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A Conceptual Study of Using an Isothermal Compressor on a Supercritical CO_2 Brayton Cycle for SMART Application

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1. Introduction

The attention towards small modular reactors (SMRs) has been increasing due to their potential coming from modularization. With capacity of less than 300MWe, SMRs consist of modularized components, which can bring the overall size down and reduce the construction period. In addition, the system designs can be further improved by other applications of nuclear energy such as desalination, district heating, propulsion, and hydrogen production.

To maximize the benefits of modularization, the supercritical CO_2 (S-CO_2) power cycle can replace the conventional steam Rankine cycle to increase the cycle efficiency and reduce its system size. Previous works have been conducted to evaluate potential advantages of applying the S-CO_2 cycle to SMRs, specifically to SMART (System-integrated Modular Advanced Reactor) which is an integral SMR developed by KAERI (Korea Atomic Energy Institute) [1].

One of the optimized S-CO_2 cycle layouts is the recompressing Brayton cycle. This paper attempts to improve the cycle layout by replacing the conventional compressor with an isothermal compressor, of which its potential in the S-CO_2 power cycle is conceptually being evaluated [2]. An isothermal compressor minimizes compression work and further reduces the system size by having smaller heat exchanger requirements. The study also will perform an optimization process for pressure ratio maximizing cycle efficiency.

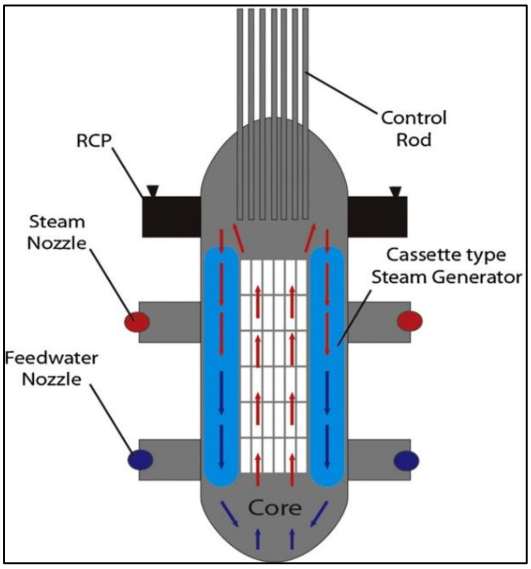

Fig 1. SMART reactor developed by KAERI [1]

2. Methods and Results

In order to evaluate the advantages of using the isothermal compressor in an S-CO_2 cycle layout, a framework definition must be established for the turbomachinery.

2.1 Defining the isothermal compressor

Isothermal compression is a process in which the working fluid undergoes compression at constant temperature. However, to model the real work required to define the isothermal efficiency of the turbomachine, a method to calculate the real work is required. The authors have suggested an 'infinitesimal approach', which divides an isothermal compression process into a series of isentropic compression and constant pressure cooling processes, as shown in Fig. 2.1. An additional parameter of stage number represents how the isothermal process can be modelled similarly to a multistage compression with intercooling process.

To verify that this framework is mathematically valid, it can be seen that as the number of stages increases, the real work, or the sum of work of isentropic compression processes, approaches the ideal isothermal compression work. This is shown evident in Fig 2.2 displaying the value of $\eta_{iso,c} \left(= \frac{ideal\ work}{actual\ work}\right)$ approaching the $\eta_{isen,c}$ value.

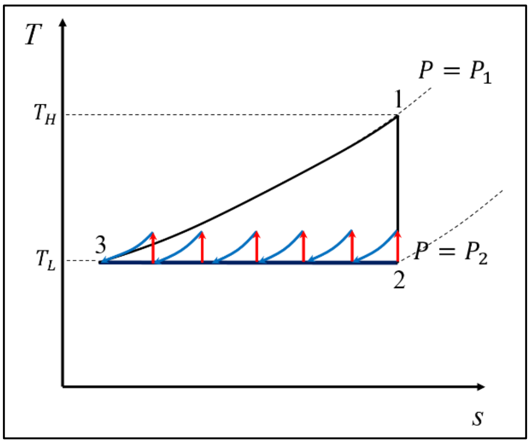

Fig 2.1. T-s diagram of Brayton cycle with isothermal compression in the infinitesimal approach (red – isentropic compression, blue –cooling at constant pressure)

