Turbomachinery Performance Map Application for Analyzing Cycle Off-Design Behavior of KAIST MMR

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1. Introduction

A supercritical CO_2 (S-CO_2) Brayton cycle has been considered for Generation IV nuclear reactor applications. The S-CO_2 cycle has the potential for high efficiency in the moderate turbine inlet temperature (450~750℃), and also the compact system size, with the potential for lower capital cost for construction. These advantages are very appealing to the Small Modular Reactor (SMR) [1].

The steam Rankine cycle has been mainly applied in the Power Conversion Unit (PCU) of the existing SMRs. For this reason, modularization and downsizing of the nuclear power plant including PCU is difficult due to complexity and large volume. To solve these problems, KAIST research team proposed a new concept of SMR, called KAIST MMR (Micro Modular Reactor), which utilizes S-CO_2 as the working fluid. Due to high density of S-CO_2 and the development of heat exchanger technology, such as the printed circuit heat exchanger (PCHE), it can achieve small PCU and modularization of system.

In previous works, performance of turbomachinery was expected in design point and off-design points by using in-house design code, called KAIST_TMD. However, these results are for the fixed inlet conditions only (inlet temperature, pressure and so on) [2]. In reality, each state property of actual system changes because of many reasons such as seasonal heat sink temperature variation, unexpected situations and so forth. Thus, this paper describes the method of using turbomachinery performance maps to predict the performance of the system for different compressor inlet conditions.

2. Methods

In the previous study, simple recuperated S-CO_2 Brayton cycle was selected as the layout of KAIST MMR [3]. To operate in the inland area where water is insufficient, dry air cooling system was adopted. As this result, a compressor inlet temperature is a bit far from the critical point (31℃, 7.4MPa) because of design limitation of air cooling system. Fig. 1 shows the state properties applied design parameters in Table I. The isentropic efficiencies of compressor and turbine were determined from n_s d_s diagrams. Each specific speed (n_s) of compressor and turbine is 0.644 and 0.510. During analyzing suggested cycle, thermodynamic properties of CO_2 were obtained from the NIST REFPROP database in order to reflect the real gas effect.

Table I: Main design results and design parameters of KAIST MMR

Thermal power	36.2MWth	Mass flow rates	175.34kg/s
Net electric power	12.0MWe	Thermal efficiency	33.12%
Compressor inlet pressure	7.50MPa	Pressure ratio	2.67
Rotating speed	20,200rpm	Compressor efficiency	85%
Turbine efficiency	92%	Recuperator effectiveness	95%
Design point of recuperator	Hot side inlet : 432.7℃, 7.58MPa Cold side inlet : 149.9℃, 20.0MPa Temperature difference : 22-58℃		

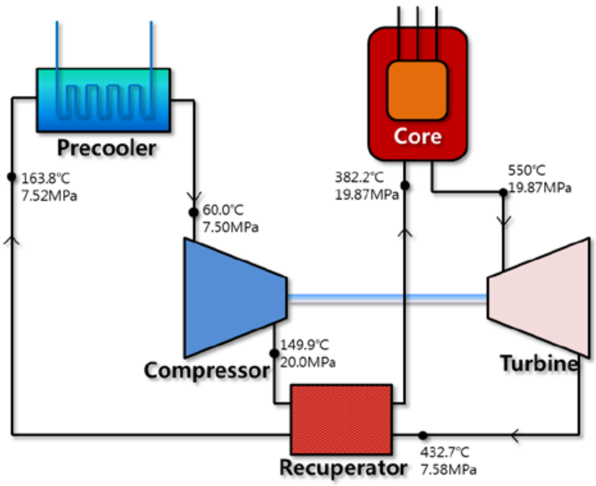

Fig.1. State properties of simple recuperated S-CO_2 Brayton cycle

Compressor performance maps which include on-design point and off-design points were obtained by using an in-house code, called KAIST_TMD. These results have limitation because it can only use in fixed inlet conditions. However, seasonal variation and unexpected situations influence each state property in the actual system. In these cases, all the correlations require to reflect changing conditions between obtained performance maps and the real conditions.

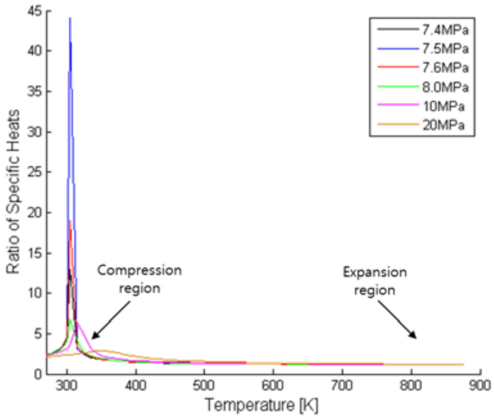

Fig.2. Efficiency prediction of compressor

One of the most well-known methods is equivalent conditions. Using equivalent conditions, such as corrected mass flow, corrected total specific enthalpy change, and corrected speed, is very convenient to predict the performance under standard conditions of temperature and pressure and sometimes of fluid molecular weight and ratio of specific heat. The performance variables of mass flow, specific work, and speed expressed on the basis of these standard conditions. The following properties are used for the compressor design: pressure, 7.5MPa; temperature, 60℃; molecular weight, 44.01kg/kmol; and specific heat ratio, 2.0771. In the case of turbine, the design conditions are: inlet pressure, 19.87MPa; inlet temperature, 550℃; molecular weight, 44.01kg/kmol; and specific heat ratio, 1.2413.

