Quasi-static Cycle Performance Analysis of Micro Modular Reactor for Heat Sink Temperature Variation

Seong Kuk Cho [a], Jekyoung Lee [a], Yoonhan Ahn [a], Jeong Ik Lee [a*], Jae Eun Cha [b]
[a] *Dept. of Nuclear & Quantum Engineering, KAIST, 373-1, Guseong-dong, Yuseong-gu, Daejeon, 305-701, Republic of Korea*
[b] *Korea Atomic Energy Research Institute, 1045 Daedeok-daero, Yuseong-gu, Daejeon, 305-353, Republic of Korea*
[*] *Corresponding author: jeongiklee@kaist.ac.kr*

1. Introduction

A Supercritical CO_2 (S-CO_2) cycle has potential for high thermal efficiency in the moderate turbine inlet temperature (450~750℃) and achieving compact system size because of small specific volume and simple cycle layouts [1]. These features are very attractive to the Small Modular Reactor (SMR).

Due to complexity and large volume of the Power Conversion Unit (PCU), the existing SMRs have not achieved complete modularization of nuclear power plant including PCU. To overcome these issues, KAIST research team suggested an innovative concept of SMR, called KAIST Micro Modular Reactor (MMR). It adopts S-CO_2 as the working fluid. Owing to small specific volume of S-CO_2 and the development of heat exchanger technology, it can accomplish complete modularization of the system [2].

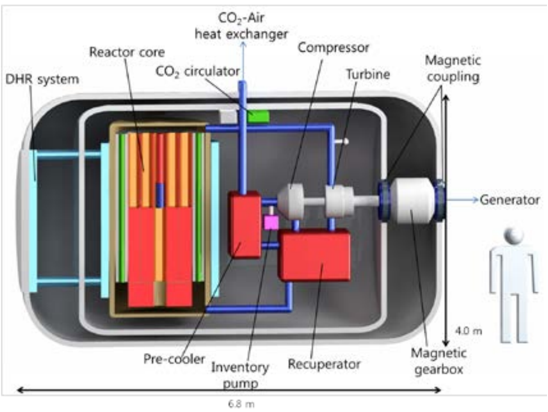

Fig. 1. Schematic configuration of MMR

The previous works focused on the cycle performance analysis for the design point only. However, the heat sink temperature can be changed depending on the ambient atmosphere condition, i.e. weather, seasonal change. This can influence the compressor inlet temperature, which alters the cycle operating condition overall. To reflect the heat sink temperature variation, a quasi-static analysis code for a simple recuperated S-CO_2 Brayton cycle has been developed by the KAIST research team. Thus, cycle performance analysis is carried out with a compressor inlet temperature variation in this research.

2. Methods and Results

2.1 Cycle description

From the preceding researches, a simple recuperated S-CO_2 Brayton cycle was selected for MMR to reduce PCU volume and system complexity. Furthermore, a dry air-cooling system for inland installation was suggested. Considering the air-cooling capability, a compressor inlet temperature was adopted to be 60 ℃, which is quite far from the critical point (31℃, 7.4MPa) [2].

Table I: Summary of main design results

Thermal power	36.2MWth	Mass flow rates	175.34kg/s
Net electric power	12.0MWe	Thermal efficiency	33.12%
Generator efficiency	98%	Mechanical efficiency	98%
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℃		

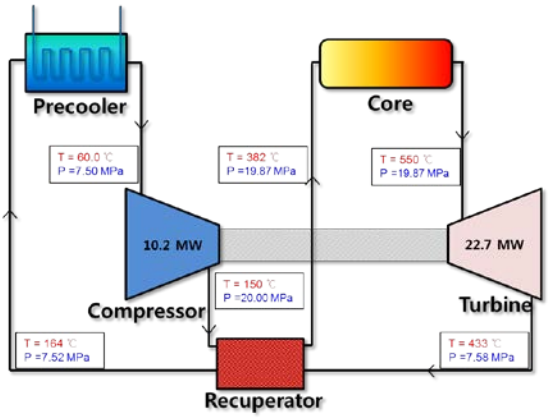

Fig. 2. State properties of simple recuperated S-CO_2 Brayton cycle

Fig. 2 shows the state based on Table I. To reflect thermodynamic properties of S-CO_2, in-house codes were integrated with the NIST REFPROP database.

