Study of S-CO$_2$ power cycle off-design performances for SFR applications

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1. Introduction

A development of highly efficient and safe power conversion system for nuclear application has received worldwide attention. As an advanced technical solution for rising energy demand and global warming issues, a sodium-cooled fast reactor (SFR) with the supercritical carbon dioxide (S-CO$_2$) Brayton cycle has been suggested [1].

The S-CO$_2$ power conversion cycle can achieve high efficiency by reducing compression work Due to the liquid-like fluid characteristic (e.g. High density, low compressibility) of the CO$_2$ near the critical point (31℃, 7.4MPa). Moreover, the S-CO$_2$ power cycle can reduce the accident consequence compared to the steam Rankine cycle because of the mild sodium-CO$_2$ interaction.

For the industrial utilization, highly accurate off-design performance prediction is needed for stable operation. To understand system characteristic under transient conditions, KAIST_QCD (quasi-steady state cycle evaluation code) is developed.

However, the effect caused by dramatic change of thermodynamic property near the critical point, the conventional turbomachinery off-design performance mapping should be re-assessed. In this paper, the difference of the correction methods and their effect on the system are briefly discussed.

2. Methods and Results

In this section, the main algorithm of KAIST_QCD code is described with conventional turbo machinery off-design performance mapping methods.

2.1 Quasi-steady state system simulation code

The KAIST research team developed KAIST-QCD code to evaluate the system performance characteristic under quasi-steady state condition [2]. The figure 1 describes the main algorithm of the developed code.

As shown in the algorithm, the thermodynamic calculation iterates with the usage of off-design turbomachinery maps. The turbomachinery map can be obtained from the vendor or can be generated by turbomachine design and analysis code.

According to the previous research [1, 2], the best performing S-CO$_2$ cycle has several turbomachines. However, to evaluate the sole effect of the difference with off-design performance mapping methods, the recuperated closed Brayton cycle with single compressor-turbine set was selected. The schematic diagram with T-s diagram is shown in the figure 2.

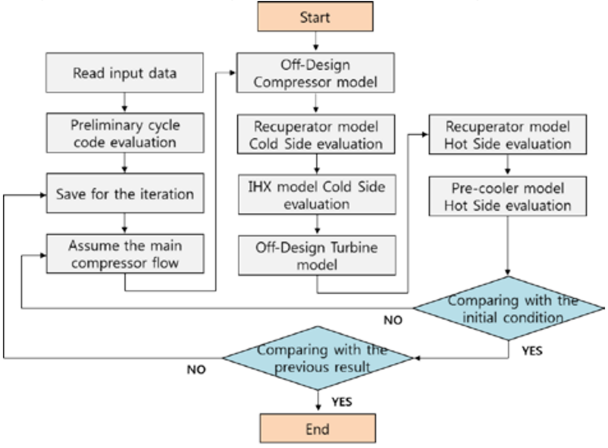

Fig. 1. Algorithm of the developed KAIST_QCD code

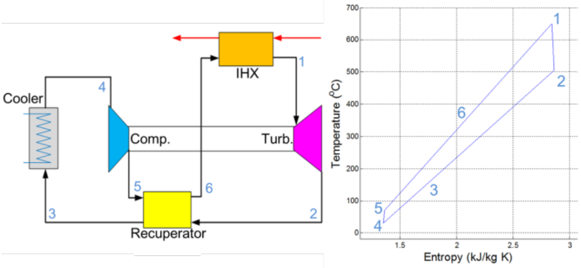

Fig. 2. Schematic diagram of recuperated closed Brayton cycle with T-s diagram

2.2 Performance correction methods for off-design operation

Commonly, the system or even a single component is hard to be operated at accurate designed condition. In the industrial gas turbine, therefore, the correction method is used to obtain equivalent performance at off-design conditions.

