1. Facility schematic of ABC loop.

The AMB-TAC is shown in Fig. 2. The oil utilized in a ball bearing system can dissolve to sCO_2 fluid [3]. In the AMB system, this bearing uses magnetic force to control displacement and vibration in both radial and axial directions, enabling active adjustment of the rotor position.

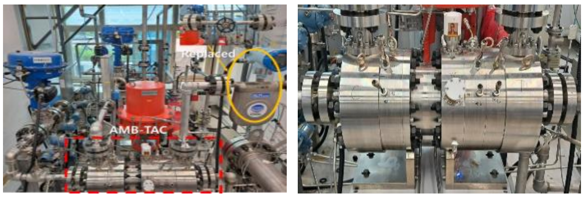

Fig. 2. ABC loop (Left) and AMB-TAC (Right)

2.2 Analysis code – KAIST-TMD

Fig. 3 is a detailed flowchart of KAIST-TMD code [4]. The KAIST-TMD code (Turbomachinery Design Code) is a code that designs compressors and turbines using the 1-D streamline method. In a radial compressor, the fluid passes through impeller, diffuser, and volute, whereas in a radial turbine, fluid passes through volute, nozzle, and rotor. Using the velocity triangles at the inlet and the outlet of each abovementioned section, the KAIST-TMD code calculates the change in temperature, enthalpy, and pressure [5].

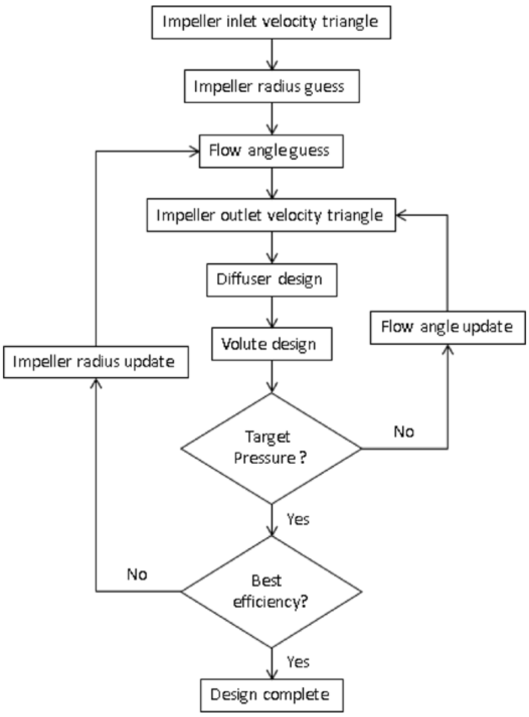

Fig. 3. Design optimization algorithm of KAIST-TMD [4]

KAIST-TMD code also takes into account the blockage effect. Flow separation can cause the blockage effect, especially in a compressor when there is an adverse pressure gradient near the blade surface [6]. This involves a region with very little flow in the exit direction, which KAIST-TMD code quantitatively analyzes and corrects the velocity triangle. Afterwards, this code modifies the velocity triangle using loss models and designs a turbomachinery for the desired pressure ratio [5].

2.3 Experimental conditions

The design conditions of the compressor and the turbine are shown in Table I. Density changes significantly for small changes in temperature and pressure near the critical point. In order to obtain an exact pressure ratio in turbomachinery, density is the key parameter [7]. To maintain compressor inlet temperature and pressure, the heater power and the pre-cooler cooling are precisely controlled. It is noted that although the TAC design RPM, is 36,000, the testing was conducted between 6,000 and 29,000 RPM so far.

Table I: Design conditions

	Compressor	Turbine
Inlet Temperature (K)	308.15	333.15
Inlet Pressure (bar)	76	91.2
Pressure Ratio	1.20	1.11
Mass flow rate	1.5 kg/s	
TAC RPM	36,000	

2.4 Test data and KAIST-TMD validation

The test results are presented in Table II. The flow resistance curve has the form of a quadratic equation that increases monotonically with the flow rate. The flow rate and pressure ratio are determined at the point where the flow resistance curve and turbomachinery performance map meet each other [8]. The maximum mass flowrate predicted by TMD is at the right end of each black line in Fig. 4, but the flowrate generated in the experiment with all three valves open was still smaller than that. There are two reasons for this. One is that the capacity of TAC is designed to be smaller than that of ABC loop. This is because the ABC loop was designed to have a substantial flow resistance due to heat exchanger experiments and bypass experiments. The other reason is that leakage flow occurred in the direction from the compressor to the turbine inside the TAC. Compressor and turbine are coupled with one rotating shaft, and leakage flow occurs through the clearance between the rotor and the non-rotating body.

