Off-design performance prediction of Radial Compressor of Supercritical CO_2 Brayton Cycle for KAIST Micro Modular Reactor

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1. Introduction

Supercritical carbon dioxide (S-CO_2) Brayton cycle has been receiving attention as one of the promising power conversion systems for a Generation IV nuclear reactor because of its high cycle efficiency at relatively low turbine inlet temperature (450~750℃). Also, it has compact heat exchangers and turbomachineries. These characteristics are highly suitable for Small Modular Reactor (SMR). Despite all the advantages, certain technical difficulties of the S-CO_2 power cycle still exist for commercialization.

KAIST research team suggested a new concept of SMR, which utilizes S-CO_2 as the operating fluid and coolant. It was named as KAIST MMR(Micro Modular Reactor). Compared with existing SMR concepts, this reactor has advantages of (1) achieving smaller volume of power conversion unit (PCU) (2) containing the core and PCU in one vessel for the complete modularization (3) passive air-cooling system (4) more flexible installation in the inland area.

In previous study, performance of turbomachinery in PCU was considered only on-design. But, off-design performances of each component can affect not only PCU but also the core because this reactor adopts the direct S-CO_2 loop in GFR. Nuclear system is applied by relatively conservative criteria of safety. Thus, off-design performances of each component should be considered in order to be more realistic reactor.

2. S-CO2 Brayton cycle design for KAIST MMR

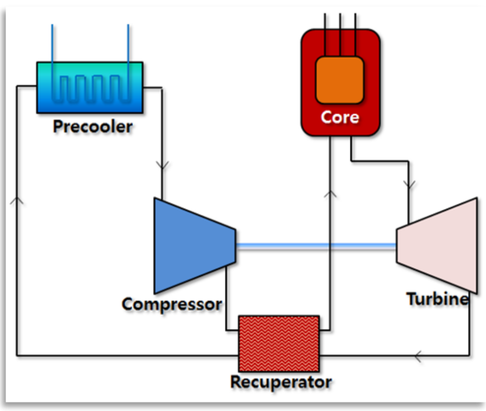

Fig.1. S-CO_2 Recuperated Brayton cycle layout

The previous study presented that the best layout is S-CO_2 Recuperated Brayton cycle [1]. The one of main characteristics of KAIST MMR is a concept that can run at the inland area where water is insufficient because this adopted dry air cooling system [2]. For adequate air cooling system, a compressor inlet temperature is required to be far away from the critical point. Table I shows cycle design conditions.

Table I: Cycle design conditions (10MWe Reactor)

Thermal Power	36 MWth
Compressor inlet Temperature	60 ℃
Compressor inlet Pressure	7.5 MPa
Compressor outlet Pressure	20 MPa
Turbine inlet Temperature	550 ℃
Mass flow rate	175.35 kg/s
Compressor Efficiency	84.97 %
Turbine Efficiency	92.28%
Rotating speed	20200 rpm
Thermal efficiency	34.48 %
Net electric output	11.99 MWe

3. Conceptual design of turbomachinery

3.1 Selection of turbomachinery type

According to Ref. [4], turbomachinery type depends on a range of cycle electrical power output. Selection of type is important, since the correct selection can affect cost and performance. The authors of Ref. [4] did make a recommendation radial type turbine up to about 30 MWe, because its blade heights would be too small to be efficient below this power output. Also, a radial unit is preferred as using main compressor for most power levels (at least for the first stage) to assure wider operating range near the critical point. If the inlet condition of compressor is far away from the critical point, compressors would transition to an axial type above about 100 MWe. Thus, for this reason, authors adopted both of compressor and turbine as radial type.

3.2 Balje's non-dimensional number analysis

One of the most widely used methods for tubomachinery sizing is to use Balje's non-dimensional number analysis [3]. The contour line in Fig.2 and Fig.3

means a iso-efficiency line of compressor and turbine. The highest efficiency is the innermost contour line.

The horizontal axis and vertical axis represent specific speed (n_s) and specific diameter (d_s), respectively. Each non-dimensional number can be obtained by Eq. (1).

$$n_s = \frac{\omega\sqrt{V_1}}{(gH_{ad})^{\frac{3}{4}}},\ d_s = \frac{D(gH_{ad})^{\frac{1}{4}}}{\sqrt{V_1}} \qquad (1)$$

Each parameter means angular velocity(ω), gravitational acceleration(g), impeller diameter(D), inlet volumetric flow rate(V_1) and adiabatic head(H_{ad}).