Following mathematical equations are conventional methods to define equivalent mass flow rate, equivalent speed and equivalent enthalpy change. The subscript ‘eq’, ‘ref’ and ‘a’ stand for ‘equivalent’, ‘reference’ and ‘actual condition’ respectively.

$$\dot{m}_{eq} = \frac{\dot{m}_a \sqrt{\theta}}{\delta}$$

$$N_{eq} = \frac{N_a}{\sqrt{\theta}}$$

$$\Delta h_{eq} = \frac{\Delta h_a}{\theta}$$

$$\text{where, } \theta = \frac{T_{0,a}}{T_{0,ref}},\ \delta = \frac{p_{0,a}}{p_{0,ref}}$$

In order to match the kinematic similarity of the different operating conditions, those equations are developed under ideal gas assumptions, such as constant specific heat ratio and isentropic expression of sound speed $\left(a = \sqrt{\gamma RT}\right)$. However, the S-$CO_2$ compressor operates near the critical point which can't be approximated by ideal gas assumptions. Also, the difference between specific heat ratios from the inlet to the outlet is significantly large, nearly one order of magnitude in comparison.

To improve the correction methods while considering the real gas effect, the equivalent parameters are re-established by additional corrections with compressibility factor and specific heat ratio [3]. Th following set of equations are described with the differences.

$$\dot{m}_{eq} = \frac{\dot{m}_a \sqrt{\theta}}{\delta} \varepsilon$$

$$N_{eq} = \frac{N_a}{\sqrt{\theta}}$$

$$\Delta h_{eq} = \frac{\Delta h_a}{\theta}$$

$$\text{where, } \varepsilon = \gamma_{ref} \left(\frac{2}{\gamma_{ref}+1} \right)^{\frac{\gamma_{ref}}{\gamma_{ref}-1}} / \gamma_a \left(\frac{2}{\gamma_a+1} \right)^{\frac{\gamma_a}{\gamma_a-1}},$$

$$\theta = \frac{V_{cr,a}{}^2}{V_{cr,ref}{}^2},\ \delta = \frac{p_{0,a}}{p_{0,ref}}$$

$$(V_{cr} = \sqrt{\gamma Z R T_o} \text{ or } \sqrt{\frac{2\gamma}{\gamma+1} Z R T_o}\ )$$

The difference between ideal gas approach, compressibility correction and specific heat ratio correction are tabulated in Table I. The expressions of sonic speed in each method are also described.

Table I: Description of correction models with restrictions

Methods	Description	Restrictions	
	Sonic speed (a)	Compressibility factor (Z)	Specific heat ratio (γ)
Ideal gas approach	$\sqrt{\gamma RT}$	Z = 1	γ = constant
Compressibility correction	$\sqrt{\gamma ZRT}$	Z ≠ 1	γ = constant
Specific heat ratio correction	$\sqrt{\frac{2\gamma}{\gamma+1} ZRT}$	Z ≠ 1	γ ≠ constant

2.3 Results

Through the KAIST_QCD code, 500MW thermal scale system with increase of compressor inlet temperature case (29℃-34℃) was studied. Using the three different methods, system performance are compared. The following figures show discrepancy of the methods by reporting the generation work, system efficiency and mass flow rate. Also the traces of compressor inlet temperature and pressure conditions are reported.

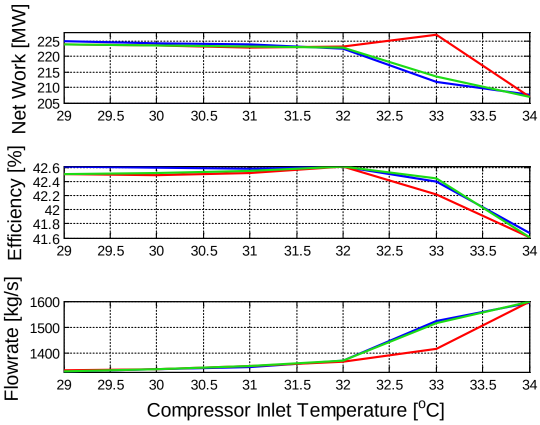

Fig. 3. Net work, system efficiency and mass flow rate comparison

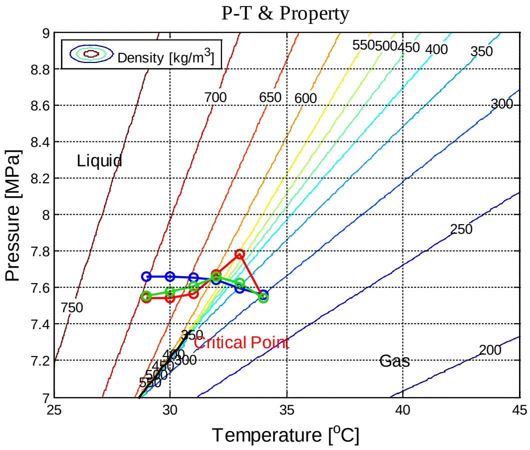

Fig. 4. Trace of compressor inlet conditions with density contour line

The blue, red and green colors represent the results of ideal gas approach, compressibility correction and specific heat ratio correction methods respectively. The discrepancies are caused of the difference in sonic speed approximations.

