Application of Isothermal turbine to a simple recuperated cycle for KAIST Micro Modular Reactor

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1. Introduction

Among various benefits of supercritical carbon dioxide Brayton cycle (S-CO_2 cycle), compactness is regarded as one of the important figures [1]. To maximize compactness and achieve better thermal efficiency of S-CO_2 cycles, study of applying isothermal compressor to an S-CO_2 cycle has been conducted by Heo et al [2]. Heo discovered that an isothermal compressor concept increases the thermal efficiency of partial heating cycles but Heo also found that increase of thermal efficiency is not to the case for simple recuperated cycle due to lower compressor outlet temperature, which makes heater inlet temperature to become lower and recuperator effectiveness becomes limited by inner pinch point problem. These studies of isothermal compressor showed possibilities of realization of isothermal turbomachinery and constructed a framework for such system.

Derived from the isothermal compressor study, a preliminary research of using an isothermal turbine for an S-CO_2 power cycle has started in KAIST. The key idea of isothermal turbine is containing fissionable material in the stator blade of axial gas turbine blade. The axial gas turbine has rotor blades which convert heat energy into mechanical energy and stator blades which adjust direction of flow path for the rotor blades. Thus, the isothermal turbine concept is after working fluid passes through rotor blades and perform work the working fluid is reheated by nuclear heat from the stator blades during correction of flow path. The conceptual diagram is shown in Fig .1. If the system is well designed, the system will approach to near isothermal turbine. The axial gas turbine from a nuclear heat source is not brand new technologies. US Air Forces already designed an axial gas turbine of nuclear heat source for propulsion purpose and conducted many experiments in the past [3].

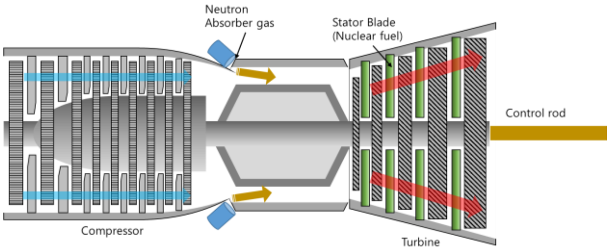

Fig. 1. Conceptual diagram of isothermal turbine with fissionable stator blade.

Before further developing the isothermal turbine concept, the advantages of when the isothermal turbine is applied has to be first studied. According to Göktun et al. the recuperated Brayton cycle of ideal gas with isothermal heat addition showed better cycle efficiency than original recuperated Brayton cycle under the pressure ratio around 10 [4]. Its result demonstrated that isothermal gas turbine has potential in terms of efficiency and compactness of size despite ideal gas. In this paper, various S-CO_2 simple recuperated layouts will be compared in terms of efficiency with respect to turbine inlet pressure and temperature: 1. Isentropic turbine and compressor, 2. Isentropic turbine and isothermal compressor, 3. Isothermal turbine and Isentropic compressor, 4. Isothermal turbine and Isothermal compressor.

2. Methods and Results

2.1 Isothermal turbine efficiency

According to Heo, isothermal compressor efficiency is defined as equation (1).

$$\eta_{iso-c} = \frac{W_{ideal}}{W_{actual}} = \frac{\int vdP}{\sum \delta w} \tag{1}$$

δw represents infinitesimal specific work during isothermal process. In Fig. 2, isentropic efficiency of compressor is applied to a single infinitesimal compression and it is found that the isothermal compressor efficiency approaches to isentropic efficiency of a single infinitesimal compression as the infinitesimal process become infinite as shown in Fig. 3.

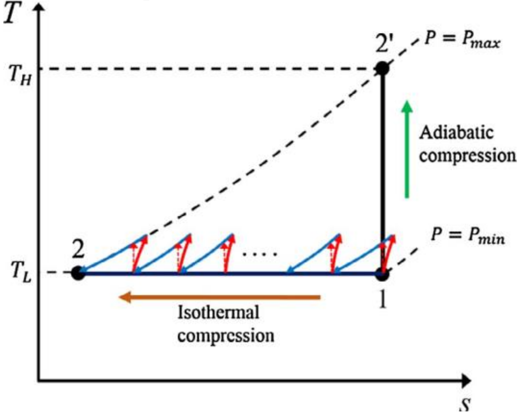

Fig. 2. Diagram of the isothermal compression process using the infinitesimal approach.