In many cases, such as air and water, (1)-(5) equations are simplified because specific heat ratio is almost constant. Because the fluid properties of CO_2 vary significantly near the critical point or compression region, the original equations are used to reflect the effect of specific heat ratio effect [4].

$$m_{correted} = m\sqrt{\left(\frac{V_{cr}}{V_{cr,ref}}\right)^2}\left(\frac{p_{o,ref}}{p_{o,in}}\right)\varepsilon \quad (1)$$

$$\Delta h_{o,corrected} = \Delta h_o\left(\frac{V_{cr,ref}}{V_{cr}}\right)^2 \quad (2)$$

$$N_{corrected} = N\sqrt{\left(\frac{V_{cr,ref}}{V_{cr}}\right)^2} \quad (3)$$

where

$$\varepsilon = \frac{\gamma_{ref}\left(\frac{2}{\gamma_{ref}+1}\right)^{\frac{\gamma_{ref}}{\gamma_{ref}-1}}}{\gamma\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma}{\gamma-1}}} \quad (4)$$

and

$$V_{cr}^{\ 2} = \frac{\gamma}{\gamma+1}RT_o \quad (5)$$

3. Results

Existing methodologies based on ideal gas are unsuitable for performance prediction of turbomachinery for S-CO_2 Brayton cycle. Because fluid properties of CO_2 near the critical point vary steeply. For this reason, many commercial codes have convergence problem near the critical point. To solve this problem, KAIST_TMD has been developed and validated with experimental data of the compressor. This code is implemented in MATLAB environment, and adopts equations based on enthalpy. These are coupled to the NIST data base to reflect real gas effect. Comparison of the predicted and measured compressor data with Sandia National Laboratory was conducted in the previous work [5].

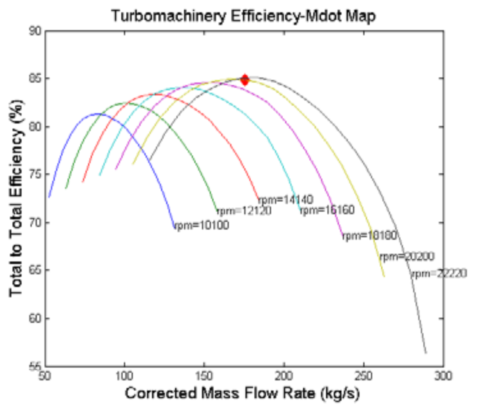

Fig.3. Efficiency prediction of compressor

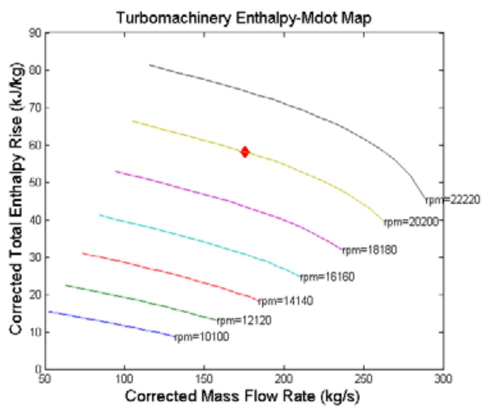

Fig.4. Corrected total enthalpy rise of compressor

The performance maps consist of two curves. The first is shown in Fig. 3 and Fig. 5. These plot the efficiency change depending on corrected mass flow rate. The corrected mass flow is defined as equation (1). The efficiency plots are shown at seven different shaft speeds. The design efficiencies are the red markers. The compressor efficiency is 85% and the turbine efficiency is 92%. The second performance maps of compressor and turbine are shown in Fig. 5 and Fig. 6. These plot the corrected specific enthalpy change as a function of corrected mass flow rate. The corrected values account for differences between the actual conditions and the standard conditions. Pressure ratio can be calculated through corrected specific enthalpy change.

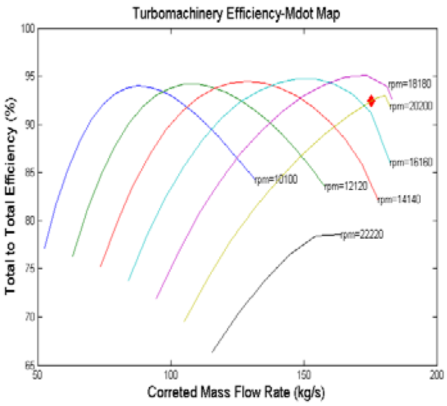

Fig.5. Efficiency prediction of turbine

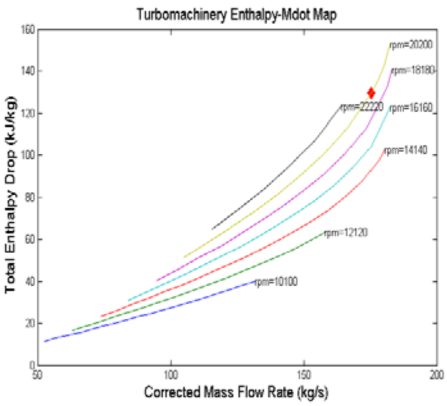

Fig.6. Corrected total enthalpy drop of turbine

4. Summary and further works

This paper describes the method of performance maps to predict the turbomachinery performance for different inlet conditions. One of the most well-known methods is equivalent conditions which include corrected mass flow, corrected total enthalpy rise, and corrected speed. Appropriate performance at any conditions which are different from the design condition can be calculated.

As further works, the predicted data from KAIST_TMD will be compared to other experimental data. Also turbine code will be validated. The suggested equations in this paper can be used to find the equivalent conditions of S-CO_2 Brayton cycle turbine. These data will be finally utilized for estimating the cycle off-design behavior of KAIST MMR.

ACKNOWLEDGEMENT

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