The compressibility factors of different conditions are described in figure 5. At the design point (32℃ 7.7MPa), the compressibility factor is 0.222. During the case study, the compressibility factor changes from 0.2 to 0.4.

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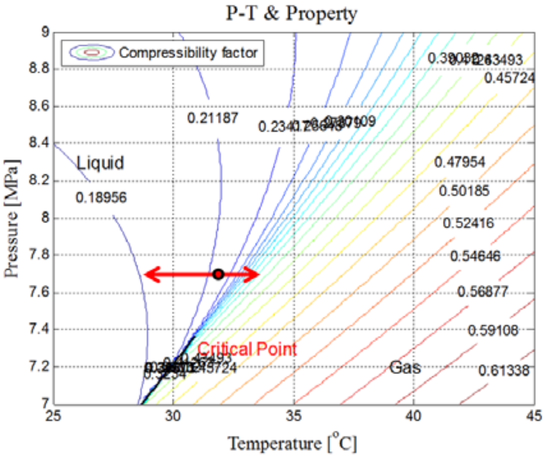

Fig. 5. Compressibility factor of CO_2 near critical point

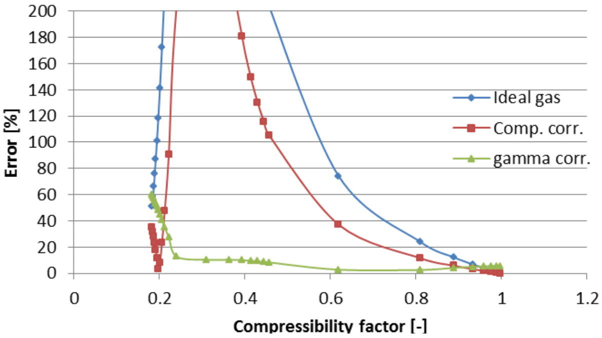

Fig. 6. Sonic speed approximation error of different methods

At 7.7MPa of CO_2, the sonic speed approximation errors are plotted in figure 6.

The ideal gas approximation can be applied in compressibility factor range of 0.95-1, and the range is improved to 0.9-1 with compressibility factor correction. By specific heat ratio correction, the range was significantly improved to 0.4-1 but it still has a limitation for S-CO_2 compressor operating conditions (0.2-0.4). Also the error increases as the operating conditions are approached to the design conditions.

3. Conclusions & Further works

To utilize the S-CO_2 power cycle technology for SFR application, the KAIST_QCD code is developed to understand system characteristic under transient conditions. Through the developed code, off-design performance correction methods are studied. Due to the difference between ideal gas approach, compressibility correction and specific heat ratio correction, the system behavior predictions showed difference while the compressor inlet temperature was being increased (29℃-34℃).

The authors concluded that the performance of the compressor is an important factor on the off-design operation in the S-CO_2 Brayton cycle and the correction methods for near critical point regime are needed to be improved.

The developed code will be validated with the experimental data of KAIST S-CO_2 test facility. Also, the mixture of CO_2 working fluid with helium or xenon as an alternative solution for mitigating the near critical point effects will be investigated.

REFERENCES

[1] V. Dostal, M.J. Driscoll, P. Hejzlar, A Supercritical Carbon Dioxide Cycle for Next Generation Nuclear Reactors, MIT-ANP-TR-100, 2004.

[2] Y. Ahn, Study of innovative Brayton cycle design and transient analysis for Sodium-cooled fast reactor application, Ph.D. Dissertation, 2016

[3] A. J. Glassman, Turbine Design and Application, NASA SP-290, pp 58-60.

[4] J. Lee, S. Baik, S. K. Cho, J. E. Cha, J. I. Lee, Issues in performance measurement of CO2 compressor near the critical point, Applied Thermal Engineering, 2016.

[5] E.W. Lemmon, M.L. Huber, M.O. McLinden, NIST Reference Fluid Thermodynamic and Transport Properties, U.S. Department of Commerce (2010).