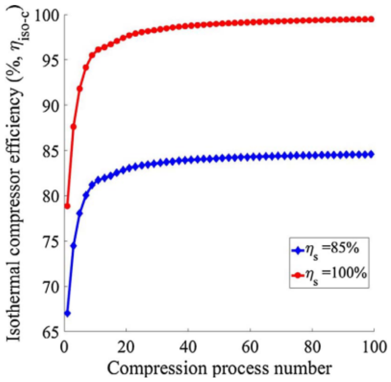

Fig. 3. Diagram of verifying isothermal compressor efficiency (CIT = 35°C, CIP = 7.5MPa, PR=2.67)

Even though this correlation was only numerically validated, it could be analytically proven by assuming ideal gas equation of state and thermodynamics in this paper. Firstly, ideal specific work during isothermal process can be analytically obtained from equation of state of ideal gas as shown in equation (2).

$$w_{ideal} = \int v dP = RT_{in} \int \frac{1}{P} dP = RT_{in} \ln\left(P_{ratio}\right) \qquad (2)$$

The actual work also can be obtained from the definition of infinitesimal work. The pressure ratio of single infinitesimal process is defined as equation (3).

$$P_{ratio,\inf} = (P_{ratio})^{\frac{1}{m}} \qquad (3)$$

Superscript 'm' means stage number of infinitesimal process which is an imaginary stage number for analyzing the isothermal process. Therefore, single infinitesimal specific work can be obtained by introducing isentropic efficiency η_c .

$$\begin{aligned}\delta w_i &= \frac{h_{i,isen} - h_i}{\eta_c} = \frac{C_p (T_{i,isen} - T_{in})}{\eta_c} \\ &= \frac{C_p T_{in}}{\eta_c}\left(\frac{T_{i,isen}}{T_{in}} - 1\right) = \frac{C_p T_{in}}{\eta_c}\left(P_{ratio,\inf}^{\frac{k-1}{k}} - 1\right)\end{aligned} \qquad (4)$$

During the process, any i_{th} infinitesimal process has the same pressure ratio, $P_{ratio,inf}$, so that single infinitesimal specific work can be obtained as shown in equation (4). Thus, the total actual work can be calculated by equation (5)

$$\begin{aligned}w_{actual} &= \lim_{m\to\infty} \sum_{i=1}^{m} \frac{C_p T_{in}}{\eta_c}\left(P_{ratio,\inf}^{\frac{k-1}{k}} - 1\right) \\ &= \lim_{m\to\infty} \frac{C_p T_{in}}{\eta_c}\left(\frac{(P_{ratio}^{\frac{k-1}{k}})^{\frac{1}{m}} - 1}{\frac{1}{m}}\right)\end{aligned} \qquad (5)$$

After infinitesimal stage number approahces infinite, the specific actual work can be calculated with equation (6).

$$w_{actual} = \frac{C_p T_{in}}{\eta_c} \ln P_{ratio}^{\frac{k-1}{k}} = \frac{RT_{in}}{\eta_c} \ln P_{ratio} \qquad (6)$$

Thus, isothermal compressor efficiency can be defined as a single infinitesimal isentropic efficiency as shown in equation (7).

$$\eta_{iso-c} = \frac{w_{ideal}}{w_{actual}} = \eta_c \qquad (7)$$

Even though this correlation is proven by ideal gas assumption, S-CO$_2$ isothermal compressor near the critical point which has large deviation from ideal gas showed that isothermal compressor efficiency approaches to a single infinitesimal compression efficiency in Fig. 3. Therefore, isothermal turbine efficiency can also be defined by using a single infinitesimal expansion like equation (7) and infinitesimal process approach is also applied to isothermal turbine. Moreover, an S-CO$_2$ turbine operates on a point where it is far from the critical point, so that the isothermal turbine efficiency will be clearly as approaching a single infinitesimal expansion because this correlation is derived from the ideal gas equation of state in equation (8).

$$\eta_{iso-t} = \frac{w_{actual}}{w_{ideal}} = \eta_t \qquad (8)$$

η_t is a single infinitesimal expansion efficiency.