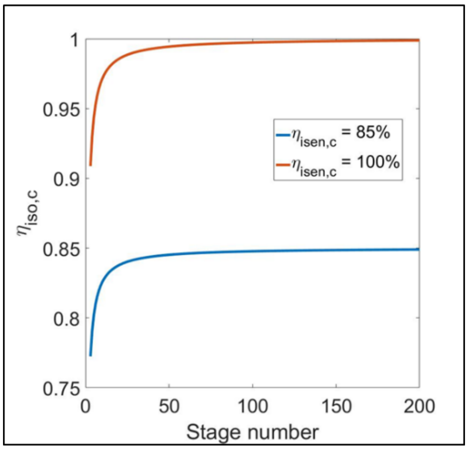

Fig. 2.2. Diagram of isentropic compression stage efficiency

2.2 Cycle operating conditions

Design parameters for performance analysis are obtained from [1], and they are selected to formulate the reference values for comparison. Table I specifies various parameters required for analysis. Here, the flow split ratio is defined as the ratio between the recuperated amount of mass flow and the total mass flow rate. Also, the efficiency for the isothermal compressor requires the value of the isentropic efficiency of infinitesimal compression processes. This value is equal to the given compressor efficiency value in Table I.

Table I: Design specifications of the S-CO_2 cycle under the SMART conditions

Design Parameters	**Values**
Thermal power (MWth)	330
Turbine inlet temperature (℃)	310
Compressor outlet pressure (MPa)	15
Compressor inlet temperature (℃)	32
Turbine pressure ratio	1.88
Turbine efficiency (%)	90
Compressor efficiency (%)	89
Recompressing compressor efficiency (%)	89
Recuperator effectiveness (%)	98
Recuperator pressure drop (hotside) (kPa)	100
Recuperator pressure drop (coldside) (kPa)	100
Cooler pressure drop (kPa)	80
IHX pressure drop (kPa)	130
Generator efficiency (%)	98
Flow split ratio	0.3

2.3 Cycle analysis method for layout options

The analysis has been conducted using the KAIST-Closed Cycle Design (KAIST-CCD) in-house code for cycle analysis. The recompressing Brayton cycle shown in Fig. 2.3. is selected as a reference cycle layout for comparison. The recompressing iso-Brayton cycle refers to the modified system that replaces the conventional main compressor with an isothermal compressor.

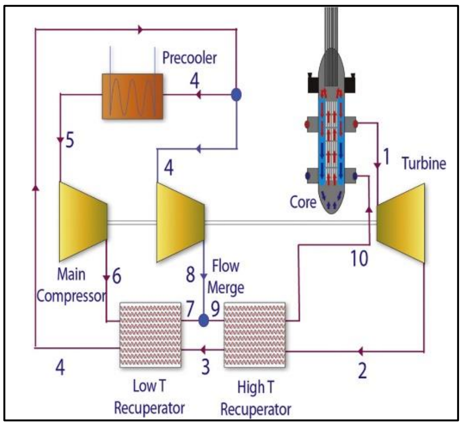

Fig. 2.3. Recompression Brayton cycle layout [1]

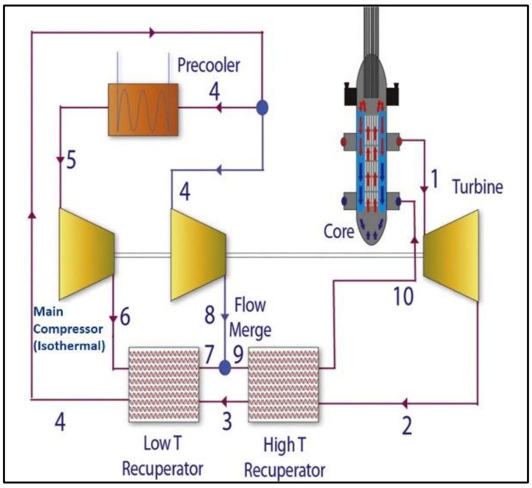

Fig. 2.4. Recompression Brayton cycle layout with an isothermal compressor [1]