Table II: Test data

RPM	Mass flow rate (kg/s)	Compressor PR	Turbine PR
6,000	0.184	1.00676	1.00274
9,000	0.286	1.01320	1.00570
12,000	0.392	1.02220	1.00981
15,000	0.523	1.03627	1.01617
18,000	0.644	1.05296	1.02371
21,000	0.746	1.06989	1.03126
24,000	0.870	1.09289	1.04139
27,000	0.978	1.11575	1.05126
28,000	1.004	1.12254	1.05272
29,000	1.034	1.13101	1.05616

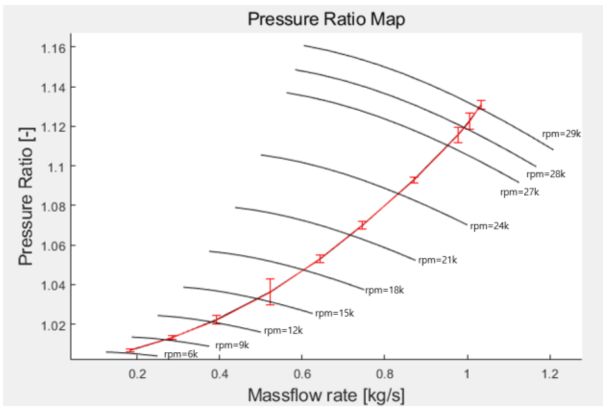

Fig. 4. Compressor Pressure Ratio-Mass Flow rate Testing Result (Red) and KAIST-TMD Prediction (Black line)

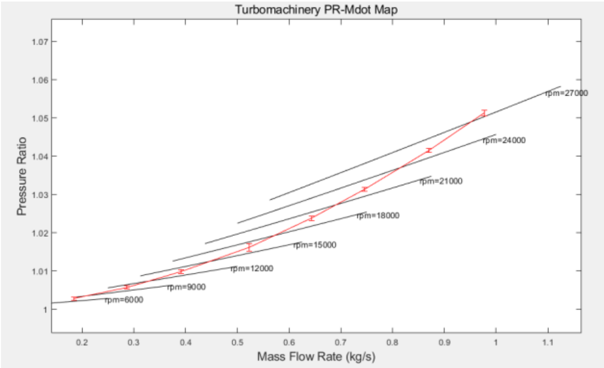

Fig. 5. Turbine Pressure Ratio- Mass Flow rate Testing Result (Red) and KAIST-TMD Prediction (Black line)

Figs. 4 and 5 compare the pressure ratio-mass flowrate data of the compressor and the turbine from the experimental data to those values predicted by KAIST-TMD. Black lines are the performance map predicted by KAIST-TMD, and the test data are shown in red curve with uncertainty band for 95% confidence level. For the two reasons described above, the mass flowrate was slightly smaller than that of KAIST-TMD. It is noteworthy that the difference becomes larger at lower RPM. The equation used to quantify error is shown in equation 1:

$$Error = \left|\frac{PR_{TMD}(\dot{m},rpm)-PR_{test}(\dot{m},rpm)}{PR_{test}(\dot{m},rpm)}\right| * 100(\%) \qquad (1)$$

where PR is pressure ratio, and the test data and the predictions of KAIST-TMD are indicated with subscripts.

The test results for the pressure ratio of the compressor and the turbine for each RPM, the values predicted by TMD, and the error values are shown in Tables 3 and 4, respectively.

Table III: Validation of TMD, Compressor

RPM	Compressor Pressure Ratio		
	Test	TMD	Error (%)
6,000	1.00676	1.00504	0.170845
9,000	1.01320	1.01158	0.159889
12,000	1.02220	1.02031	0.184895
15,000	1.03627	1.02952	0.653750
18,000	1.05296	1.04370	0.879426
21,000	1.06989	1.06145	0.788866
24,000	1.09289	1.08327	0.880235
27,000	1.11575	1.10992	0.522518
28,000	1.22254	1.12002	0.224491
29,000	1.13101	1.13080	0.018567

Table IV: Validation of TMD, Turbine

RPM	Turbine Pressure Ratio		
	Test	TMD	Error (%)
6,000	1.00274	1.00204	0.069809
9,000	1.00570	1.00477	0.092473
12,000	1.00981	1.00879	0.101009
15,000	1.01617	1.01471	0.143677
18,000	1.02371	1.02194	0.172901
21,000	1.03126	1.03002	0.120241
24,000	1.04139	1.03981	0.151720
27,000	1.05126	1.05026	0.009512
28,000	1.05272	1.05367	0.090527
29,000	1.05616	1.05738	0.115702

3. Conclusions

By utilizing AMB-TAC in KAIST, this paper shows the test results of pressure ratio and mass flow rate of the sCO_2 compressor and the sCO_2 turbine. The obtained test data is used to validate KAIST-TMD code. The testing data and KAIST-TMD code show very good agreement which means the design results obtained from KAIST-TMD have high confidence. It is also emphasized that the turbine module of KAIST-TMD is also validated for the first time in this study.

ACKNOWLEDGEMENT

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