2.2 Case study of simple recuperated cycle with isothermal turbomachinery.

The reference system is MMR which has been developed to be an integral modular reactor so that the whole system can become transportable . For this MMR, the simple recuperated cycle was selected which has a simple layout and achieve high compactness while providing reasonable efficiency. Fig. 4, shows the diagram of a simple recuperated cycle of MMR.

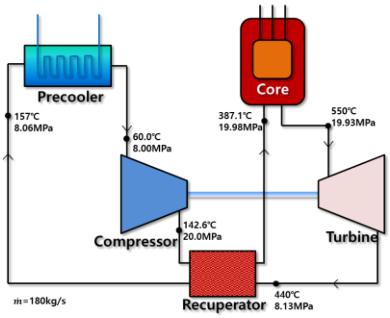

Fig. 4. The reference simple recuperated cycle of MMR

With this reference system, isothermal compressor, isothermal turbine, and both isothermal compressor and turbine are applied to the simple recuperated cycle and each cycle configurations are optimized by KAIST CCD which is an in-house code [5]. The optimized design parameters are summarized in the Table I.

Table I: optimized design parameters of each cycles

	Reference cycle	Isothermal Compressor	Isothermal turbine	Isothermal compressor and turbine
Qin (MW_{th})	36.18	36.18	102.75	69.47
W_{turb} (MW)	21.84	15.8	62.13	31.07
W_{comp} (MW)	9.45	4.25	24.8	7.71
η_{eff} (%)	34.24	31.92	36.32	33.62
$\dot{m}$ (kg/s)	180.0	130.63	473.82	236.97

The reason why cycles with isothermal turbine needs larger heat source is to maintain the turbine outlet temperature as same as the turbine inlet temperature. Because of that, cycles with isothermal turbine should have larger heat source than the reference system. The following figures shows the T-S diagram of each cycle.

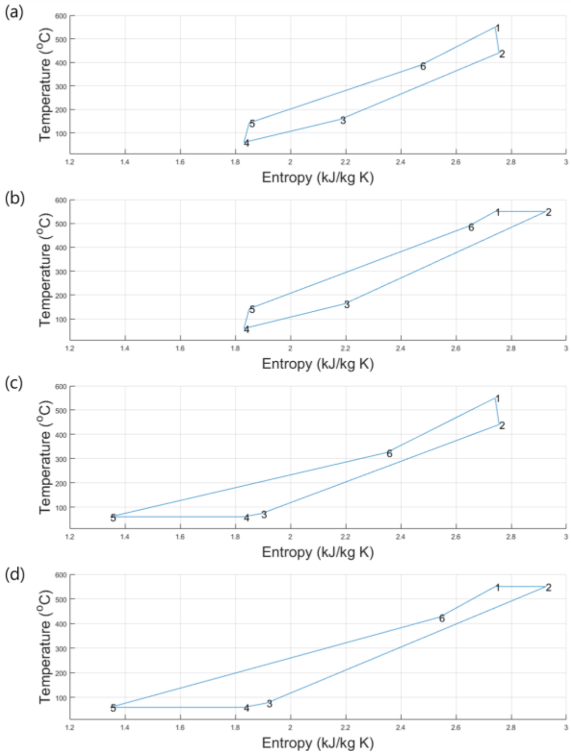

Fig. 5. T-S diagram of the (a) reference cycle, (b) with isothermal compressor, (c) with isothermal turbine, and (d) with isothermal turbine and compressor.