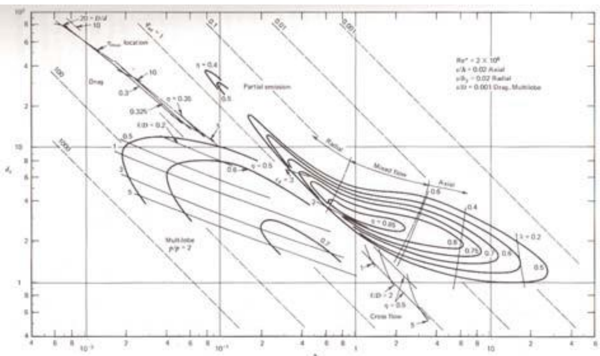

Fig.2. ns-ds diagram for single stage compressor

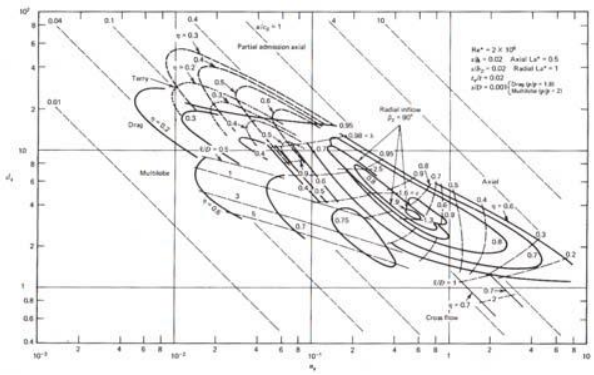

Fig.3. ns-ds diagram for single stage turbine

After engineer pick out target efficiency, some of specific speeds and specific diameters are determined from each diagram (Fig. 2, Fig. 3). Angular velocity and impeller diameter can be calculated with given specific speed and specific diameter because of volumetric flow rate, adiabatic head and gravitational acceleration are determined from the cycle conditions. Thermodynamic properties of S-CO_2 utilized REFPROP database.

Table II: Results of Balje's diagram for KAIST MMR

	Compressor	Turbine
Specific velocity	0.644	0.510
Specific diameter	4.060	3.586
Rotating speed	20200 rpm	20200 rpm
Efficiency	84.97 %	92.28 %
Diameter	0.274 m	0.323 m

3. Turbomachinery performance analysis

Turbomachinery performance analysis can categorize into on-design and off-design. Analysis of on-design is performed on the preferential basis. Because on-design has relatively narrow range and it is used to describe criterion of performance. And all design parameters are determined from on-design condition.

Operation of turbomachinery often departs from on-design conditions by limiting conditions for operation or unforeseen circumstances. In this case, its performance must be reassessed. Off-design performance analysis is essential because nuclear power plants are required to achieve high reliability and safety on applied technologies. As a part of this endeavor, research team conducts off-design performance analysis on main compressor of S-CO_2 brayton cycle.

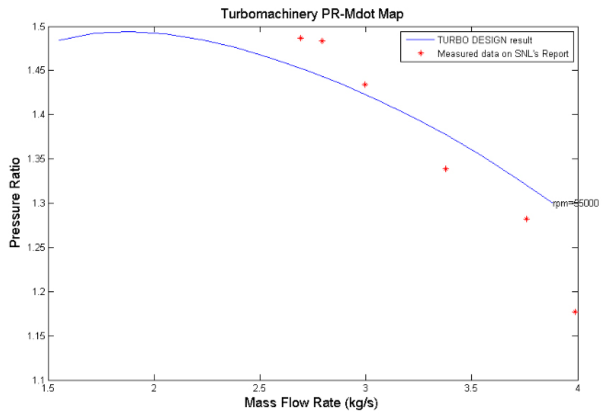

Fig.4. Performance comparison (Pressure Ratio)