2.2 Turbomachinery

Many commercial codes have convergence problem near the critical point. To improve it, turbomachinery in-house code, called KAIST_TMD, has been developed and validated with experimental data [3].

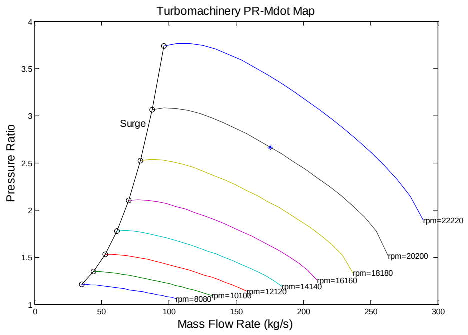

Fig. 3. Pressure ratio prediction of compressor

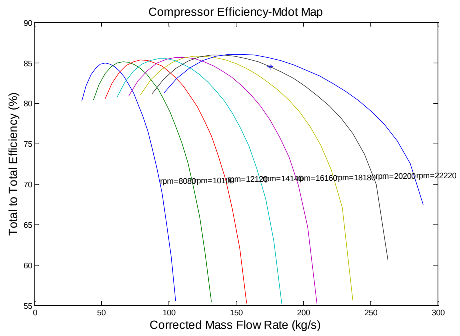

Fig. 4. Efficiency prediction of compressor

Surge and choke should be avoided in order to prevent from unstable operation. In the case of compressor, surge is predicted when the diffusion ratio of the impeller (W_{1s}/W_2) is equal to 2.4 [4]. Also, choke occurs when one of the relative flow velocities at the impeller inlet and outlet or diffuser reaches the speed of sound [5].

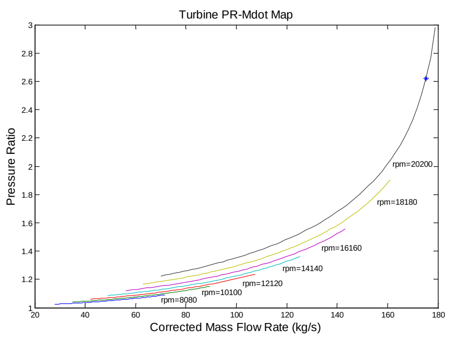

Fig. 5. Pressure ratio prediction of turbine

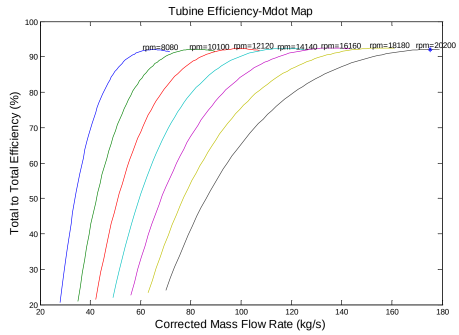

Fig. 6. Efficiency prediction of turbine

Meanwhile, a turbine has pressure ratio limits when the flow chokes. Choked flow usually occurs when the absolute velocity of flow at impeller outlet reaches the speed of sound. In practice, exhaust choke occurs at nominal values of $M_3 = 0.7$ instead of $M_3 = 1.0$ because of non-uniform exit flow [5].

2.3 Quasi-static code

In the case of dry air-cooling system, the ambient temperature of the local environment can affect the compressor inlet temperature. To estimate the S-CO_2 cycle performance for various compressor inlet conditions, a quasi-static analysis code was developed. Its main algorithm is depicted in Fig. 7.