With the reference cycle parameters isothermal turbine has the highest cycle efficiency. This is because isothermal turbine makes the turbine inlet temperature high enough so that the transferred heat through recuperation becomes larger and it also makes the high core inlet temperature. This is the reason behind the high efficiency. Moreover, pinch problem is not present in the case of cycle with only isothermal turbine because the recuperator hot side inlet temperature is also higher than the reference.

2.3 Cycle efficiency with respect to turbine inlet temperature and pressure.

In this part, cycle efficiencies of each cycles with respect to turbine inlet pressure and temperature will be reported.

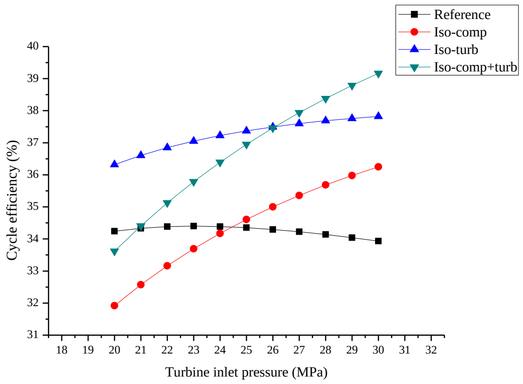

Fig. 6. Cycle efficiencies of each cycles vs. turbine inlet pressure

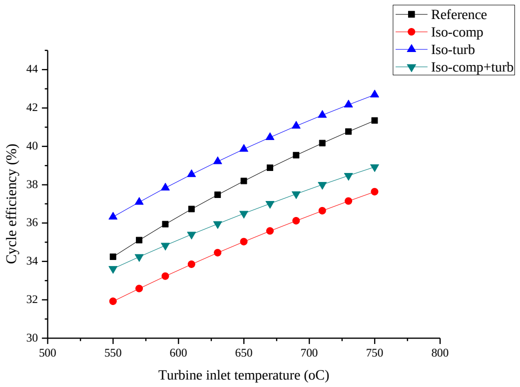

Fig. 7. Cycle efficiencies of each cycles vs. turbine inlet temperature

Efficiencies of simple recuperated cycle with an isothermal turbine with respect to turbine inlet pressure show that the highest efficiency under turbine inlet pressure is 26MPa. This is because the reduction of compressor work is significant than increasing of turbine work at high turbine inlet pressure as shown in Fig. 6. In Fig .7, all of cycles show monotonic increase with respect to turbine inlet temperature. The simple recuperated cycle with an isothermal turbine has the highest cycle efficiency for the increase of turbine inlet temperature.

3. Conclusions

To maximize thermal efficiency and minimize system size, isothermal turbomachinery concept is considered. A thermodynamic framework of isothermal compressor was directly applied for the isothermal turbine analysis. In this paper, various cases of the simple recuperated cycle are optimized and parametric study of the simple recuperated cycle is performed in terms of turbine inlet pressure and temperature. The results show that isothermal turbine shows some promising performances and therefore, it will be further pursued in the future.

REFERENCES

[1] V. Dostal, M. J. Driscoll, and P. Hejzlar, "A supercritical carbon dioxide cycle for next generation nuclear reactors," *USA: Massachusetts Institute of Technology*, vol. MIT-ANP-TR-100, 2004.

[2] J. Y. Heo, M. S. Kim, S. Baik, S. J. Bae, and J. I. Lee, "Thermodynamic study of supercritical CO 2 Brayton cycle using an isothermal compressor," *Applied Energy*, vol. 206, pp. 1118-1130, 2017.

[3] R. Colon, "Flying on Nuclear, The American Effort to Built a Nuclear Powered Bomber " *http://www.aviation-history.com/articles/nuke-american.htm*.

[4] S. Göktun and H. Yavuz, "Thermal efficiency of a regenerative Brayton cycle with isothermal heat addition," *Energy Conversion and Management*, vol. 40, pp. 1259-1266, 1999/08/01/ 1999.

[5] M. S. Kim, Y. Ahn, B. Kim, and J. I. Lee, "Study on the supercritical CO2 power cycles for landfill gas firing gas turbine bottoming cycle," *Energy*, vol. 111, pp. 893-909, 2016/09/15/ 2016.