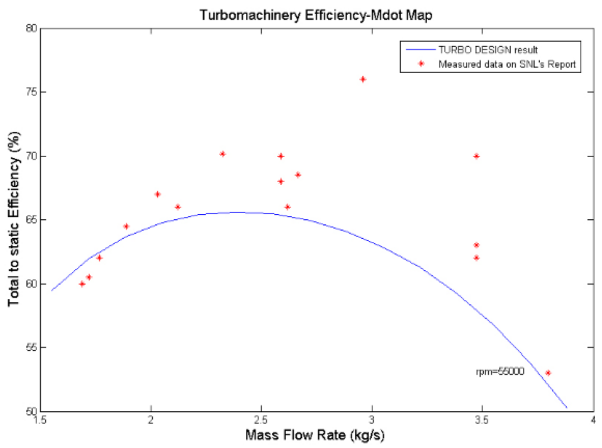

Fig.5. Performance comparison (Total to static efficiency)

Existing methodologies of ideal gas is unsuited for analysis of compressor of S-CO_2 cycle. Because thermodynamic properties of CO_2 near the critical point have sharp variation. So correlations which are based on ideal gas assumptions have to be modified. Thus, KAIST research team constructed an in-housed code, called KAIST_TMD, which is a turbomachinery design and analysis code. Ref. [5] presented the comparisons between off-design performance prediction by KAIST_TMD and experiment data from SNL report in Fig.4 and Fig.5. The trend can receive as suitable off-design performance prediction.

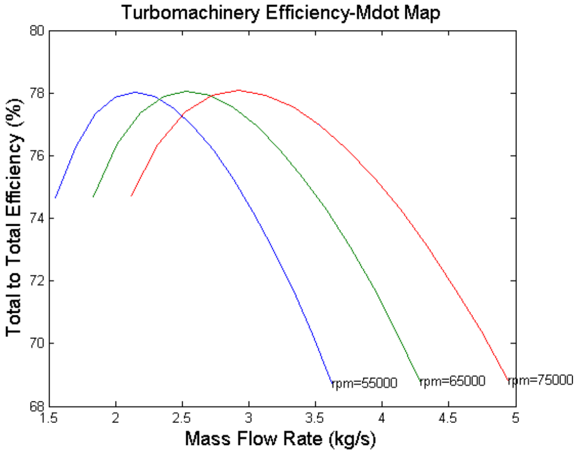

Fig.6. Efficiency prediction of compressor

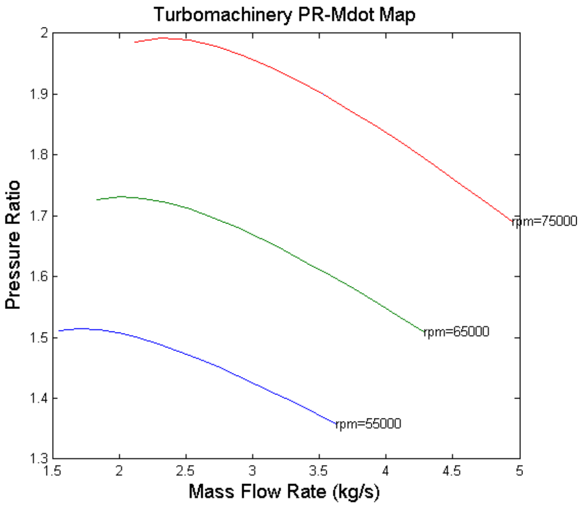

Fig.7. Pressure ratio prediction of compressor

This code was still verified with experiment data for radial compressor. Because experiment of component with S-CO_2 operating fluid has many constraints, radial compressor module was preferentially tried to be verified. Fig. 6 and Fig. 7 are the results of off-design analysis of radial compressor for KAIST MMR. Depending on variations of mass flow rate and rotation speed, compressor performance has various values. Also, compressor efficiency of on-design conditions is obtained 84.51 %. This is similar to results of Balje's diagram.

4. Summary

The suggested turbomachinery size of the S-CO2 cycle is relatively smaller than those of helium Brayton cycle and steam Rankine cycle. Performance analysis of compressor is conducted by KAIST_TMD in case of on-design and off-design. Compressor efficiency in on-design conditions is obtained 84.51 %. But compressor performance in off-design conditions decreases certainly. This means that more heat than existing prediction is rejected by air-cooling system.

KAIST_TMD will be verified with more experiment data for providing the results of more accurate analysis. Also, this code will be modified to couple with safety analysis codes and S-CO_2 cycle analysis codes in the future. Furthermore, authors will consider aerodynamic performance analysis and various losses for more realization.

ACKNOWLEDGEMENT

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