2.4 Optimized cycle results

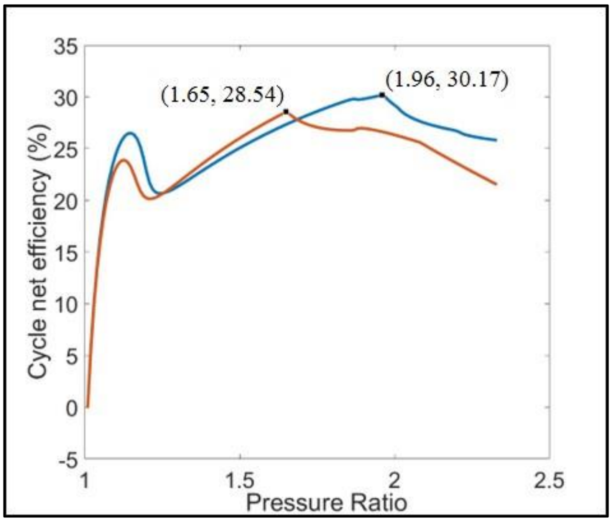

Fig. 2.5. Cycle net efficiency as a function of pressure ratio

The two cycle layouts are optimized for turbine pressure ratio and flow split ratio. The points that maximize the cycle net efficiency, while holding flow split ratio constant at 0.3, are noted in the Fig. 2.5. It is seen that when pressure ratio = 1.65, the cycle net efficiency is maximum for 28.5% for the reference, whereas at pressure ratio = 1.96, efficiency point is highest at 30.2% for recompressing iso-Brayton cycle layout.

In order to optimize with both parameters, pressure ratio and flow split ratio, a 3-D plot is created to check for the global maximum.

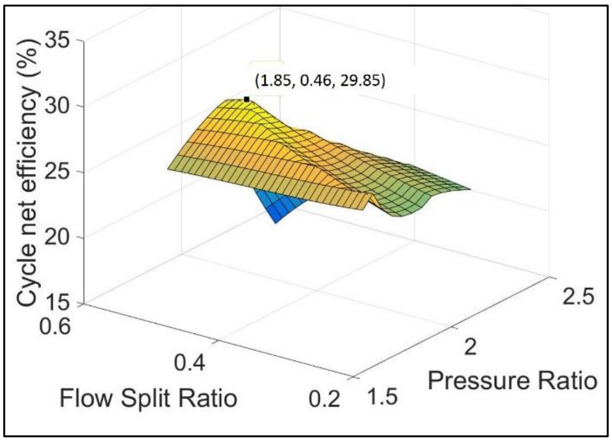

Fig. 2.6. Cycle net efficiency as a function of pressure ratio and flow split ratio for reference cycle layout

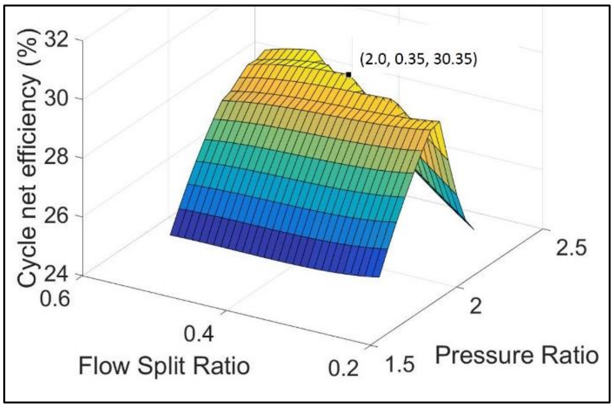

Fig. 2.7. Cycle net efficiency as a function of pressure ratio and flow split ratio for recompression iso-Brayton cycle layout

It can be seen that the two parameters affect one another in the optimization process. By comparing the two results, the optimized recompression iso-Brayton cycle has slightly improved cycle net efficiency than the reference cycle.

The T-s diagrams can also be compared between the two layouts as shown in Fig. 2.8.

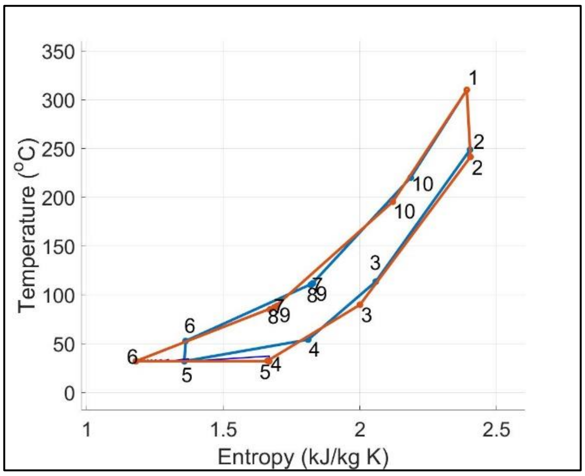

Fig. 2.8. T-s diagram of two cycle layouts in comparison (red – recompression iso-Brayton, blue – reference)

3. Conclusions

The SMR applications, for which SMART reactor has been represented, can take advantage of the currently developing S-CO_2 cycle greatly by the reduction of size. By introducing the isothermal compressor, the cycle layout considered in [1] has been further improved by increasing the cycle net efficiency by around 0.5%.

Further works for this research include the heat exchanger sizing done through the in-house code KAIST-HXD, and further parametric study for other cycle parameters.

REFERENCES

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