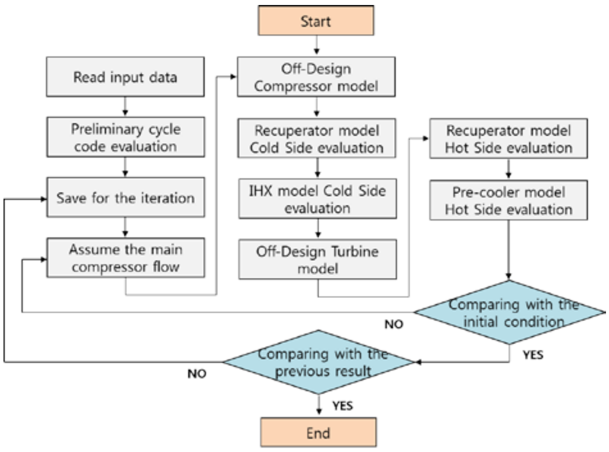

Fig. 7. Quasi-static system code algorithm

Equivalent conditions are used to reflect changing conditions between obtained performance maps and the off-design conditions. Equations (1) through (5) are used to reflect the variation of specific heat ratio in the S-CO_2 compression region.

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

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

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

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

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

The thermal efficiencies and generated work are obtained when the compressor inlet temperature is varying, as shown in Fig. 8. As the compressor inlet temperature increases, the thermal efficiency and generated work decreases. When the compressor inlet temperature reaches 70°C, the generation work is 9.74MWe. Considering the target generation work of MMR is 10MWe class, MMR can produce required electricity until the cycle minimum temperature attains 70°C.

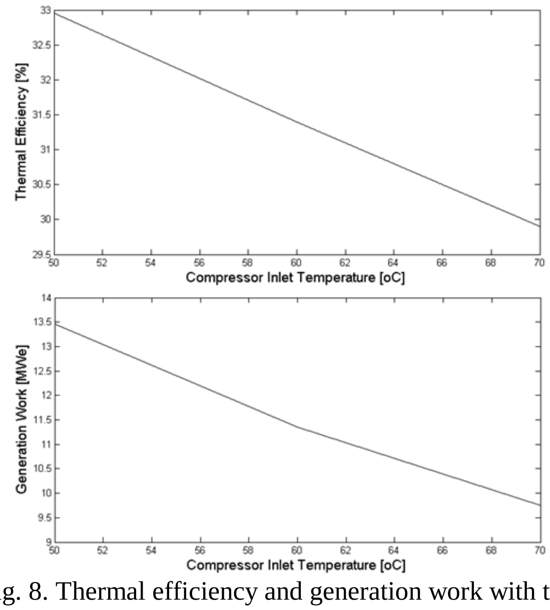

Fig. 8. Thermal efficiency and generation work with the compressor inlet temperature variation

3. Summary and further works

In the case of dry air-cooling system, the ambient temperature of the local surrounding can affect the compressor inlet temperature. To estimate the S-CO_2 cycle performance for various compressor inlet conditions, a quasi-static analysis code was developed. As the compressor inlet temperature increases, thermal efficiency and generated electricity decrease.

As further works, the experiment of S-CO_2 integral test loop will be performed to validate in-house codes, such as KAIST_TMD and the quasi-static code.

ACKNOWLEDGEMENT

Authors gratefully acknowledge that this work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government (MSIP)

REFERENCES

[1] V. Dostal, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, Ph. D. Thesis, Massachusetts Institute of Technology, 2004.
[2] S. G. Kim, et al., Conceptual System Design of a Supercritical CO2 cooled Micro Modular Reactor, Proceedings of ICAPP, 2015.
[3] S. K. Cho, et al., Off Design Performance Map Similarity Study of Radial Type Turbomachinery in Supercritical CO2 Brayton Cycle, Proceedings of the AJK Joint Fluids Engineering Conference, 2015.
[4] P. Harley, et al., Assessing 1D Loss Models for the Off-design Performance Prediction of Automotive Turbocharger Compressors, ASME Turbo Expo, 2013.
[5] S. L. Dixon, Fluid Mechanics: Thermodynamics of Turbomachinery, Butterworth-Heinemann, Oxford, UK.
[6] Glassman A. J., Turbine Design and Application, NASA SP-290, pp 58-60, 1972